A procedure for delineating a search region in the UAV-based SAR activities

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ABSTRACT
We propose a simple geometrical approach for delineating a region above which an Unmanned Aerial Vehicle (UAV) should fly to support the Search and Rescue (SAR) activities. The procedure is based on the concept of a crow's flight distance travelled by a lost person and its probability distribution, for areas in which there does not exist any SAR database that can be used to estimate parameters of such a distribution. The novelty of the procedure lies in its indirect character, namely we do not estimate these parameters but we seek regions that reveal comparable topographic settings in order to borrow the parameters from where they are known. Our analysis focuses on the Wakeby probability distribution of the crow's flight distance, the parameters of which are known for Alberta in Canada. We compare topographic and ecological characteristics of Alberta with the same features in Poland and argue that – under a few assumptions – it is allowed to use the Wakeby probabilistic model for the Canadian region in Polish conditions. Having borrowed the parameters in question, we present the skills of the geometrical approach in an experiment that utilizes flight simulations carried out with two professional micro UAV systems.

KEYWORDS
Search and Rescue (SAR); Unmanned Aerial Vehicle (UAV); Wakeby distribution; flight planning; geomorphometry

1. Introduction
Search and Rescue (SAR) missions aim to locate a lost person in the shortest possible time. While time is the key element influencing a probability of a successful scenario (when a missing individual is found alive) it is crucial to put SAR resources in the right location as quickly as possible. According to recent studies, if a person is not found within 51 hours since becoming lost, the possibility of surviving declines significantly (Adams et al. 2007). This time period could be even shorter (24 hours) for Alzheimer’s disease patients (Koester & Stooksbury 1995).

There is a great body of knowledge about behaviour of a lost person. The chance for a lost subject to be in the area under consideration is described by the notion of the probability of area (POA) (Koester 2008). Studies of SAR incidents show that both the characteristics of a given person as well as environmental factors have a strong impact on where a lost person can be found (Lin & Goodrich 2010; Doherty et al. 2014). Person-related features (e.g. activity in which a lost person was involved when becoming lost, age, health condition) together with geographical factors (e.g. terrain, climate, vegetation, presence of streams, number of roads) can affect the ease of travel and motion as well as can influence a lost person behaviour (Heth & Cornell 1998; Ciolli et al. 2006; Koester 2008; Doherty et al. 2014). Whenever the information is available, it can be used at the initial phase of search to
define POA in order to optimally allocate resources, and consequently shorten the field search (Koester 2008).

The wealth of theoretical knowledge on how a lost person behaves should be associated with airborne tools for observing terrain in real time. These include airplanes and helicopters equipped with numerous sensors as well as Unmanned Aerial Vehicles (UAVs) equipped with cameras sensitive to different ranges of spectrum. UAVs can support SAR procedures by performing two types of tasks: (1) searching for a lost person without increasing risk and (2) providing general situation overview images that present possibly the largest part of the area of interest at the appropriate resolution (Murphy et al. 2008). There were many attempts to use UAVs for supporting SAR activities. They include for instance: detecting human shapes using video cameras (Goodrich et al. 2008), detecting human body using colour and thermal images (Rudol & Doherty 2008; Molina et al. 2012), detecting injured civilians using charge-coupled device (CCD) and thermal cameras (Doherty & Rudol 2007), tracking person’s movement with infrared sensors (Miller et al. 2008). Not only visible light images, near infrared photographs and thermal images are used to support SAR activities. For instance, synthetic aperture radar was also found to be a valuable tool for target detection (Lukowski & Charbonneau 2002; Jia et al., 2015). Recently, the UAV-assisted SAR missions are not limited to observation and detection but also include transportation of loads to victims (Doherty & Rudol 2007; Bernard et al. 2011). There are different aspects of using UAVs to support search practices in urban, wilderness and maritime environments. One of them answers the question on how to optimally plan the UAV-flight path in order to achieve different operational goals (Goodrich et al. 2008; Lin & Goodrich 2009; Clark & Goodrich 2013). There are many algorithms supporting that task in civil or military applications and most of them take into account different UAV constraints such as kinematic restrictions (Bourgault et al. 2006; Wang et al. 2014) or communication range limitations (Tseng et al. 2014). In SAR procedures path-planning algorithms should be performed in a specific region where the probability of a finding lost person is maximized (Lin & Goodrich 2014). For instance, Goodrich et al. (2008) propose the method, named Generalized Contour Searches, that creates a continuous path following the contours of two important probability distributions. The algorithm approximates two optimal paths: spiral for the unimodal and symmetric distribution and the lawn-mower search over the rectangular area for the uniform distribution. The authors claim that the use of the algorithm leads to such camera-based observations which guarantee the highest probability of containing and gives complete and maximally efficient search (Goodrich et al. 2008). In another approach, Lin & Goodrich (2009) model the UAV path-planning task as a discretized combinatorial optimization problem and propose a set of path-planning algorithms using novel techniques such as ‘global warming effect’ and path crossover/mutation. The authors evaluate the performance of their algorithms on representations of typical Wilderness SAR probability distribution maps – i.e. unimodal, bimodal and bimodal with overlap solutions – and show that these algorithms operate within reasonable computation time with good efficiency. An extension of the UAV path planning (or re-planning) is the problem of avoiding obstacle and collision during the flight (Qu et al. 2005; Meng & Gao 2010; Dong et al. 2011), tracking a subject that is moving and coordinating robots in a multi-robot missions (Ryan & Hedrick 2005). An additional dimension of complexity to the task of finding an optimal UAV-flight path can be the problem of subject-detection limitations associated with vegetation density, lighting conditions, weather conditions and other sensor-related factors (Lin & Goodrich 2014). Probability of containing good information, quality of material collected during the flight and assessment of its spatial coverage quality (Ryan & Hedrick 2005; Morse et al. 2010; Lin & Goodrich 2014) are only a few problems of the remote detection. Finally, integration between the UAV-supported system (Lin et al. 2010; Goodrich et al. 2008) and already existing search procedures is another aspect that needs to be encountered in order to utilize the potentials of UAVs in SAR missions.

In this paper, we attempt to address a problem of the initial stage of search, also known as a priority search phase (Goodrich et al. 2008; Lin & Goodrich 2009), in which the probability distribution map is created based upon terrain features, profile of the missing person, weather conditions and
subjective judgment of expert searchers. The map, also called the POA map (Doherty et al. 2014), is based on the prediction of area where a lost person can be present, following the information that is available after the person is reported missing (Cooper et al. 2003; Goodrich et al. 2008; Lin & Goodrich 2009). As the priority search phase precedes the path-planning actions and there are requirements for the sensor to collect the most valuable material, UAV path-planning algorithms should take the POA maps into account and operate inside the search region that exhibits the highest probability of containing a lost person.

Attempts to plan the UAV flights for SAR purposes may follow a few different concepts of delineating areas where a lost person may be present, namely the concepts of the ring model (Heth & Cornel 1998), mobility model (Doherty et al. 2014) and solutions based on the Bayes’ theorem (Bourgault et al. 2006; Lin & Goodrich 2010). Other examples of similar models include: the dedicated decision support system to generate maps of the minimum reach time (Ciollini et al. 2006), watershed model (Doke 2012) and combinations of several models (e.g. Sava et al. 2016). The simplest is the ring model, however its application requires the estimates of parameters of the probability distribution of the Euclidean distance from the Point Last Seen (PLS), known as a crow’s flight distance. Estimation of the parameters may often be impossible due to lack of SAR databases for a given area. In this paper, we propose a simple procedure, based on the Wakeby distribution of a crow’s flight distance, for delineating a region where UAV should carry out a SAR mission. We provide a simple geometrical concept of delineating a search region, but a novelty of our approach lies in seeking parameters of the Wakeby distribution controlling the crow’s flight distance travelled by a lost person when they cannot be explicitly estimated from SAR databases. Indeed, for a region for which such an explicit estimation cannot be performed, we detect areas in which terrain features are similar to regions for which Wakeby parameters describing a crow’s flight distance are known. Borrowing the crow’s flight distances from areas where they are already estimated is recommended by Heth and Cornel (1998), provided the two regions reveal similar wilderness characteristics.

2. Context for the study

Since March 2015 the Department of Geoinformatics and Cartography of the University of Wrocław (Poland) has carried out the research project, the aim of which is to build a system supporting the UAV-based SAR activities. We believe that our proposition is novel as it integrates UAV-based observations of terrain in visual light and near infrared spectrum (Figure 1) with mathematical models for lost person behaviour. One of such models is the above-mentioned probabilistic approach to estimate the crow’s flight distance using the Wakeby probability distribution (Heth & Cornel 1998). The model allows us to compute a radius of a circle delineated around a PLS for a given probability of finding a lost person who belongs to one of activity groups.

The crow’s flight distance – also known as the distance between the Initial Planning Point (IPP), often the analogue of PLS or the Last Known Point (LKP), and the Find Location (FL) – belongs to the most common statistics on lost person behavior used in many SAR approaches (Heth & Cornell 1998; Syrotuck 2000; Doherty et al. 2014). This parameter frequently supports a process of assigning POA by providing statistics to delineate search-area rings. Radii of the rings correspond to the values of quartiles and the 95 percentile of distance data. The first quartile (25%) represents the area most adjacent to the IPP, the median (50%) is equivalent to the distance at which half the cases were found within the distance while half the cases were found farther out. The third quartile (75%) often presents the practical distance where sector searching is possible depending upon available resources. The distance corresponding to the 95 percentile can determine the maximum search zone or can be used to establish an early containment area.

Based on the concept of the crow’s flight distance, we proposed a simple geometrical approach to delineate a region in which the UAV search should be carried out (Figure 2). On one of the ring model circles we superimpose: a circle drawn around the take-off location (TOF) with a radius that is constrained by the maximum range of a given UAV, a triangle representing the zone in which a
Figure 1. The example of UAV-based observations of terrain in visual light and near infrared spectrum. Square brackets indicate location of people.

Figure 2. Simple geometrical approach to delineate a region of priority in which the UAV search should be carried out. PLS – point last seen, ID – intended destination, TOF – take-off location, r – radiomodem range.
lost person can travel towards the intended destination (ID). The intersection of the three figures produces a polygon which may serve as a search region for the UAV mission. Many UAVs for image acquisition require a polygon which is used by the mission planning software prior to take off, and hence the automatic production of such a SAR-targeted polygon may significantly reduce the time of SAR flight preparation. Although our approach is very simple it has one constraint that makes it impossible to apply when the Wakeby parameters cannot be estimated explicitly from SAR databases.

There are several SAR incident datasets available to empower understanding of interactions between the person behavior and the environment (Syrotuck 2000; Koester 2008). The largest dataset consisting of incidents from places around the world is the International Search and Rescue Database (ISRID) (Koester 2008) which takes into account 41 subject categories and classifies the search area according to ecoregions (Bailey 1995). However, as the ISRID statistics are based on global data there is concern if they are adequate for local-scale incidents (Doherty et al. 2014).

We faced a similar problem in the above-mentioned UAV-assisted SAR project for Poland, since we had no access to SAR databases that include information on local incidents. To overcome that problem we hypothesized whether we were allowed to adopt the Wakeby parameters published by Heth and Cornell (1998). Those parameters, however, are correct for 12 wilderness user categories acting in the two areas of the southwestern Alberta, Canada (the Rocky Mountain House and the Kananaskis Country). Since Poland is remotely located from Alberta in Canada, borrowing these parameters may be highly disputable. Thus, we performed simple geomorphometric analysis of terrain of Poland and Alberta in order to check if these areas are comparable in terms of ecological and topographic features. If the areas are comparable in terms of such characteristics, we are more inclined to positively verify the aforementioned hypothesis and, consequently, adopt the Wakeby parameters to the Polish case study.

The latter condition of comparability or similarity of two areas has been identified by Heth and Cornell (1998) as a requirement which, when is met, allows the search managers to use the estimates of the crow’s flight distance from the Albertan case study in their SAR activities carried out in remote, but similar wilderness.

3. Data and methods

The analysis presented in this paper is performed for two regions of interest where SAR incidents occur: in Alberta (the Rocky Mountain House and the Kananaskis Country), in Poland (the entire country and one of its Southwestern voivodeships, named Dolnośląskie). The Canadian regions are spatially disjoint, which is not the case for the analysed Polish study areas. The boundaries of the Canadian study areas were depicted on a basis of the coordinates provided by Heth and Cornell (1998). The borders of Poland and the Dolnośląskie Voivodeship were adopted from the National Register of Boundaries of Poland (Państwowy Rejestr Granic) that can be accessed courtesy of the Documentation Centre of Geodesy and Cartography of Poland (Centralny Ośrodek Dokumentacji Geodezyjnej i Kartograficznej). We focus on the Dolnośląskie Voivodeship along with the entire Poland since our forthcoming UAV-assisted field experimental SAR campaign is limited to the Southwestern Poland.

Poland and Alberta are located on different continents and their distances to the nearest water reservoirs are dissimilar. Moreover, their sizes differ significantly. Poland is a country having the area of 312,685 km² which is approximately 1.5 times larger than the size of the Albertan study area delineated by Heth and Cornell (1998). In addition, Poland has a much smaller latitudinal extent than the Canadian area. They are both located on similar latitudes of the Northern Hemisphere, and due to their different latitudinal extents the light supply is dissimilar within each of the study areas.

We use the Ecoregions of the Continents map which presents the major World’s ecological zones based on the Robert G. Bailey’s classification (Bailey 1995). By taking into account macroclimatic
conditions and dominating plant formations determined by these conditions the author of the map
divided continents into categories with three levels of detail. Domains are the broadest category con-
taining divisions that are subsequently divided into provinces (Bailey 2005). The map is available
courtesy of the Forest Service of United States Department of Agriculture.

We also make use of the ETOPO1 Global Relief Model (Amante & Eakins 2009) – a dataset gen-
erated by the National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric
Administration (NOAA) of the USA. ETOPO1 is a global one arc-minute resolution grid, and con-
tains topographic, bathymetric and shoreline information. Based on the model we calculated two
terrain derivatives, i.e. slope and aspect for both areas of interest.

In addition, we utilize the concept of geomorphons, i.e. geomorphologic phonotypes that repre-
sent patterns of specific terrain morphology types (Jasiewicz & Stepinski 2013a; Stepinski et al.
2015). We use the ETOPO1 Global Relief Model together with the Geomorphons App web applica-
tion to compute a set of geomorphometric maps, namely interpreted maps of topography (Jasiewicz
& Stepinski 2013b) which present spatial patterns of the most common landform elements occur-
ring in both areas of interest.

The method that we propose for delineating spatial coverage for the UAV in order to support the
first phase of SAR activities is very simple. According to Koopman (1979), the search task would
not be worth the effort if there were not enough clues to show that certain relatively restricted
regions had a much higher probability of containing the target than others. Such areas serve as pri-
ority sectors for the UAV flights where the data should be collected first. The main clues to delineate
the region of priority in our approach are: PLS, ID and lost person category. Those three, together
with UAV technical limitations, can indicate where to target the vehicle in the first phase of the
search.

Starting with PLS and information about the lost person’s activity we depict crow’s flight distance
circles with radii based on the Wakeby parameters adopted from Heth and Cornel (1998). The
crow’s flight distance has been calculated by these authors using quantiles of the Wakeby probability
distribution (Hosking & Wallis 1997; Eqn. A.102) for ten wilderness-user categories. Heth and Cor-
nel (1998) juxtaposed the obtained distances in their Table 5, and we aim to borrow them according
to these authors’ suggestion which reads as follows ‘we recommend that search managers use Table 5
for estimating the crow’s-flight distance travel of persons lost in similar wilderness.’ The similarity of
wilderness between Alberta and Poland is extensively discussed in this paper in order to apply the
approach for the region of our interest.

The first ring is the most important at the initial stage of the SAR mission as it is known that
many FLs are within a relatively short distance from IPPs (Koaster 2008, Fig. on p. 50). The line
between PLS and ID determines the center of the first focus direction sector, presenting the course
that the lost person was going to travel through. The first focus direction sector can be limited by
two lines, each making angle of dispersion with the line passing PLS and ID (Heth & Cornell 1998;
Koester 2008). We assume the angle of dispersion of 45° (it can be set differently according to user’s
experience or available data) which, when drawn on both sides of the PLS–ID line, delineates the
first focus direction sector of 90°.

Subsequently, following terrain characteristics such as topography and land cover, we locate sev-
eral places suitable for the UAV to take off. From the available locations we select such a TOF which
is situated in the closest vicinity of PLS. We then draw a potential fly ring around TOF with radius
(r) corresponding to the maximum range of a given UAV radio modem. Potential flight ring, having
its centre located in the closest distance to PLS, allows us to fly over the biggest possible area of inter-
section between the potential flight ring and the first circle from the ring model. This implies the
opportunity to fly over the largest possible area where the missing person is most likely to be found.

Finally, intersection of the three figures – namely: first ring, first focus direction sector and poten-
tial flight ring – produces a polygon which may serve as a region of priority for the UAV SAR mis-
ion (first flight). We suggest to use this region as an area of interest in the UAV path-planning
process. To verify the applicability of the simple geometrical approach in two different search
scenarios (despondents and hikers in the Izerskie Mountains – SW Poland) we additionally perform a feasibility study in which we validate the technical possibility for UAV to cover the region of priority in a single flight. In order to verify whether it is reasonable to adopt the parameters of the Wakeby distribution describing the crow’s flight distance (Heth & Cornel 1998) to Polish conditions, we compare Alberta with Poland in term of their ecological and topographical features. Our approach uses two different input datasets, and the conceptual sketch of the procedure is presented in Figure 3.

Based on the Ecoregions of the Continents map (Bailey 1995) we first indicate the domains, divisions and provinces occurring in both Alberta and Poland, then we compare the percentage of terrain being occupied by corresponding units within both locations.

As a result of utilizing the Geomorphons App (Jasiewicz & Stepinski 2013a) we obtain a set of geomorphometric maps representing our study areas classified into 10 landform categories: flat terrain, peak, ridge, shoulder, spur, slope, hollow, footslope, valley and pit. We tested several configurations of two input parameters (flatness and radius) that are obligatory in the Geomorphons App. We considered the following values: flatness of 0.1° and 1° as well as radius of 5, 25 and 50 cells. For further comparisons we adopt flatness of 0.1° and radius of 50 cells. Finally, we calculate the area of terrain occupied by corresponding categories and compared their proportions in both locations. Analogically, we computed the similar percentages for the Dolnośląskie Voivodeship.

The third part of our approach, including the comparison between Alberta and Poland in terms of their topographical characteristics, is based on derivatives of the ETOPO1 Global Relief Model. For both locations:

1. We calculate slope and subsequently divide the terrain into six slope categories:
   - 0–1°, 1–2°, 2–3°, 3–4°, 4–5° and >5°;

2. We compute aspect and classify the terrain into the following aspect bins: N, NE, NW, S, SE, SW, W, E.
Similarly to the first and second approaches, we calculate the area of terrain being occupied by slope/aspect categories and express them as percentages of total area of the corresponding regions.

Both the data that we have taken into consideration (Ecoregions, Geomorphons Map, DEM derivatives) and the method of comparison (comparing the area percentage of different thematic classes of terrain in the total territory of the area of interest) are only simple examples of what can be done to verify the similarities between the area of interest and the Albertan study area. Only when such a similarity is confirmed it is possible to adopt Albertan Wakeby parameters as an input to our simple geometric method of delineating area for UAV observations.

4. Results

According to the analysis of ecoregions (Figure 4), the most general difference between Polish and Albertan territories seems to be the effect of sea proximity for both locations and their latitudinal extent difference. Alberta has more continental character than Poland, which is the coastal country located in the vicinity of the Baltic Sea. In addition, straight line distance to the bigger sea reservoir is smaller for Poland (to the North Sea) than for Alberta (to the Pacific Ocean). A difference in humidity between Poland and Alberta is also associated with huge orogenic barriers located on the west coast of Canada, making Albertan climate dry. Therefore, Poland is more humid in contrast to the Albertan territory. In addition, Alberta is dominated by polar domain which does not occur in Poland.

Although the above-mentioned differences are meaningful, there are a few similarities between the two study areas. The similarities are investigated by checking the occurrence of the same domains, divisions and provinces within each territory (Figure 4). According to the map of ecoregions, most of Polish territory (99.5%) is located in the humid temperate domain, while in Alberta this domain is represented by 8.9% of land only. Certain similarities can be sought in the presence of forest-alpine meadows. They cover 8.7% and 23.8% of territories of Poland and Alberta, respectively. Moreover, 8.7% of the area of Poland fits the mountainous regime. Identical regime in Alberta occupies over 27% of the study area. Taking into considerations these three characteristics, it is clear
that Alberta and Poland are ecologically miscellaneous. Even though there are similar categories present in both areas, they cover significantly different proportions of land. We did not carry out the ecoregion-based analysis of the Dolnośląskie Voivodeship as its area is too small to seek similarities.

More similarities between Alberta and Poland can be found through the investigation into topography (Figure 5). Both sites are rather flat since slopes in most of the two territories do not exceed 1° (97% and 83% for Poland and Alberta, respectively). Slopes between 1° and 2° occur rarely in Poland with 2% of the total area, whereas in Alberta the corresponding percentage value is approximately equal to 8% (Table 1). When in Poland the terrain rarely exceeds 2° of slope (0.69% of the total area), in Alberta this value is higher (approximately 9%). Even more significant topographical similarities can be found when we compare the Dolnośląskie Voivodeship with the Albertan study area. It is apparent from Table 2 that percentages of terrain within 0°–1°, 1°–2° and 2°–3° slope bins are very similar in the Dolnośląskie Voivodeship and Alberta. Indeed, the first slope class corresponds to 89% of the Dolnośląskie Voivodeship and 83% of Alberta. The percentages for the second and third classes are almost identical for the two study areas (Table 2). According to the hiking function (Tobler 1993), slope has an influence on the pedestrian travel speed. Hence, having found the aforementioned slope similarity, we can assume that walking person will behave analogically in both locations.

Figure 5. Aspect and Slope characteristics of Poland, dolnośląskie voivodeship and Albertan study area.
The analysis of aspect characteristics of land in Poland and Alberta reveals that there is no prevailing direction that most of the terrain is exposed to. The differences between proportions of land being exposed to the same direction in Poland and Alberta do not exceed the value of 4.1% (Table 3). Similarly, when comparing Alberta with the Dolnośląskie Voivodeship the analogical maximum offset is approximately equal to 3.4% (Table 4). Such values confirm the similarities of topographies of the analysed regions, thus we can assume that the aspect impact on a person’s behaviour does not differ between Poland and Alberta.

The analysis of geomorphons (Figure 6) shows that the most similar area proportions for both Poland and Alberta are among the group of three geomorphons: peak, ridge and pit (Table 5).

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**Table 1.** Percentage of area occupied by different slope categories in Polish and Albertan study area.

| Slope (°) | Poland | Alberta | Difference |
|----------|--------|---------|------------|
| 0–1      | 97.26  | 83.45   | 13.81      |
| 1–2      | 2.05   | 7.67    | −5.62      |
| 2–3      | 0.65   | 3.38    | −2.73      |
| 3–4      | 0.01   | 2.38    | −2.37      |
| 4–5      | 0.03   | 1.46    | −1.43      |
| > 5      | 0      | 1.66    | −1.66      |

**Table 2.** Percentage of area occupied by different slope categories in Dolnośląskie Voivodeship and Albertan study area.

| Slope (°) | Dolnośląskie Voivodeship | Alberta | Difference |
|----------|--------------------------|---------|------------|
| 0–1      | 88.92                    | 83.44   | 5.48       |
| 1–2      | 7.56                     | 7.67    | −0.11      |
| 2–3      | 3.00                     | 3.38    | −0.38      |
| 3–4      | 0.36                     | 2.38    | −2.02      |
| 4–5      | 0.16                     | 1.46    | −1.30      |
| > 5      | 0.00                     | 1.67    | −1.67      |

**Table 3.** Percentage of area occupied by different aspect categories in Polish and Albertan study area.

| Aspect | Polska | Alberta | Difference |
|--------|--------|---------|------------|
| N      | 8.96   | 10.63   | −1.67      |
| NE     | 13.90  | 16.21   | −2.31      |
| E      | 13.43  | 15.65   | −2.22      |
| SE     | 11.10  | 11.96   | −0.86      |
| S      | 11.00  | 10.85   | 0.15       |
| SW     | 13.32  | 9.25    | 4.07       |
| W      | 14.57  | 11.56   | 3.01       |
| NW     | 13.72  | 13.89   | −0.17      |

**Table 4.** Percentage of area occupied by different aspect categories in Dolnośląskie Voivodeship and Albertan study area.

| Aspect | Dolnośląskie Voivodeship | Alberta | Difference |
|--------|--------------------------|---------|------------|
| N      | 7.52                     | 10.63   | −3.11      |
| NE     | 19.57                    | 16.21   | 3.36       |
| E      | 15.24                    | 15.65   | −0.41      |
| SE     | 9.50                     | 11.96   | −2.46      |
| S      | 9.81                     | 10.85   | −1.04      |
| SW     | 12.58                    | 9.25    | 3.33       |
| W      | 13.88                    | 11.56   | 2.32       |
| NW     | 11.90                    | 13.89   | −1.99      |
ever, these are not the most common landform elements in both areas. In Alberta the most frequent are slopes, occupying over 25% of the total area. In contrast, Poland is dominated by flat terrains, and slopes cover only 12% of the country area. The remaining groups of geomorphons occur with similar frequencies in Poland and Alberta. It is apparent from Table 5 that, except for flat areas and slopes, the percentages of occurrence of the analyzed geomorphons are similar in Poland and Alberta. Hence, we again are allowed to assume that certain lost person’s behaviours may be comparable in Poland and Alberta, however the differences in a person’s travel speed are likely to occur within flat areas and slopes. Slightly different results are obtained from the comparison between Alberta and the Dolnośląskie Voivodeship, where landform patterns are quite similar (Table 6).

Table 5. Percentage of area occupied by different geomorphons in Polish and Albertan study area.

| Geomorphons | Alberta | Poland | Difference |
|-------------|---------|--------|------------|
| 1 Flat      | 6.27    | 24.62  | 18.35      |
| 2 Peak      | 4.77    | 4.43   | -0.34      |
| 3 Ridge     | 9.80    | 9.54   | -0.26      |
| 4 Shoulder  | 5.36    | 10.29  | 4.93       |
| 5 Spur      | 11.79   | 7.13   | -4.66      |
| 6 Slope     | 25.20   | 12.29  | -12.91     |
| 7 Hollow    | 13.48   | 10.17  | -3.31      |
| 8 Footslope | 13.48   | 10.17  | -3.31      |
| 9 Valley    | 13.48   | 10.17  | -3.31      |
| 10 Pit      | 2.35    | 0.93   | -1.42      |

Table 6. Percentage of area occupied by different geomorphons in Dolnośląskie Voivodeship and Albertan study area.

| Geomorphons | Alberta | Dolnośląskie Voivodeship | Difference |
|-------------|---------|--------------------------|------------|
| 1 Flat      | 6.27    | 9.21                     | 2.94       |
| 2 Peak      | 4.76    | 2.86                     | -1.90      |
| 3 Ridge     | 9.80    | 8.84                     | -0.96      |
| 4 Shoulder  | 5.36    | 6.82                     | 1.46       |
| 5 Spur      | 11.79   | 9.62                     | -2.17      |
| 6 Slope     | 25.20   | 17.64                    | -7.56      |
| 7 Hollow    | 13.48   | 14.10                    | 0.62       |
| 8 Footslope | 9.19    | 16.39                    | 7.20       |
| 9 Valley    | 13.48   | 14.10                    | 0.62       |
| 10 Pit      | 2.35    | 0.93                     | -1.42      |
both areas the most common geomorphons are slopes, valleys and footslopes. In contrast, flat areas do not occur frequently. The most comparable area proportions for the Dolnośląskie Voivodeship and Alberta are valleys, ridges and pits. In addition, area percentage differences are also small for the other geomorphon types.

The identified similarities allow us to believe that it is reasonable to adopt the Wakeby parameters published by Heth and Cornell (1998) for a purpose of SAR activities to take place in Poland. According to the topographical context of our study, there are even stronger premises in that we can use these parameters for delineating the crow’s flight distance in the area of the Dolnośląskie Voivodeship.

5. Experiment

In Section 4, we have shown that the parts of terrain in Alberta investigated by Heth and Cornell (1998) reveal similar geomorphometric characteristics as the area of Poland and, even more pronouncedly, its Southwestern part known as Lower Silesia (Dolnośląskie Voivodeship). Thus, we were allowed to borrow the parameters from their study in question to depict the Wakeby rings in Lower Silesia and test our procedure for delineating a search region in the UAV-based SAR activities (Figure 2). In order to do so we herein propose an experiment which aims to serve as a feasibility study that leads to a confirmation that the approach is practically applicable with real UAVs.

We selected two UAVs, swinglet CAM and eBee, both manufactured by senseFly. They reveal numerous technical constraints, one of which is radio modem range (1 km and 3 km, for swinglet CAM and eBee, respectively). We produced four rings based on the crow’s flight distances for hikers and despondents, in both cases for 25 and 50 percentiles (Heth & Cornell 1998, Table 5). Hence, there are following eight combinations of the two rings (UAV range, crow’s flight distance): swinglet + hiker 25%, swinglet + hiker 50% (Figure 7), swinglet + despondent 25%, swinglet + despondent 50% (Figure 8), eBee + hiker 25%, eBee + hiker 50% (Figure 9), eBee + despondent 25%, eBee + despondent 50% (Figure 10).

We placed our experiment in the Izerskie Mountains (Lower Silesia, SW Poland) where we carry out an extensive observational campaign, the aim of which is to acquire a large collection of UAV-taken photographs of persons located in the wilderness at different seasons of a year, different periods of a day and for dissimilar land cover (Figure 1). For the purpose of the experiment we assumed that a person travels from Hala Izreska to the ID point in the town of Świeradów-Zdrój, both situated in the Izerskie Mountains. The only available TOF is located at Polana Izerska (isolated mountain meadow of approximate dimensions 250×170 m, surrounded by spatially-large forest areas). In the exercise, the PLS was assumed to be located south of Polana Izerska (figures 7–10). In addition, we produced a wedge around a PLS-ID line, with 45° dispersion angle. The rings and the wedge superimposed on each other have been taken as input parameters to our procedure for calculating the search region. Their intersection, in accordance with Figure 2 as well as Sections 2 and 3, leads to a new polygon which is assumed to be a search region.

Having obtained real UAV ranges and borrowed crow’s flight distances as well as knowing the destination wedge, the experiment aims to check if the two drones are capable of executing the mission in a single flight (the other parameters should be additionally taken into account, i.e. battery endurance). Such an assessment may be done using the swinglet CAM and eBee simulators. The aforementioned new polygon, which corresponds to the first-priority search area, was imprinted into the LIDAR-based DEM projected into the UTM projection. The resulting GeoTIFF data became input to MapTiler 1.0 beta2 which produced tiles that have been subsequently used as background source maps in the navigation software (e-mo-tion for swinglet CAM and eMotion2 for eBee). This allows us to precisely draw the mission area and, after setting up flight parameters, obtain information on flight feasibility or a number of flights needed to accomplish the mission. For the sake of brevity, and in order to keep the same geometries of the polygon-like mission areas produced in e-mo-tion and eMotion2, we use escribed rectangles of polygons that correspond with the
first-priority search area. This overestimates the ground coverage, but allows us to compare the usefulness of the two UAVs for SAR applications.

Table 7 presents flight characteristics and juxtaposes the resulting information on coverage-related issues (number of flights, total ground coverage, estimated flight distance, estimated flight time) which are obtained for swinglet CAM and eBee, the two UAVs employed to perform the simulated SAR missions (search for hikers and despondents) on a basis of the approach proposed in this paper. For the 25% circle of the ring model despondents can be searched in one flight by either swinglet CAM or eBee. Hikers, however, may walk far from the PLS, and the SAR observations based on our resource allocation approach require two eBee flights and at least two swinglet CAM flights. Noteworthy is the fact that the latter number is likely to be bigger than two as swinglet CAM reveals

Figure 7. Feasibility-study scenario from Izerskie Mountains for hiker and swinglet CAM with simple geometrical approach to delineate a region of priority presented in real environment. PLS – point last seen, ID – intended destination, TOF – take-off location, \( r \) – radiomodem range.
lower endurance than eBee (note also that the e-mo-tion software does not estimate the exact number of the required swinglet CAM flights, hence for swinglet CAM the inequality >1 is used to account for this problem). If the radius of a circle of the ring model is greater than in the above exercise, and corresponds to the 50% probability, the number of the required flights remains the same (one, either for eBee or swinglet CAM) in the case of search for despondents. A meaningful differences between the 25- and 50-percent probabilities can be found for hikers. Based on the approach outlined in this paper, the SAR mission should employ seven eBee flights or at least one swinglet CAM flight. Likewise, the latter number is probably greater than seven due to the above-mentioned reasons on endurance.

The experiment serves as a feasibility study and shows that the procedure for delineating a search region in the UAV-based SAR activities, the overview of which has been presented in this paper, is
applicable to two real, professional micro UAVs. Thus, the fixed-wing UAVs of similar technical parameters as swinglet CAM or eBee may be practically utilized to perform SAR mission over the terrain, the boundaries of which are pre-selected using the methods proposed in the paper.

6. Summary and conclusions

According to Heth and Cornell (1998), wilderness user categories fall into two homogeneous groups for which the crow’s flight distance is characterized by different parameters of the Wakeby distribution. The first group consists of walkaways and despondents and the other group is appropriate for the rest of wilderness user categories (campers, skiers, hikers, hunters, mountain bikers, scramblers,
and other users). In order to support SAR activities in areas where Wakeby parameters cannot be estimated, for instance due to no access to a SAR database, we propose the analytical approach which identifies differences and similarities between topographical/ecological characteristics of Alberta and a given area. If there exist meaningful similarities, we suggest that it is possible to apply the simple geometrical method for delineating a region where the UAV-based search should be carried out in the first place. The procedure is thus especially useful for areas where there is lack of past SAR incidents record or where the database is incomplete.

The results indicate that, based on the topographical similarity between Poland and Albertan study areas, we are allowed to adopt the parameters of the Wakeby distribution published by Heth and Cornel (1998) for the purpose of SAR activities performed in Poland (especially for

![Figure 10. Feasibility-study scenario from Izerskie Mountains for despondent and eBee with simple geometrical approach to delineate a region of priority presented in real environment. PLS – point last seen, ID – intended destination, TOF – take-off location, r – radiomodem range.](image-url)
Dolnośląskie Voivodeship). Since our approach may be disputable due to limited number of methods applied (terrain derivatives and geomorphons) it is recommended to adopt additional methods that may support our exercise on the similarity between remote areas.

The method could be extended by including different global data into the investigation, for example: high-resolution map of the global environmental stratification (Metzger et al. 2013 – Appendix S4), WorldClim climate surfaces (Hijmans et al. 2005), updated World Map of Köppen–Geiger Climate Classification (Kottek et al. 2006; Peel et al. 2007), Global Land Cover Characterization (Loveland et al. 2000), output data from Topographic Position Index ArcGIS extension (Jenness 2006) or Automated object-based classification of topography from SRTM data output data (Drăgăț & Eisank 2012). Additionally, one could incorporate more detailed ecological and topographical data presenting the local environment more precisely. Moreover, similarity analysis could be based on different methods and tools such as Kappa statistic (Monserud & Leemans 1992), an improved Fuzzy Kappa statistic (Hagen-Zanker 2009), Fuzzy set approach (Hagen 2003), Map Comparison Kit (Visser & de Nijs 2006), Geospatial Pattern Analysis Toolbox – GeoPAT (Jasiewicz et al. 2015). The computation of mobility models for both sites could also support the validation of the method. Taking into account all the possibilities arising from the available data, methods and tools our goal for future work is to perform similar analysis based on different data and other methods to support our hypothesis.

In this work we discuss the problem of generating probability distribution map presenting most probable locations of containing a lost person. Information that we take into consideration is the location of PLS and ID points. As long as we consider this problem in the context of possible UAV support for the search missions, we are forced to take into account possible TOF location limitations as well as radio modem range constraints. As a result of our study we propose the method of delineating search region, where the UAV can be sent in order to collect valuable aerial photographs with high probability of containing the signal of a missing person. Lin and Goodrich (2010) also suggest that probability distribution map can be used by UAV path-planning algorithms. They propose a method to create such a map automatically, based on a Bayesian approach for modelling lost-person behaviours according to the terrain features such as topography type, vegetation coverage, local slope and others. The advantage of their approach is that the probability distribution map can be dynamically updated during the search when more information is being collected so that rescue workers can observe how it changes with time and adapt the search to new conditions. Another approach which models the target location using the Bayesian framework and probability density function (PDF) was presented by Bourgault et al. (2006). Their procedure allows for updating the target’s location as the search continues what might be useful in the process of delineating second priority regions for further UAV flights.

### Table 7. Results of the feasibility study.

| Probability rings | Parameters | eBee | Swinglet CAM |
|-------------------|------------|------|--------------|
|                   | Number of flights | 1    | 2            |
| 25%               | Total ground coverage [ha] | 5.7  | 293          |
|                   | Estimated flight distance [km] | 3.9  | 58.6         |
|                   | Estimated flight time [h:min:sec] | 00:05:22 | 2:00:41:17 |
|                   | Number of flights | 1    | 7            |
| 50%               | Total ground coverage [ha] | 42.6 | 1048.2       |
|                   | Estimated flight distance [km] | 12.2 | 203.8        |
|                   | Estimated flight time [h:min:sec] | 00:16:28 | 7:00:43:47 |

**Settings:** desired altitude: 123 m/ATO (eBee), 122.5 m/ATO (swinglet CAM), lateral overlap: 60%, ground resolution: 4.3 cm/px (eBee), 3.7 cm/px (swinglet CAM), single image coverage: 172 × 129 m (eBee), 148 × 111 m (swinglet CAM), wind speed: 0 m/s
Yet another approach for delineating a search area is based on the concept of iso-probability curves in the Wilderness SAR performed by ground robots (Macwan et al. 2015). Unlike our procedure, which uses equidistant rings, these authors use equal-probability lines. In addition, the strategy adopted by these authors determines the target’s motion and delineates regions within which a subject may be located with a given probability at any given time in order to plan an optimal path for ground robots in a multi-robot search.

The work that focuses on the utility of Geographic Information System (GIS) in SAR operations is published by Söylemez and Usul (2006) who demonstrate how probability distribution maps can be created with GIS tools and how they can support the search process in the case of plane crash. There is one similarity between the procedure proposed by Söylemez and Usul (2006) and our simple geometrical approach for delineating a search region in the UAV-based SAR activities. In the above-mentioned plane crash case study, flight direction has a positive influence on the probability of finding a missing object in the area or its vicinity. Probability decreases with the \( \frac{10}{\pi} \) angle increase on both sides from the direction line. In our approach this angle is fixed (giving the sector of the 90° angle), but it can be set by the experts according to their knowledge.

Ferguson (2008) discusses the application of GIS in the search for missing person as a platform that can integrate information from behavioural and probability theory studies together with terrain data and resource management strategies. He provides the details about segmenting the designated search area into probability regions based on statistical analysis and a behavioural profile of a missing person. He state that ‘although there are number of methods for establishing the search area, a common approach is to utilize a form of behavioural profiling that not only involves developing specific scenarios regarding the missing subject, but also includes the use of statistical databases that have been derived from thousands of previous incidents.’ By this statement he confirms the legitimacy of our actions presented in this paper.

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