# Identification of Sustainable Locations in Pigeon Flights using Flow Simulation Method

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Keywords: Visual Perception, Spatial Navigation, Flow Simulation.

Abstract: Navigation behaviour in nature is based on data obtained from perception of the terrain where movement occurs. The aim of this work is to study the influence of visual factors on the flight of birds over medium distances (about 10 km). In this study, we propose a method for probabilistic analysis of pigeon flights over combined countryside and urban terrain, based on surface flow simulation. Z-value – an altitude analogue that describes the characteristic gradient of the flow – is calculated as a function of "landscape complexity" based on the density of significant landscape objects. The calculated probabilistic model is compared with data on GPS-tracks of untrained and trained pigeons. As a result, significant features of terrain that determine sustainable locations in pigeon flights are identified. In the study, visual characteristics of the territories over which pigeons flew are calculated using remote sensing data from open sources, and spatial data are processed using the geographical information system QGIS.

## 1 INTRODUCTION

Here we studied the properties of pigeon flight trajectories over combined countryside and urban terrain. The aim of this study is to identify the interdependence of the characteristics of the trajectories of pigeons and the visual properties of the landscape, based on surface topology.

Study of the typical ways in which pigeons respond to changes in the landscape over which they fly shows that pigeons rely on visual perception of the terrain to determine their routes. Their perception of the terrain allows them to distinguish characteristic features that are suitable for guiding flight above terrain. These features are determined by such parameters as tone, colour, and density of detached objects.

Moreover, the way in which a pigeon orients itself based on visual data is directly influenced by the degree to which the landscape is filled with separate stimuli. Mann et al. (2014) studied the influence of “landscape complexity” on pigeon navigational behaviour. The authors concluded that pigeons orient themselves better when flying above territory where “landscape complexity” is neither too high nor too low.

To assess the probabilistic characteristics of a flight over surface, the visual perceptibility factor is used here, depending on saturation of the terrain with visual objects. It can be represented as z-value, an analogue of height, which describes the characteristic directions of flight. To find potential flight trajectories, the flow paths over the surface caused z-value differences are calculated. The computational model is compared with pigeon GPS-track data over this area.

Visual features in the landscape that are important for long-range navigation can be identified by Kano and colleagues (Kano et al., 2018). These authors discuss the training of a particular route by repeated flights on the same terrain.

The properties of trained and untrained birds can be reflected in perception preferences for objects on the ground and in flight paths, which is also shown in this work.

This paper is structured as follows. In Section 2, we provide a brief review of the following topics: *i)* visual perception of the terrain during flight; *ii)* formation of flight trajectories based on visual data perceived by a pigeon; *iii)* analysis of surface properties to determine the possibility of external dynamic processes; and *iv)* representing the density of objects as a surface on which flow can potentially

Zaleshina, M. and Zaleshin, A.
Identification of Sustainable Locations in Pigeon Flights using Flow Simulation Method.
DOI: 10.5220/0009000305350541
In *Proceedings of the 9th International Conference on Pattern Recognition Applications and Methods (ICPRAM 2020)*, pages 535-541
ISBN: 978-989-758-397-1; ISSN: 2184-4313

occur. In Section 3, we describe data and data processing methods for calculations used for surface flow simulation. In Section 4, we compare data on calculating flows over a landscape and real flight paths for untrained and weakly trained pigeons. In Section 5 we discuss the applicability of identification of sustainable locations in pigeon flights using flow simulation method.

# 2 BACKGROUND AND RELATED WORKS

## 2.1 Visual Perception of the Terrain during Flight

Navigation mental maps can be formed by animals based on the results of perception of the terrain. Birds can orient themselves based on both "landscape complexity" and individual reference objects. In general, during medium-distance flights, bird trajectories are determined by visual perception of the terrain and reflect the visible characteristics of the surface.

Figure 1 shows adjustment of pigeon trajectories caused by perception of the terrain.

Figure 1: The consecutive places of "attraction" caused by terrain perception: (A) Satellite view, (B) map view, (C) pigeon flight near places of "attraction".

The navigational behaviour of pigeons in different situations is described in many publications. Mann et al. (2014) showed that pigeons can make use of some form of navigational map, combined with time-compensated solar compass information, to orient homeward from distant unfamiliar places. Blaser et al. (2013) showed that birds knew their geographical position in relation to targets, and chose a flight direction according to their needs – clearly the essence of a cognitive navigational map. Also, in paper (Blaser et al., 2013) the authors proved that pigeons are able to remember routes and fly to the objects which are important to them, such as home or feeding spots, and that they can also choose where to turn depending on the degree of their satiety.

The significance of visual stimuli is different for investigatory flights, when a pigeon surveys unknown terrain, than for purposeful flights, when a pigeon flies along the known path to the known goal. In an unknown place untrained pigeons first try to explore the area, and perform survey flights in different directions, while trained pigeons head straight to the goal (Blaser et al., 2013; Wiltschko and Wiltschko, 2015; Pettit et al., 2012).

The path of the investigatory survey flight may cover a large territory. It is during the survey flight that a pigeon actively reacts to the terrain features in a way that is noticeable based on its flight. A trained pigeon mostly flies almost directly to the goal with insignificant deviations from a set route. Biro et al. (2007) state that when orienting itself while flying above known terrain, a pigeon may combine purposeful movement in a chosen direction with landmark guidance. Even over previously unfamiliar terrain pigeons demonstrate fairly stable sets of behaviour. For example, they prefer not to fly over a wide water surface. At the same time, pigeons have a tendency to use linear structures, such as roads, rivers, or boundaries between dissimilar surfaces (Kano et al., 2018; Lipp et al., 2004; Vyssotski et al., 2009).

To simulate the flight of untrained and trained pigeons, the following assumptions can be adopted:

- When choosing a route, untrained pigeons are guided by the visual perceptibility of the terrain; their flight route is directed from the places that are least visually attractive to more attractive places.
- Trained pigeons are guided by routes that they learned earlier, and to which they try to return when they have deviated from their accustomed route. As a result, they may stop responding to many visual stimuli, except for the main reference points.

## 2.2 Formation of Pigeons' Routes based on Visual Data Perception

In unfamiliar conditions, birds look for objects that they have previously encountered, stable options for the location of these objects, and the usual sequence in which these objects appear as a basis for recognition of other information.

A bird's behaviour over previously familiar terrain changes during flights. Thus, repeated viewing of the same point of the terrain (or localized site) forms changes in behaviour over this point.

Visually, terrain is perceived from different heights and viewing angles, at different scales, and with different degrees of detail. Thus, when flying over a forest, only the boundary line of this forest can be tracked, but smaller details – such as commonly viewed margins and clearings – can also be observed, although transitions between them are less noticeable and significant.

A bird flying along a certain trajectory forms a panoramic perception of its environment, complementing, if necessary, the general visual scene with elements that are not always observable at some specific instant. At the same time, it is possible to fully observe the borders and extended areal interrelations of the terrain elements, including those outside the current viewing angle of the bird. Moreover, in the process of panoramic viewing during flight, such extended areal interrelations can be established or not established for a short time.

In addition, with repeated observation of the same mixed and erratic data, birds can form unstable interrelations, while maintaining a stable composition of the data. This differs from rare observations of the same mixed and erratic data, when perception of different data occurs separately and the interrelations are not formed.

Depending on the scale and the flight route, selection of individual terrain elements – which differ from each other in some ways – may not occur. Similarly, selection of boundaries and extended area objects may not occur (Figure 2).

Figure 2: Adjustment of the pigeon flight route, taking into account perception of elements of the terrain that are not visually connected and preference for flying over linear objects. (A) schematic view of water objects, (B) satellite view.

## 2.3 Analysis of Surface Properties to Determine the Possibility of External Dynamic Processes

The properties of a surface affect the dynamics of external processes that occur over it. Thus, landscape have a significant impact on urban development: interpretation of time series processing is represented in urban growth monitoring (Sexton et al., 2013). Fluid dynamics simulation methods are also applied in biomedical analysis (Ferrari et al., 2018; Rispoli et al., 2015). Shape of a river bank, and formation of its bends, inflow and inner islands are determined by relief over which it flows. Interpretation of complex flow patterns is represented in geosciences (Gallien et al., 2018; Graser et al., 2019) and geological survey (Essaid, 1990; Essaid et al., 2015) in generalized analysis of topography induced stream subsurface exchange (Stonedahl et al., 2010) and in considering ground water and surface water as a single resource (Winter et al., 1998).

Probable pigeon flight routes can be calculated using surface flow simulation, on different parts of the routes. To accomplish this, the isolines with the same "landscape complexity" are used to construct typical cases of pigeon "flow". In particular, surface flow can be constructed for places with a sharp change in "landscape complexity" and/or for places with dense accumulations of isolines. Such a method, in general, resembles typical methods for calculating for water stream on hilly terrain.

Formation of the flow path, taking into account the steep slope, is limited on the sides in watershed. (Figure 3). Similarly, the location of arc-shaped thresholds is formed where pigeon route cross the texture border isolines. When flying over texture boundaries, perception of a pigeon can change abruptly. Differences in density of perceived textures can either be presented in the form of a "sharp change" or be smoothed. A considerable height differential, as a rule, is localized in a small area.

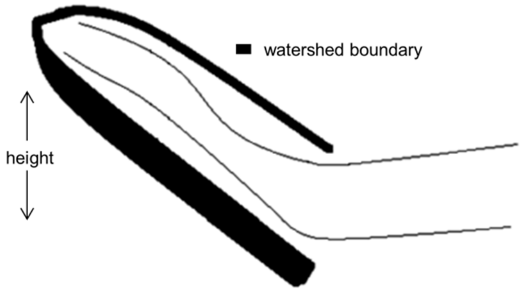

Figure 3: Formation of the flow path in watershed.

### 2.4 Representing the Density of Objects as a Surface on Which Flow Can Potentially Occur

Computational methods for modelling flows can be applied in cases where there is a certain “height” analogue (z-value). Density of stand-alone distinguishable objects, variation in density and direction makes it possible to create a flow model for the terrain, where the density of objects is used to determine the height, taking into account the perceptibility of the terrain. Surface characteristics which are attributed to all units of the surface, providing sets of direction gradients "top-down".

Based on the fact that pigeons prefer a certain density of separately standing distinguishable objects for flight (Mann et al., 2014), it is possible to snap such points by lines in cases where the points are close to each other and the density drop is insignificant.

Figure 4 shows an example of representing the density of objects as a surface on which flow can potentially occur: layer contains “voronoi polygons” corresponding to input data about density.

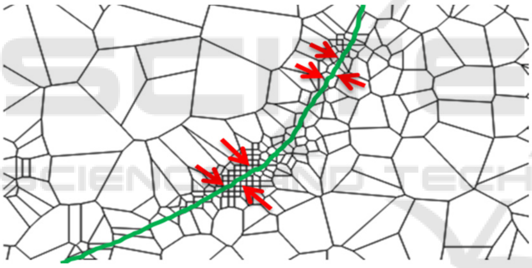

Figure 4: Flow path calculation using data on the density of objects as a “height” analogue. Red arrows indicate direction of gradient, leading to flow formation (green line).

## 3 MATERIALS AND METHODS

### 3.1 Materials

The calculated flow paths over the surface can be compared with observed flight paths of pigeons. In this work, data on the flights of pigeons and remote sensing data for terrain over which these flights took place were used as primary source materials. Data packages with GPS-tracks of pigeons were collected from Dryad Digital Repository (https://datadryad.org, dataset (Pettit et al., 2012), publication (Pettit et al., 2012)) in the form of CSV files.

The pigeons flew over two types of heterogeneous terrains: over countryside terrain covered with forests and fields (site 1, where the distance between start and finish points was 11.5 km) and over urban terrain with buildings and roads (site 2, where the distance between start and finish points was 12.5 km). Measurements of coordinates between individual points of GPS-tracks were taken one time per second. The characteristic distance between separate coordinate values of pigeons’ GPS-tracks is in the range of 20-40 meters. The areas at a distance of 150 meters from flying up and landing of pigeons were not considered (in these areas paths crossed themselves more often and movement direction was constantly changing).

The study was performed for flights of untrained pigeons (the first flights over the previously unknown terrain) and weakly trained pigeons (the second and third flights over the previously unknown terrain): 21 flights over site 1, 27 flights over site 2.

Remote sensing data (satellite images) in the form of OpenLayers (http:// openlayers.org) was used for ground surface information about the surface of terrain. The coordinate system for the project was WGS 84/Pseudo-Mercator (EPSG:3857).

### 3.2 Methods

Z-value and flight characteristics calculation was accomplished for the untrained and trained pigeons. Calculations were performed in the following steps:

- Creation of primary data layers:
  - Point and line vector layers with pigeon flight data based on GPS-tracks.
  - Raster layers with satellite image materials for the area of pigeon flights.
- Mapping “landscape complexity”

“Landscape complexity” map was built based on the remote sensing data. Visual features of the landscape (“landscape complexity”) were identified according to the density of visually observed objects. Firstly, boundaries of individual homogeneous surfaces were identified by constructing isolines. A density map of the existing terrain inhomogeneities was then constructed based on the resulting clusters of isolines for characteristic inhomogeneity dimensions of 50 and more meters. The specified accuracy for the inhomogeneity map corresponds to the typical distance between two neighbouring points of the GPS pigeon tracks.

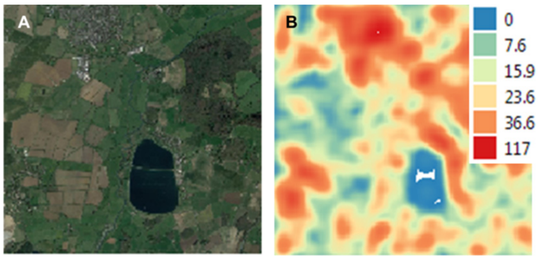

Figure 5: Construction of the terrain inhomogeneity map: (A) the analyzed area (site1); (B) "landscape complexity" map; the range shows the density of perceived elements in the territory.

Figure 5 shows an example of the analysed area (a) and the corresponding "landscape complexity" map in the form of a "heat map" (b).

- Z-value definition and flow mapping using z-value

Z-value and flight characteristics were calculated for pigeons. Based on the "landscape complexity" map, z-value was calculated (as Invert Grid) for all parts of the terrain; this is the equivalent of the height used in relief maps. Z-value determines flow direction for pigeon flight ("top-down") in the absence of additional stimuli. Flows were calculated on the basis of the constructed heat map, using the plugin GRASS r.watershed (Figure 6).

Thereafter, base centroids of calculated flow paths points were constructed, and then applied to analyse the results. This calculation takes into account the fact that the distance between neighbouring z-value isolines is significantly less than distance between start and finish points (about 1%).

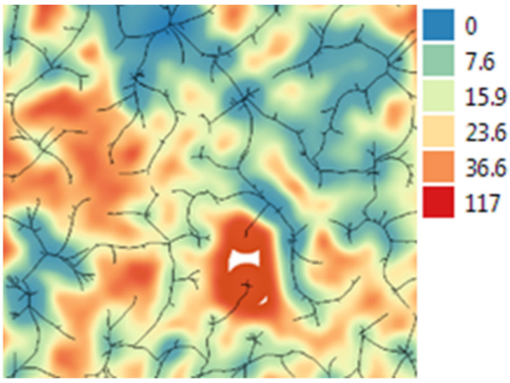

Figure 6: The calculated flows in the z-value map, built from data on "landscape of difficulty".

### 3.3 QGIS Plugins

The data were processed using the open source software program QGIS (http://qgis.org), including additional analysis plugins: QGIS geoalgorithms and GDAL tools (http://www.gdal.org) integrated into QGIS. The source data layers were added using the OpenLayers Plugin in QGIS, which allows to obtain Google Maps, Bing Maps and another open layers.

In addition, analogues of "hydrological parameters" were calculated in our model and a set of maps was formed indicating the accumulation of runoff towards the most saturated complex landscape.

The applied QGIS tools and plugins are presented in Table 1.

Table 1: Applied QGIS tools and external plugins.

| Plugin | Description |
|---|---|
| OpenLayers Plugin:<br>https://github.com/sourcepole/qgis-openlayers-plugin | QGIS plugin embeds OpenLayers (http://openlayers.org) functionality.<br>It allows to obtain Google Maps, Bing Maps, OpenStreetMap and another open source layers. |
| Points2One:<br>http://plugins.qgis.org/plugins/points2one | Create lines and polygons from vertices. Connects points in a layer to form lines and polygons. |
| Heatmap Plugin:<br>http://www.qgistutorials.com/en/docs/creating_heatmaps.html | Create a density raster of an input point vector layer based on the number of points in a location, with larger numbers of clustered points resulting in larger values. |
| GRASS r.watershed<br>https://grass.osgeo.org/grass76/manuals/r.watershed.html | Calculates hydrological parameters and generates a set of maps indicating flow accumulation, drainage direction, the location of streams and watershed basins. |
| SAGA Invert Grid<br>http://sagagis.org/saga_tool_doc/7.1.1/grid_tools_34.html | Inverts a grid, i.e. the highest value becomes the lowest and vice versa. |

# 4 RESULTS

## 4.1 Calculated Flow Paths and Real Flight Routes for Pigeons

We compared the flow paths calculated based on the surface flow simulation and the real GPS-trajectories of untrained pigeons, using QGIS.

After simulation was completed, calculated flow paths and real flight routes were compared using pigeon GPS-tracks.

As the result of calculations, it was obtained that for the countryside terrain (site 1), pigeons prefer to fly over the calculated flow paths with a probability of 16% greater than to not fly (p-value < .05). For the urban area (site 2), there is no significant dependence of flight over the calculated flow paths.

The samples of calculated flow paths and real trajectories are shown in Figure 7.

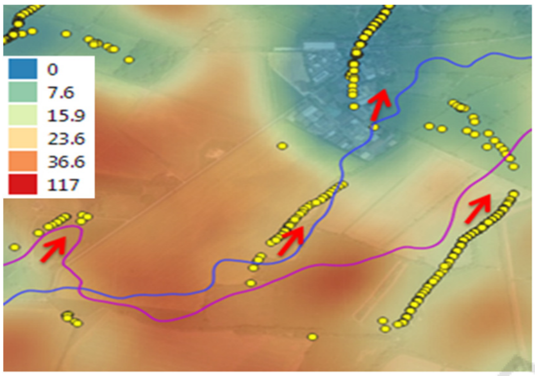

Figure 7: The flow paths calculated based on the surface flow simulation and real flight routes of pigeons. Yellow dots shows calculated flow paths, blue and magenta lines shows real pigeons' flight routes. A heat map with z-value is shown as an additional layer (the legend for z-value is shown in the upper left corner). Red arrows indicate places of "adjustment" in the flight routes of pigeons, depending on the surface properties.

Based on comparison of untrained and weakly trained pigeons' flights, it is apparent that training leads to cases of reducing in the perceptibility of terrain parameters (Figure 8).

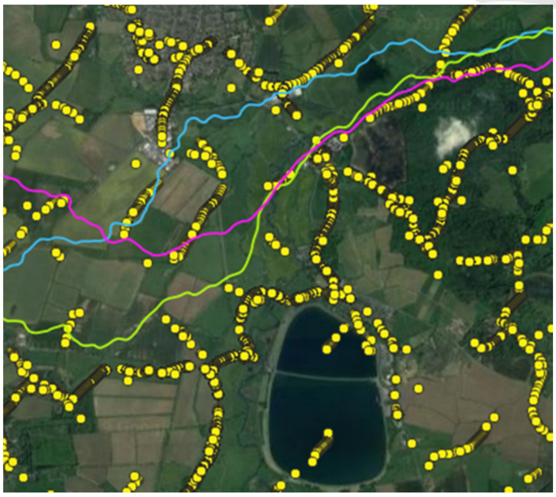

Figure 8: Difference between the real route parameters for one pigeon in first, second and third flights. Magenta line – Flight1, green line – Flight2, blue line - Flight3, yellow dots – centroids of calculated flow paths.

It was obtained that pigeons prefer to fly over places with noticeable extended variations on countryside landscape, with a probability of 16% greater than to fly not over them.

Table 2 shows the ratio of the length of the flight path within the flow area to the total length of the flight path for untrained (1st flight) and weakly trained (2nd and 3rd flights) pigeons.

Table 2: Comparison of results for untrained and weakly trained pigeons.

| Pigeons | Untrained 1st flight | Weakly trained 2nd flight | Weakly trained 3rd flight |
|---|---|---|---|
| Pigeon 1 | 15,70% | 29,80% | 28,00% |
| Pigeon 2 | 37,30% | 17,60% | 19,70% |
| Pigeon 3 | 20,30% | 32,20% | 37,00% |
| Pigeon 4 | 39,00% | 36,50% | 32,50% |
| Pigeon 5 | 36,60% | 33,00% | 30,30% |
| Pigeon 6 | 30,40% | 20,20% | 18,00% |
| Pigeon 7 | 37,00% | 25,80% | 27,60% |

The results of the comparison of calculated flow paths and real flight routes were different for untrained and weakly trained pigeons.

## 5 CONCLUSIONS

When pigeons fly across medium distances (about 10 km), visual features of the surface significantly affect the probability of pigeon flights over this area.

The paper explored the flights of different pigeons over mixed terrain. The trajectories of flight of untrained and weakly trained pigeons are guided not only by reference points or extended landmarks, but also by the general structure of the terrain. After perception, terrain's surface determines the sequential flow forms and influences the choice of the direction of movement.

The influence of external visual information causes birds to change their trajectories, which are partially "attracted" not only to specific points of interest, but also to areas with the most saturated landscape.

In the present work it is shown that the attention of untrained pigeons was most often diverted, they deviated from the usual path selection algorithm, and began to shift to the areas of "saturated landscape complexity".

The results of this work can be used to understand the selection algorithms for the navigational behavior of birds, other animals, or humans.

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