Original Research Article

Bird Migration with Visual Avian Navigation: The PnP Linear Geometries-based Geo-referencing Functionality

Abstract

Birds and all animals on Earth, including humans, live in a complex physical world in which they must navigate. In migratory birds, the photochemical magnetoreception in their eye is believed to be the primary biophysical avian navigation tool supporting them with a magnetic sense functionality (magnetic "compass") thanks to cryptochrome-based magnetoreceptors in birds' retina and the bird's eye protein Cry4. Also, according to bibliography and scientific reports (nature research) low-density structured environments rich in trees, flora, and vegetation, as well as urban woodlands with roads, railways, and power lines should be regarded as the auxiliary geo-referencing avian navigation tool. Despite some differences, the visual process and geometric structure of the eye are roughly the same in humans and birds (known as the pinhole model). The cutting-edge technology "machine vision" follows the same (geometric) structure of vision (i.e., the perspective of the pinhole camera model). Even more, in machine vision, robots compute their own temporal position and navigation routes (pose determination/georeferencing) according to known closed PnP ("Perspective-n-Point") shapes and mutually detect parallel or perpendicular line pairs in observed linear or rectangular image-geometries that normally occur in low-density constructed urban environments (linear geometries). In this paper, we first introduce and document the innovative notion of "PnP linear geometries". It then first assumes (hypothesizes) that birds follow the same visual process for geo-referencing as robots in machine vision, and then proves (a proof based on a synthesis of evidence from eBird datasets and Flickr images, and statistical analysis/correlation matrix) that birds, apart from their primary biophysical magnetic "compass" and the auxiliary geo-referencing avian navigation tool, also follow the same visual avian navigation process for geo-referencing based on "PnP linear geometries" as robots.

Keywords

Bird migration, Bird visual avian navigation, Human eye structure, Bird eye structure, Machine vision, PnP Pose determination, Linear geometries, Geo-referencing, eBird datasets, Flickr imagery.

1. Introduction

Birds and all animals on earth, including humans, live in a complex, physical world through which they must move. According to the bibliography (nature research / scientific reports), the magnetic “compass” (thanks to cryptochrome-based magnetoreceptors in birds’ retina and the bird’s eye protein Cry4) is an important tool of birds’ avian navigation system, which allows migratory birds to solve complex geo-referencing tasks on travelling in flyways for spring and wintering locations [Bojarinova, J., 2020], [Starr, M., 2018].

In this case, the cryptochrome-based photochemical magnetoreception in birds’ eyes (located in the central part of the retina) is regarded to be the primary biophysical avian navigation tool. Also, according to bibliography and scientific reports (nature research) low-density structured environments rich in trees, flora, and vegetation, as well as urban woodlands with roads, railways, and power lines should be regarded as the auxiliary geo-referencing avian navigation tool (Fig. 1).

Figure 1. Bird Migration with Visual Avian Navigation. COURTESY MICHELLE STARR [Starr, M., 2018]

Despite some differences, the visual process and geometric structure of the eye of humans and birds are broadly the same (the so-called pinhole model) [Spiesman, B. J., et al., 2021], [De Jong Yeong, et al., 2021], [Bojarinova, Julia, et al., 2020].

The cutting-edge technology "machine vision" follows the same (geometric) structure of vision, namely the pin-hole camera model (perspective). The pin-hole camera model describes the mathematical relationship between the coordinates of a point in three-dimensional space and its projection onto the image plane of an ideal pinhole camera, where the camera aperture is described as a point and no lenses are used to focus light (Fig. 2).

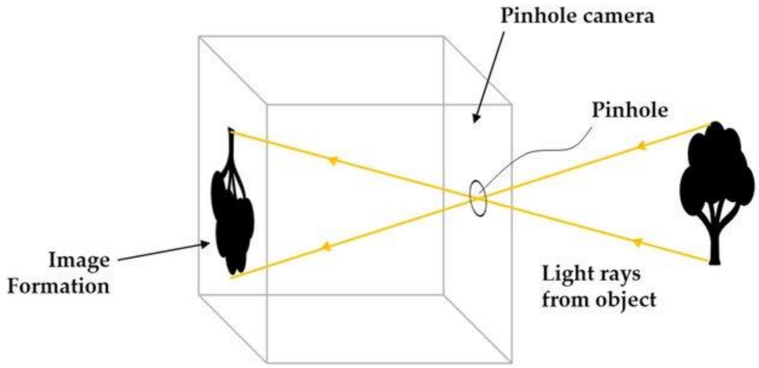

Figure 2. The Pin-hole Camera Model.

Even more, in machine vision, the robot computes its own temporal position (pose determination) by recognizing PnP ("Perspective-n-Point") shapes and mutually parallel or orthogonal line pairs in observed rectangular geometries usually found in natural images [Styliadis, A. & Sechidis, L., 2011], [Xiao Xin Lu, 2018], [Vincent Lepetit, Francesc Moreno-Noguer, Pascal Fua, 2009].

The innovative term "PnP linear geometries"

In this paper, we introduce the new term "PnP linear geometries" to describe the PnP shapes and the detected line pairs that are parallel or perpendicular to each other in observed on-images geometries with rectangular shapes, usually found in urban environments.

In this paper, we first assume that birds follow the same visual process in geo-referencing as robots (machine vision, pose determination). Then we prove statistically (a proof based on a synthesis of evidence from eBird datasets and Flickr images, and a statistical analysis/correlation matrix) that birds also follow the same visual process in georeferencing as robots!

Hence, we prove that birds, apart from their primary biophysical magnetic "compass" and the auxiliary geo-referencing avian navigation tools (low-density structured environments rich in trees, flora, and vegetation, as well as urban woodlands with roads, railways, and power lines), also follow, for geo-referencing, the same as robots' visual avian navigation process based on "PnP linear geometries".

The paper is organized as follows: In Section 2 ("Eye Structure (Human, Bird)") we discuss similarities in geometry and a number of differences in eye structure between humans and birds. In Section 3 ("Machine Robot Vision & Geo-Referencing - Hypothesis"), we analyze the georeferencing procedure followed by the robot during navigation. In Section 4 ("Real Field Experiments - eBird Datasets, Flickr Image Filtering & Distribution Analysis"), we present our field experiments based on eBird data and Flickr images and discuss the results and features of the distribution analysis. In Section 5 ("Statistical Analysis of Bird Nest Distribution - Correlation of Three Variables - Confirmation of Hypothesis"), we apply correlation analysis to three variables (bird nest locations; land cover; PnP linear geometries) and prove the hypothesis statistically. Finally, in Section 6 ("Conclusions"), we conclude that visual georeferencing of birds like robots follows PnP shapes and mutually detects parallel or perpendicular line pairs in the observed rectangular shape images that are normally found in low-density urban areas with many constructions.

2. The Eye Structure (Human, Bird)

Birds and all animals on earth, including humans, live in a complex, physical world in which they must navigate if they are to survive and perhaps leave some ungrateful children as a genetic legacy. Animals must perceive the features of the physical world. This is because many of these features - such as cliffs, quicksand, predators, and sharp sticks - can lead to injury or death. Others, like food and water, are necessities that animals need to survive [Kumar, N., et al., 2020].

Thanks to evolution's long, brutal march through natural selection, animals have senses that serve as important tools for survival. Senses helped our ancestors gather data about the environment, avoid danger, and locate vital resources. And the senses continue to serve us well today.

A garden warbler with an attached portable device for local application of oscillating magnetic fields is displayed in Figure 3. Yellow circumference schematically shows the eyeball projection on the picture plane [Bojarinova, Julia, et al., 2020].

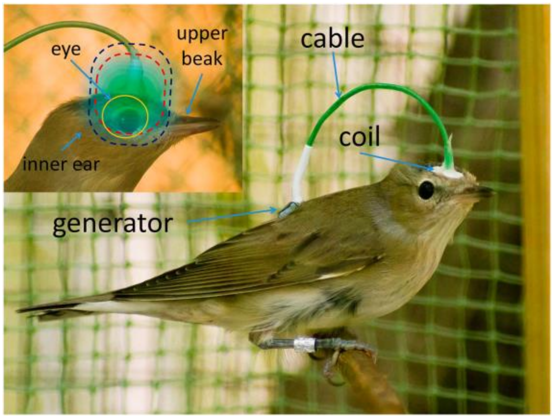

Figure 3. A garden warbler with attached portable device for local application of oscillating magnetic fields [Bojarinova, Julia, et al., 2020].

Human eye vs. bird eye: the same geometric structure

The geometric structure of humans and birds is roughly the same [Phillipsen, Ivan, 2021], [Morrison, Robyn, 2022, [Martin, G. R., 1994], [Martin, G. R., 2017]. Of course, according to bird vision expert Graham Martin (Emeritus Professor in the School of Biosciences at the College of Birmingham, UK), there are some differences that do not call into question the above general statement.

How is the human eye similar to the eye of a bird?

Both birds and humans have photoreceptive 'cones' in the retina, located at the back of the eye. These cones allow us to see colored light. The human eye contains 10,000 cones per square millimeter. Songbirds, for example, have up to 12 times as many, or 120,000 cones per square millimeter [Phillipsen, Ivan, 2022] (Fig. 4).

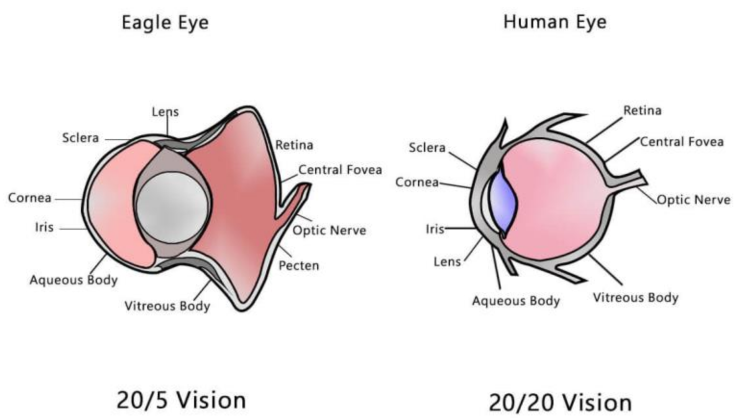

Figure 4. The photoreceptive 'cones' in the retina (located at the back of the eye).

For example, the retinas of birds have about three times as many sensory cells as our human retinas. So, like a camera with three times as many pixels, birds have much sharper vision than we humans do. Owls, in particular, have large retinas that give them no color but a maximum black-and-white vision in very low light.

The bird's eye anatomy

The following Figure 5 displays the bird's eye anatomy and structure.

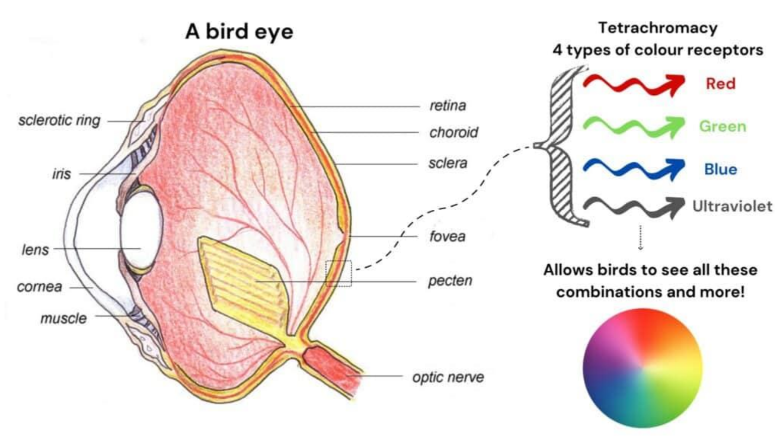

Figure 5. Bird's Eye Anatomy.

3. Machine Robot Vision & Geo-Referencing – Hypothesis

Computing the position and orientation of an object (known as the object pose problem in CAD and robotics) has important applications, such as camera calibration, determining sensor location (in digital photogrammetry), tracking and object detection (in robotics), etc. This calculation is based on images of feature points in photography when the geometric configuration of the object is known in advance [Styliadis, A., et al. 2003], [Xiao Xin Lu, 2018], [Vincent Lepetit, Francesc Moreno-Noguer, Pascal Fua, 2009].

Perspective-n-Point is the problem of estimating the pose of a calibrated camera given a set of n 3-D points in the world and their corresponding 2-D projections in the image. The camera pose consists of six (6) degrees of freedom (DOF), which are the rotation (roll, pitch, and yaw) and the 3-D translation of the camera with respect to the world.

In Styliadis, et al. paper, a technique is presented for modeling of indoor scenery based on digital images, photo-derived intra-component, geometric and topologic constraints, object-oriented graphic databases containing 3-D parametric models and a rough (generic) CAD model [Styliadis, A., et al. 2003]. This new method is based on mutually parallel or perpendicular line pairs in observed rectangular shape images usually found in photography. In man-made environments, rectangular shapes can be seen everywhere. It is thus convenient to use rectangular shapes for pose and object determination in photogrammetric engineering (close-range space rejection) and robotics (robot location).

The proposed hypothesis

From the bibliography presented above it is clear that in machine vision, the robot is actually geo-referenced continuously (i.e., with a temporal functionality) by using the so-called term "*PnP linear geometries*" introduced above. The proposed hypothesis assumes that the birds also follow the same geo-referencing procedure and in the next Section 4, we will prove statistically the correctness of this assumption (hypothesis).

4. Real World Field Experiments – eBird datasets, Flickr imagery filtering & Distribution analysis

Social media data are becoming potential sources of passive VGI (Volunteered Geographic Information) and citizen science, in particular regarding location-based environmental monitoring (Lotfian, M., and Ingensand, J., 2021).

Flickr, as one of the largest photo-sharing platforms, has been used in various environmental analyses from natural disaster prediction to wildlife monitoring. In this article, we have used bird photos from Flickr to illustrate the spatial distribution of bird locations in Possidi area / Chalkidiki / Greece, and most importantly to see the correlation between the location of birds' nests, the cover types, and the PnP linear geometries.

A chi-square test of independence has been applied to illustrate the association between birds' nests, land cover classes, and PnP linear geometries; and the results illustrated a statistically significant association between these three variables. Furthermore, birds' route distributions in Flickr imagery were compared to available eBird data, and the results demonstrated that Flickr imagery can be a possible complementary data source for geo-referencing science.

4.1 Study Area & eBird Datasets

Four eBird datasets were used in this study in conjunction with geo-tagged Flickr imagery, which were downloaded using the Flickr API (Application Programming Interface), and the CORINE land cover (https://land.copernicus.eu/pan-european/corine-landcover) from the map of Chalkidiki / Northern Greece for 2022. The initial dataset of Flickr images included only the central part of the Possidi area in Kassandra / Chalkidiki, but we later extended the dataset to include the north part as well. The next two Figures present the study area as well as the data points that indicate the position of the collected Flickr images (Figs. 6, 7).

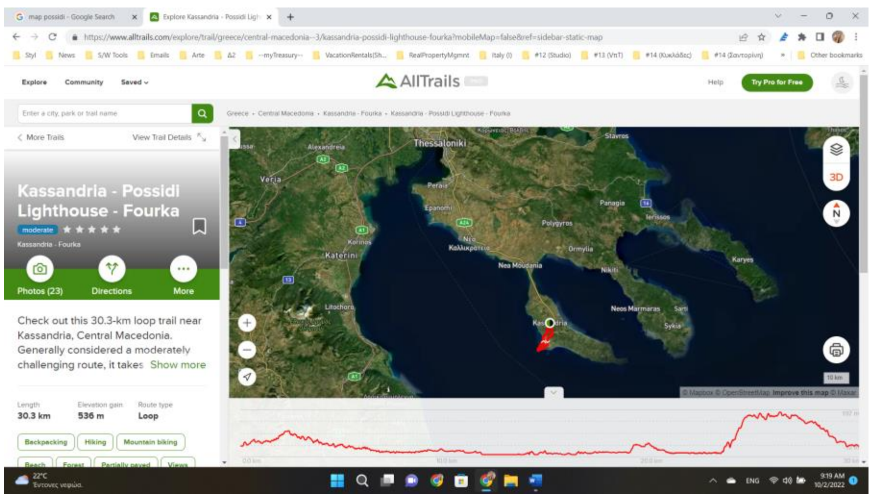

Figure 6. eBird datasets & Flickr imagery: Peninsula of Chalkidiki, Greece.

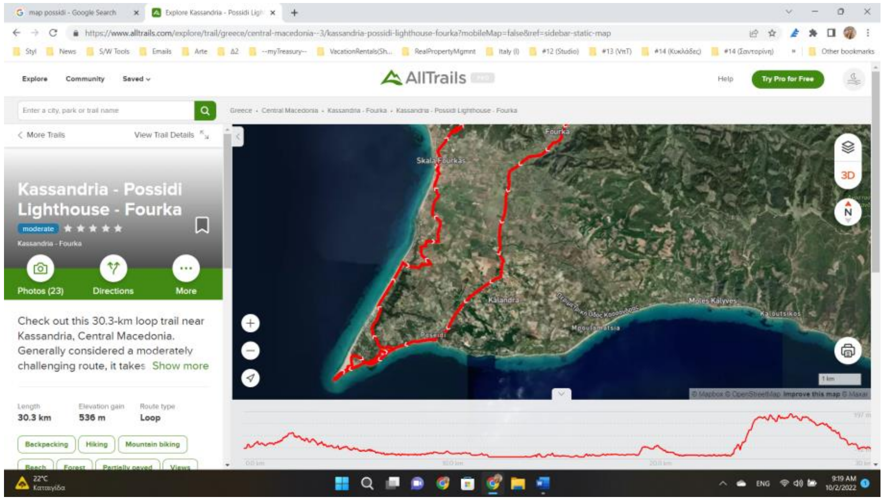

Figure 7. eBird datasets & Flickr imagery: Birds' watching area – The bounding box (Possidi / Chalkidiki, Greece).

4.2 Flickr Imagery Filtering

The first step was to download the images and to apply filters to them to obtain clean data for our analyses. As previously mentioned, we used the Flickr API and set the following requirements before beginning to download the images:

- The media was set to download only photos and not videos.
- The starting date was set as the first of January 2020.
- Only images with geo-location were downloaded.
- Due to the limit of Flickr API in returning up to 300 images per API call, the bounding box was not set to include the whole of Chalkidiki, Northern Greece.
- Finally, in order to find only photos of birds, we needed to identify the correct tag.

Flickr has two types of tags: user generated tags, which are added by Flickr contributors, and machine generated tags, which are added to images using Flickr's artificial intelligence. We set the machine generated tags as "any", and the user generated tags as "bird" in English language [Lotfian, M., and Ingensand, I., 2021]. As a result, we obtained the images as well as their metadata, which includes but is not limited to geo-location, date, image URL, image ID, and a list of all tags for each image. Following the download of the images, we applied two major filters to the dataset: image filter and tag filter (Fig. 8).

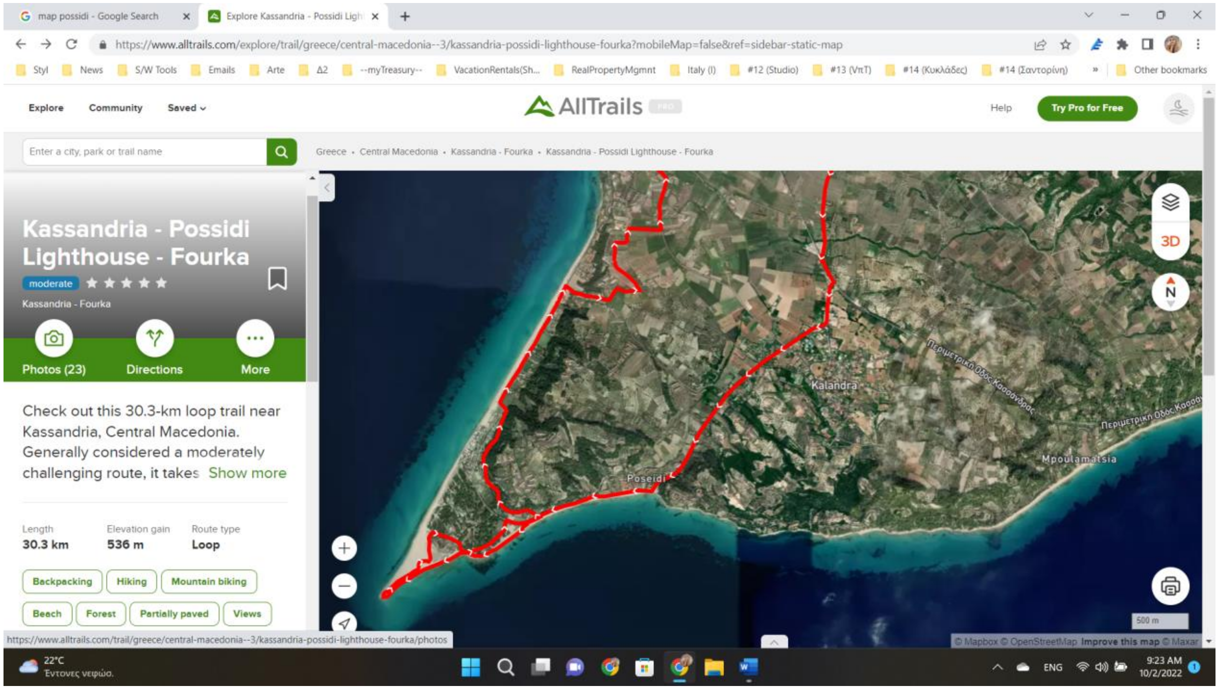

Figure 8. eBird datasets & Flickr imagery: Filtering the Birds' watching area (Fourka, Possidi, Possidi Lighthouse / Chalkidiki, Greece).

Finally, we were able to obtain the unique number of Flickr bird nests locations and flying/travelling routes observed in our study area. However, it is important to note that certain observations were filtered out due to a mismatch in the species name, and in order to provide a list of all observations, a better approach is to train a convolutional neural network (CNN) model (or to use a pre-trained CNN) to extract the species name from the images and then to perform text matching [Lotfian, M., Ingensand, J., and Brovelli, M. A. , 2020].

Our final dataset included the species names and species ID from the Institute of Avian Research (IAR), the German Ornithological Society (DO-G) and the journal Vogelwarte [IAR, DO-G, and Vogelwarte, 2022], the Flickr tag, image ID, and the geo-locations for the image (Figs. 9, 10).

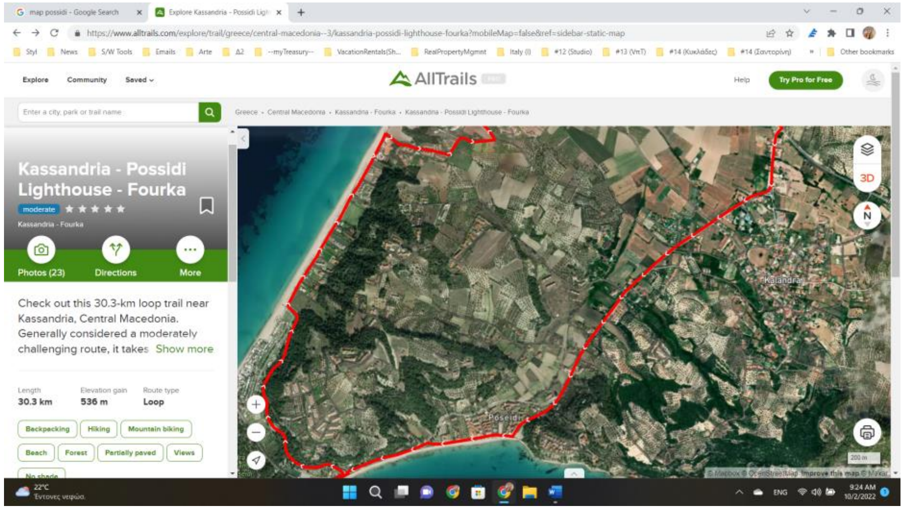

Figure 9. eBird datasets & Flickr imagery: The Flickr tag and the Image ID.

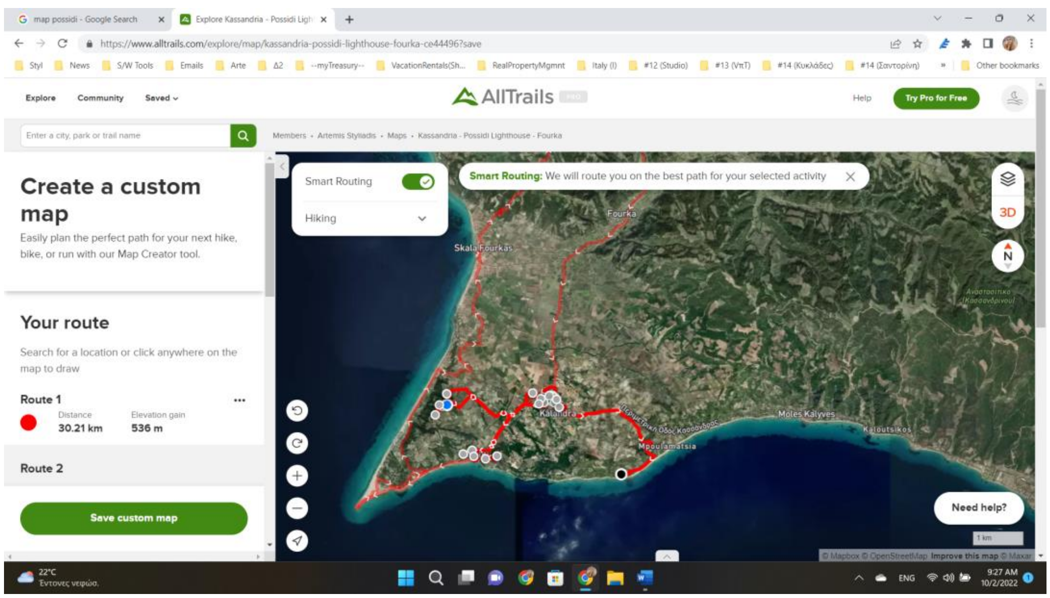

Figure 10. eBird datasets & Flickr imagery: The geo-locations for the image.

Bird migration topics

In the last decades, the study of bird migration focused on two main topics; the discovery and description of migratory routes and destinations, and the investigation of the mechanisms that regulate temporal (e.g. Summer) and spatial patterns (e.g., Travelling flyways and pathways) [IAR, DO-G, and Vogelwarte, 2022] (Figs. 11, 12, 13).

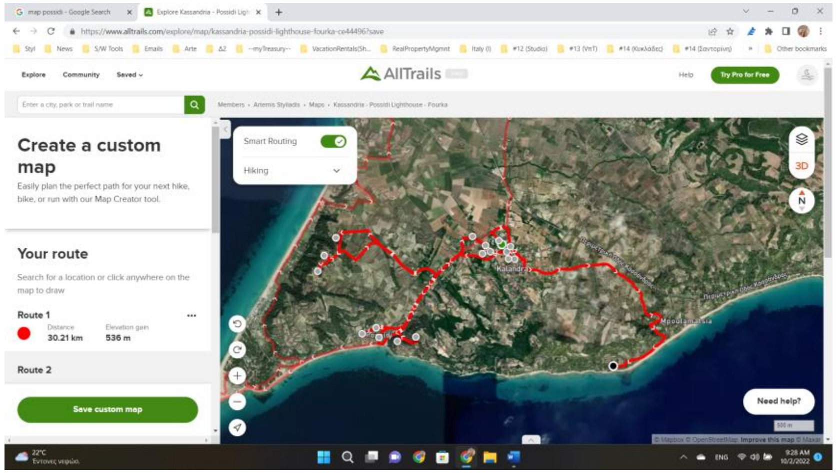

Figure 11. Bird migration: The Temporal dimension (Summer 2022 imagery).

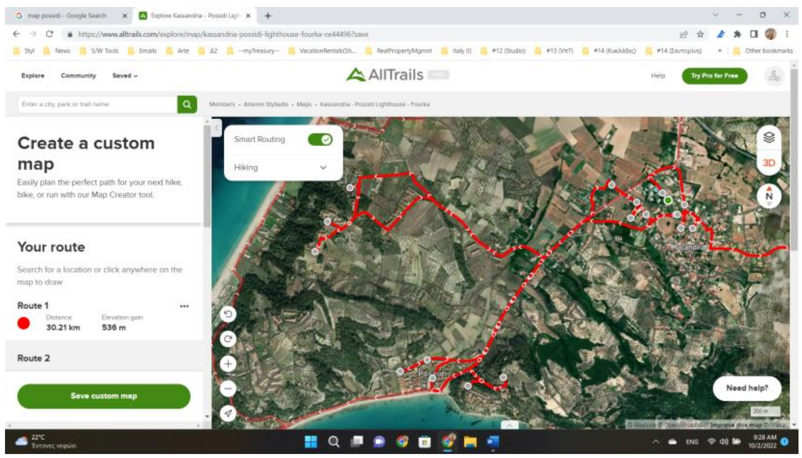

Figure 12. Bird migration: The Spatial patterns dimension (Birds' travelling flyways in Possidi area / Chalkidiki, Greece).

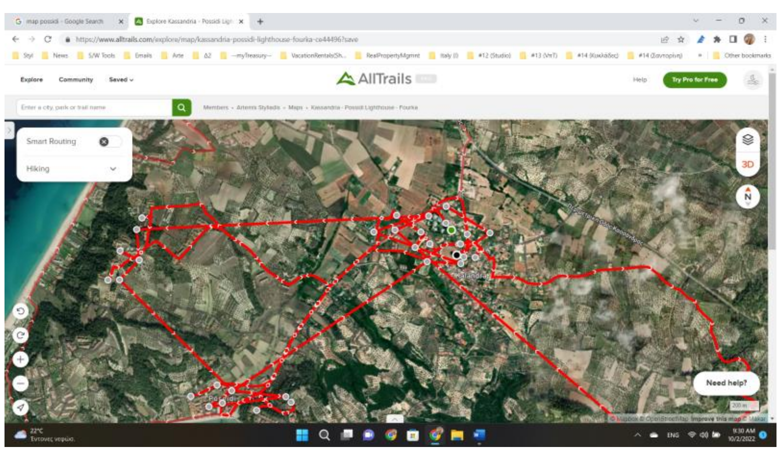

Figure 13. Bird migration: Demonstrating both, Temporal and Spatial patterns (Birds' travelling pathways in Possidi area in Summer 2022 / Chalkidiki, Greece).

4.3 Birds Distribution Analysis

After obtaining the filtered dataset, in order to visualize the density of distribution of bird observations in our study area we used kernel density analysis (KDE). Moreover, to explore the distribution of the data within various land cover classes in our study area, an additional dataset was created including the CORINE land cover values for each observation point. Thus, the frequency of birds' observations within different land cover types was observed, and a chi-square test of independence was performed to explore the association between the bird nest locations, land cover types (e.g. natural environment with trees, etc.), and PnP linear geometries.

Finally, to evaluate Flickr data using another dataset of bird observations, which is validated by experts (eBird in this case), the species distribution models (SDM) for a bird species called Common Kingfisher, were generated for both Flickr and eBird data. The Common Kingfisher datasets for eBird and Flickr included 141 and 33 unique observation points respectively, and only the land cover map was used as the input environmental variable to generate the model (SDM-Common Kingfisher, 2022).

To generate the SDMs, we used the Maxent algorithm (Phillips, S. J., and Dudík, M., 2008), and to compare the performance of the two models, the AUC (Area under the ROC Curve) metric was used (Bradley, A. P., 1997). Furthermore, the correlation between the two raster maps using their pair pixel values was computed to assess the similarity of the two species distribution maps.

Birds' visual avian navigation & migration

Currently, the focus in birds' avian migration is more on the ecological and evolutionary aspects of bird migration, and their relevance for conservation policy. While the endogenous regulation and heritability of migration strategies have been studied in detail, their interaction with the environment has received far less attention. Moreover, little is known about the fitness consequences, which are ultimately responsible for individual, population-level, and species differences in migration strategies [Bojarinova, Julia, et al., 2020].

Of relevance are the relationships between the requirement and availability of resources (i.e., fuel), and the need to balance these two factors with the allocation of time between rest and flight. The optimal strategy in this will depend on many factors. Our research on e.g., wheatears, godwits and grey plovers shows that these factors can be successfully studied with the combination of field observations, field experiments, and research under controlled conditions. These approaches are further developed within the Institute of Avian Research (IAR) [IAR, DO-G, and Vogelwarte, 2022].

In addition, the study of metabolic physiology and the biochemical basis of migratory behavior has taken flight. Technological advancement in physiological and biochemical analyses -in particular- has contributed to this, as it now allows us to study these aspects in vivo in relatively small birds. The study of differences between migratory and resident individuals, within the same species, provides especially important new insights in this respect. The scope of this work extends beyond birds, because the biophysical regulation of fat deposition for migration very much resembles the human diabetes type IIb pathology, with the added benefit that fat deposition is an annually reoccurring event.

An aspect of avian migration that has so far received little attention is its importance within the complete life history of an individual. The speed of migration may affect arrival time in the breeding area, which may in turn determine the quality of the obtained breeding territory or nest site, leading to a strong cascade of effects on fitness. Only the study of migration within a complete life-history framework can thus ultimately explain and predict responses to a changing environment [Kumar, N., et al., 2020].

In the observation area (Possidi / Chalkidiki), there are many constructions (e.g., houses, maisonettes, and villas) rich in “PnP linear geometries” structures. In this low-density structured environment rich in trees, flora, and vegetation we noticed many birds’ nests and many birds’ travelling flyways, routes, and pathways (Figs. 14, 15, 16). On the other hand, in the same environment (Possidi / Chalkidiki, rich in trees, flora, and vegetation) but in constructions without “PnP linear geometries” we didn’t find birds’ nests (Fig. 17).

Figure 14. Birds’ nests on a low-density structured environment rich in trees, flora, and vegetation and with many “PnP linear geometries”.

Figure 15. Birds' nests on a low-density structured environment rich in trees, flora, and vegetation and with many "PnP linear geometries".

Figure 16. Birds' nests on a low-density structured environment rich in trees, flora, and vegetation and with many "PnP linear geometries".

Figure 17. No Birds' nests on a low-density structured environment rich in trees, flora, and vegetation but poor in "PnP linear geometries".

In the same observation area (Possidi/Chalkidiki), there are also constructions (e.g., churches) with non-linear structures in environments poor in trees and flora. In these constructions we noticed no birds' nests and no birds' travelling flyways, routes, and pathways (Figs. 18, 19).

Figure 18. A Non-linear structure (Church) in a natural environment without trees and without PnP linear geometries → No Birds' nests found.

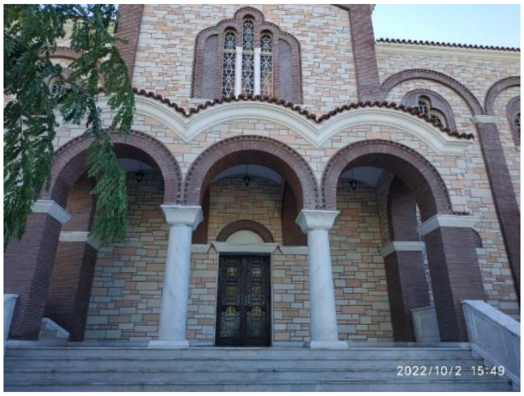

Figure 19. A Non-linear structure (Church) in a natural environment with few trees and without PnP linear geometries → No Birds' nests found.

5. Statistical Analysis of Birds' Nests Distribution – Three Variables Correlation - Hypothesis Confirmation

Correlation is a statistical term describing the degree to which two or more variables (in our case the variables are three: (i) The birds' nests locations, the travelling paths, and the pathways; (ii) the land cover types, and (iii) the PnP linear geometries) move in coordination with one another (Pauline, V., 2022).

In our case, the chi-square test was performed to measure the association between land cover types and bird species, and the Cramer's V metric was computed as a result of the test. Cramer's V is a metric to measure the strength of association between two variables. It ranges between 0 to 1, which values above 0.5 indicate strong association. Thus, the result of chi-square test illustrated a statistically significant association between the land cover types and birds species with Cramer's V= 0.5209 and p-value < 0.0001.

The model generated using eBird data performed better with AUC=0.86 compared to the one generated using Flickr data with AUC=0.7, which is reasonable given the number of records in Flickr which was nearly four times less than eBird (Pauline, V., 2022). While the distribution patterns in both maps look similar, the distribution from Flickr illustrates higher probability of occurrence in areas with discontinuous urban zones compared to eBird (Pauline, V., 2022).

Table 1 illustrates the statistics comparing the two raster maps, and it shows a very high correlation among the pixel values, supporting the similarity of the distribution between the two maps. From these analyses, it can be discussed that Flickr data might be a potential source to address the issue of lack of occurrence species data particularly in SDM studies, given that necessary filtering steps are applied to the data.

Moreover, informing the contributors about the value of their data in helping scientific projects can motivate them to contribute higher-quality data (Lotfian, et al., 2020). However, it is essential to note that many species had few data points (less than 5), and thus we could not evaluate or make any comparisons of such data with eBird observations, and it remains a point for future investigations.

Table 1. Statistical Correlation of the Birds' Nests distribution (eBird datasets & Flickr imagery)

Layer	Min	Max	Mean	Std
SDM_eBird datasets	0.0920	1.0000	0.2145	0.2090
SDM_Flickr imagery	0.4283	1.000	0.5332	0.1337

Table 2 presents the Covariance Matrix as it has been generated from (i) Table's 1 data (Statistical Correlation of the Birds' Nests distribution: eBird datasets & Flickr imagery); (ii) Birds' Nests locations and travelling routes, paths, and pathways; (iii) Land cover types; and (iv) PnP linear geometries.

Table 2. The Covariance Matrix

Layer	SDM_eBird datasets	SDM_Flickr imagery	Birds' Nests locations and Flying/Travelling flyways, routes & paths	Land Cover types (Natural environment with water, trees, and plants)	PnP Linear geometries (Mutually parallel or perpendicular line pairs in observed rectangular shape images)
SDM_eBird datasets	0.00848	0.01224	0.01230	0.01212	0.01242
SDM_Flickr imagery	0.01224	0.02075	0.01220	0.01207	0.01262
Birds' Nests locations and Flying/Travelling flyways, routes & paths	0.01230	0.01220	0.00790	0.01273	0.01263
Land Cover types (Natural environment with water, trees, and plants)	0.01212	0.01207	0.01273	0.00809	-
PnP Linear geometries (Mutually parallel or perpendicular line pairs in observed rectangular shape images)	0.01242	0.01262	0.01263	-	0.00786

Table 3 demonstrates the Correlation Matrix. Actually, we are using the Pearson correlation coefficient to examine the strength and direction of the linear relationship between these three continuous variables: (i) Birds' Nests locations and travelling routes, paths, and pathways; (ii) Land cover types; and (iii) PnP linear geometries. The correlation coefficient can range in value from −1 to +1. The larger the absolute value of the coefficient, the stronger the relationship between the variables.

Table 3. The Correlation Matrix (Birds' nests locations and flying/travelling routes, paths, and pathways; Land cover types; PnP linear geometries)

Layer	Birds' Nests locations and Flying/Travelling flyways, routes & paths	Land Cover types (Natural environment with water, trees, and plants)	PnP Linear geometries (Mutually parallel or perpendicular line pairs in observed rectangular shape images)	Rich Natural Lands with trees & Many PnP Linear geometries
Birds' Nests locations and Flying/Travelling flyways, routes and paths	1.00000	0.66732	0.73655	**0.90703**
Land Cover types (Natural environment with water, trees, and plants)	0.66732	1.00000	0	0.50448
PnP Linear geometries (Mutually parallel or perpendicular line pairs in observed rectangular shape images)	0.73655	0	1.00000	0.51087
Rich Natural Land with trees & Many PnP Linear geometries	**0.90703**	0.50448	0.51087	1.00000

A very strong positive correlation relationship (*r* = 0.90703) has been found between the layers "*Birds' Nests locations and Flying/Travelling routes & paths*" and "*Rich Natural Lands with trees & Many PnP Linear geometries*". Obviously, the birds prefer to travel in routes/paths/pathways and to build up nests in constructed natural environments rich in trees, flora, and vegetation, as well as with many PnP linear geometries (Table 3).

Statistical proof of the assumption (hypothesis) made

Hence, this very strong correlation relationship (*r* = 0.90703) should be interpreted as a great geo-referencing utility and functionality in birds' migration procedure. Hence, this should be regarded as a confirmation of the case introduced in Section 3 (Hypothesizes that birds follow the same visual process for georeferencing as robots in machine vision).

The confirmation (proof) is based on a synthesis of evidence from eBird datasets and Flickr images, and statistical analysis/correlation matrix) that birds also follow the same visual process for geo-referencing based on "PnP linear geometries" as robots.

6. Conclusions

In this paper, after introducing and documented the innovative term "*PnP linear geometries*", we prove statistically that birds' visual geo-referencing procedure follows (like robots) the PnP closed forms and geo-referencing functionalities derived from several detected mutually parallel or perpendicular line pairs in observed rectangular shape images usually found in natural and low-density structured environments. The presented research is based on available recent (2020, 2021, and 2022) eBird datasets and Flickr imagery from the Possidi area in Chalkidiki, Northern Greece.

In this paper, we have used eBird datasets and Flickr bird images from the Possidi area to observe the temporal and spatial distribution of both, the birds' travelling pathways and the birds' building up nests, as well as to determine whether or not there is any association (actually: correlation) between (i) this spatial distribution (ii) the land cover types (natural environment with or without trees, flora, and vegetation), and (iii) the PnP linear geometries.

The results illustrated that the data are more concentrated near natural environments with trees and water pockets in low-density urban areas with many constructions rich in PnP linear geometries. A very strong positive correlation relationship (*r* = 0.90703) has been found between the layers "*Birds' Nests locations and Flying/Travelling flyways, routes & paths*" and "*Rich Natural Lands with trees & Many PnP Linear geometries*". Obviously, the birds prefer to travel in routes/paths/pathways and to build up nests in low-density constructed natural environments rich in trees, flora, and vegetation, as well as with many PnP linear geometries (Section 5, Table 3).

Moreover, a statistically significant association was observed between birds' travelling pathways (spatial patterns of observations / data from Flickr imagery); birds' observers' behavior; land cover types; and PnP linear geometries.

Hence, in this paper, we prove that birds, apart from their primary biophysical magnetic "compass" (cryptochrome-based magnetoreceptors in birds' retina; bird's eye protein Cry4) and the auxiliary geo-referencing avian navigation tools (low-density structured environments rich in trees, flora, and vegetation, as well as urban woodlands with roads, railways, and power lines), also follow, for geo-referencing, the same as robots' visual avian navigation process based on "PnP linear geometries".

Data availability

All data generated or analyzed during this study are included in this published article (and its Supplementary Information files) and they are available from the author on reasonable request.

References

Bojarinova, J., Kavokin, K., Pakhomov, A., et al. (2020. Magnetic Compass of Garden Warblers is not affected by Oscillating Magnetic Fields applied to their Eyes. *Scientific Reports/Nature Research*. www.nature.com/scientificreports DOI: https://doi.org/10.1038/s41598-020-60383-x

Bradley, A. P. (1997). The use of the area under the ROC curve in the evaluation of machine learning algorithms. *Pattern Recognition*, Vol. 30, Issue 7, pp. 1145-1159. DOI: 10.1016/S0031-3203(96)00142-2.

Brian J. Spiesman, Claudio Gratton, Richard G. Hatfield, William H. Hsu, Sarina Jepsen, Brian McCornack, Krushi Patel, and Guanghui Wang (2021). Assessing the Potential for Deep Learning and Computer Vision to Identify Bumble Bee Species from Images. Scientific Report (2021) 11:7580. www.Nature.com/ScientificReports. https://doi.org/10.1038/s41598-021-87210-1

IAR, DO-G, and Vogelwarte (2022). The Institute of Avian Research "Vogelwarte Helgoland" (IAR) is a non-university research institute in the portfolio of the Lower Saxonian Ministry of Science and Cultural Affairs. The Institute members conduct fundamental research on the complex relationships between birds and their organic and inorganic environments. The central research foci are bird migration and life history biology. In addition, the Institute publishes the journal "Vogelwarte" and houses the Bird Ringing Centre for Northwest Germany. https://ifv-vogelwarte.de/en/home-ifv/publications/vogelwarte; https://ifv-vogelwarte.de/en/home; https://ifv-vogelwarte.de/en/home-ifv/research/bird-migration

Kumar, N., Gupta, U., Jhala, Y., Qureshi, Q., Gosler, A., and Sergio, F. (2020). GPS-telemetry unveils the regular high-elevation crossing of the Himalayas by a migratory raptor: Implications for definition of a "Central Asian Flyway". *Scientific Reports/Nature Research*. www.nature.com/scientificreports DOI: https://doi.org/10.1038/s41598-020-72970-z

Lepetit Vincent, Moreno-Noguer Francesc, and Fua Pascal (2009). EPnP: An accurate O(n) solution to the PnP problem. *International Journal of Computer* Vision, Vol. 81, Issue 2. DOI: 10.1007/s11263-008-0152-6

Lotfian, M., Ingensand, J., and Brovelli, M. A. (2020). A Framework for Classifying Participant Motivation that Considers the Typology of Citizen Science Projects. *ISPRS International Journal of Geo-Information*, Vol. 9, No. 12: 704. DOI: 10.3390/ijgi9120704.

Lotfian, M., and Ingensand, J. (2021). Using geo-tagged Flickr images to Explore the Correlation between Land Cover Classes and the Location of Bird Observation. *IAPRS Archives*, Vol. XLIII-B4-2021, XXIV ISPRA Congress (2021 edition). DOI: 10.5194/isprs-archives-XLIII-B4-2021-189-2021.

Martin, G. R. (1994). Form and Function in the Optical Structure of Bird Eyes. DOI: 10.1007/978-3-642-75869-0_2 (In book: "Perception and Motor Control in Birds").

Martin, G. R. (2017). Vision in Birds: Master class #6. BTO News (Winter 2017).

Morrison, Robyn (2022). How Does a Bird's Vision Compare to a Human's? Londolozi Blog. https://blog.londolozi.com/2022/02/03/how-does-a-birds-vision-compare-to-a-humans/

Pauline, Vos (2022). Pearson's correlation between three variables; Using students' basic knowledge of geometry for an exercise in mathematical statistics. *International Journal of Mathematical Education*, Vol. 40, No. 4, pp. 533-541. DOI: 10.1080/00207390802419578

Phillips, S. J., and Dudik, M. (2008). Modeling the species distributions with Maxent: New extensions and a comprehensive evaluation. *Ecography*, Vol. 31, No. 2, pp. 161-175. DOI: 10.1111/j.0906-7590.2008.5203.x

Phillipsen, Ivan (2021). The Science of Birds. https://www.scienceofbirds.com/blog/bird-eyes-and-vision

Phillipsen, Ivan (2022). How do Birds get their Colors / The Science of Birds. Podcast & Webminal tutorial on July 14, 2022. Audubon Society / Northern Virginia. www.AuduBonva.org

SDM-Common Kingfisher (2022). https://en.wikipedia.org/wiki/Common_kingfisher

Starr, Michelle (2018). Birds Can See Earth's Magnetic Fields, And Now We Know How That's Possible. NATURE (September 1, 2018). https://www.sciencealert.com/birds-see-magnetic-fields-cryptochrome-cry4-photoreceptor-2018

Styliadis, A., et al. (2003). Pose Determination From a Single Image in a Controlled CAD Environment. *Journal of WSCG*, Vol.11, No.3, ISSN 1213-6972. WSCG'2003, February 3-7, 2003, Plzen, Czech Republic.

Styliadis, A., and Sechidis, L. (2011). Photography-based façade recovery & 3-d modeling: A CAD application in Cultural Heritage. *Journal of Cultural Heritage*, Vol. 12, Issue 3, pp. 243-252. https://doi.org/10.1016/j.culher.2010.12.008

Xiao Xin Lu (2018). A Review of Solutions for Perspective-n-Point Problem in Camera Pose Estimation. *Journal of Physics*: Conference Series 1087 052009, Volume 1087, Issue 5.

Yeong, De Jong, Gustavo Velasco-Hernandez, Barry John, and Walsh Joseph (2021). *Sensor and Sensor Fusion Technology in Autonomous Vehicles*: A Review. Lab: Joseph Walsh's Lab, Sensors 21(6):2140, DOI: 10.3390/s21062140