Reconstruction and Analysis of 3D Trajectories of Brazilian Free-tailed Bats in Flight

Diane H. Theriault [1], Zheng Wu[1], Nickolay I. Hristov[2], Sharon M. Swartz[3],
Kenneth S. Breuer[4], Thomas H. Kunz[5], Margrit Betke[1]
[1] Department of Computer Science, Boston University
[2] Department of Life Sciences, Winston Salem State University, and Center for Design Innovation, University of North Carolina
[3] Department of Ecology and Evolutionary Biology and Division of Engineering, Brown University
[4] Division of Engineering, Brown University
[5] Department of Biology, Boston University

Abstract

The Brazilian free-tailed bat, Tadarida brasiliensis, roosts in very large colonies, consisting of hundreds of thousands of individuals. Each night, bats emerge from their day roosts in dense columns in a highly coordinated manner. We recorded short segments of an emergence using three spatially-calibrated and temporally-synchronized thermal infrared cameras. We applied stereoscopic methods to reconstruct the three-dimensional positions of these flying bats. We applied a multiple hypothesis tracking algorithm to obtain 7,016 reconstructed trajectories. Our analysis includes estimates of the velocities of bats in flight, the distances between animals within the emergence column, and the angles subtended by the bats and their nearest neighbors.

1. Introduction

Brazilian free-tailed bats (*Tadarida brasiliensis*) live in very large groups containing hundreds of thousands to millions of individuals [2, 4, 5]. We investigated the behavior of these bats, which emerge nightly from their roosts near sunset in large, dense columns.

We used three calibrated, synchronized thermal infrared cameras to observe the emergence behavior of these bats. We used stereoscopic methods to reconstruct the three-dimensional (3D) positions of individual animals within the column, and then applied a Multiple Hypothesis Tracker (MHT) to link the 3D positions into tracks [15, 16]. In our current work, we focus on the analysis of the resulting tracks to explore flight characteristics, such as the average speed, the distance between animals, and their relative positions with respect to one another.

2. Methods

We analyzed the nightly emergence behavior of a colony of Brazilian free-tailed bats at a cave in Texas. We used three thermal infrared FLIR SC6000 cameras that recorded 16 bit video at a resolution of 640 x 512 pixels at 125 frames per second. Example frames of video containing approximately 100 bats are shown in Figure 1.

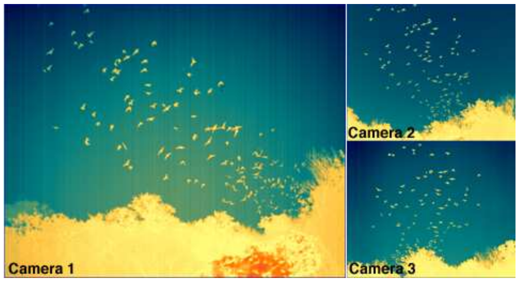
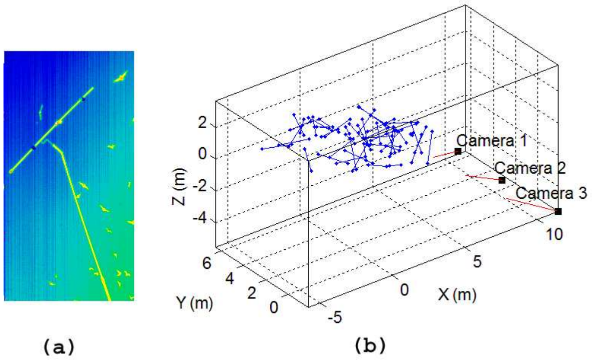


Figure 1. Images from three thermal infrared cameras.

2.1. Camera Calibration

We constructed a calibration apparatus that was visible to the infrared cameras by attaching cold and hot packs to sections of PVC tubing (Figure 2). Calibration sequences were recorded simultaneously with the three cameras. Corresponding points in each of the three views were marked manually.

We used the Eight Point Algorithm [6] to compute the pairwise fundamental matrices. We then extracted



(a) (b)

Figure 2. Thermal image of calibration apparatus (left) and camera positions and reconstructed points on apparatus (right).

the focal length and extrinsic parameters for each camera, given an initial approximation of the principal point. We further applied a local search procedure to refine our estimate of the focal length and principal point. After computing the intrinsic and extrinsic parameters, the 3D positions of the points on the calibration apparatus were estimated using the Direct Linear Transformation (DLT) method [6].

2.2. Stereoscopic Reconstruction and Tracking

We used the "reconstruction-tracking method" developed in previous work [16] to first reconstruct the 3D positions of the bats and then recursively estimate their 3D trajectories based on the reconstructed points.

We briefly summarize this method [16] as follows: At each time step and for each view, our system detected bats and represented them as sets of 2D points. For each point in a single view, we used the projection matrices, obtained from the calibration process, to create epipolar lines in the other two views. Tuples of corresponding points were determined by finding points that were near each other's epipolar lines. The reconstructed 3D points were used as input to the next step of tracking in 3D.

We applied a Multiple Hypothesis Tracking (MHT) algorithm with a sliding-time window. This method constructs a tree where the associations between tracks and measurements are hypothesized at each time step. Each track has an associated gate, which restricts the possible number of matches. Ambiguity in the association between the tracks and the measurements is allowed to persist for a fixed period of time before it is forced to be resolved.

Our goal was to compute the most likely measurement-to-track associations. We therefore formulated the problem as a maximization of the joint probabilities of all track-to-measurement associations, so that the relationship between tracks and measurements was one-to-one. Because this maximization is an NP hard problem, an iterative approximation technique, the Greedy Randomized Adaptive Local Search Procedure (GRASP) [11], was applied.

3. Analysis and Results

We focused on a 40-second segment of data that was recorded during the early part of an emergence that lasted over an hour. At any point in time during this period, we typically observed between 20 and 60 bats, with a maximum of approximately 100 bats (Figure 3).

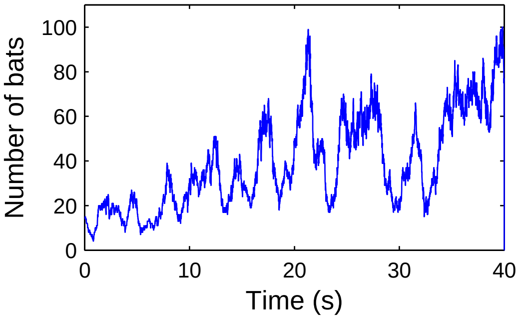


Figure 3. The number of bats observed during emergence.

Using the previously described 3D reconstruction and tracking techniques, we reconstructed 7,016 trajectories from 5,000 frames recorded by each of three cameras. Each trajectory consisted of the reconstructed 3D positions of a single animal linked across time. The average length of a track was approximately 37 frames, which corresponds to approximately 0.3 s of flight time.

We performed three analysis tasks. For the first two tasks, we partitioned the reconstructed 3D positions of bats into ten sets, where 1–10, 11–20, . . . , 91–100 bats were simultaneously present. The number of 3D positions in each set differed, ranging between 1,678 positions for the set containing between 1 and 10 bats and 42,664 positions for the set of frames containing between 61 and 70 bats.

Our first task was designed to estimate the velocity at which each individual *Tadarida brasiliensis* flew during emergence. Estimates of the magnitude of the velocity of bats in laboratory [7] and natural [5, 8, 9] environments have been made using stop watches and radar [3, 12, 14]. These estimates were based either on flight trajectories of only a few individuals, or the path of the column as a whole, without tracking individuals [14]. In contrast, we were able to estimate the velocity at which individual bats fly under natural conditions by using 7,016 reconstructed trajectories.

We computed the instantaneous velocity of each bat at every moment in time using the reconstructed tracks. Averaged over the 215,796 available measurements in our data set, we found that the bats emerged at a speed of 9.38 ± 0.02 meters per second (95 % confidence interval). For each set of 3D positions containing different numbers of bats, we computed statistics of the speed of all bats in the set, and found that the speed at which bats flew during early emergence varied slightly according to the number of bats present (Figure 4). Our results are consistent with the flight speeds reported for *Tadarida brasiliensis* by Hayward and Davis [7] under laboratory conditions.

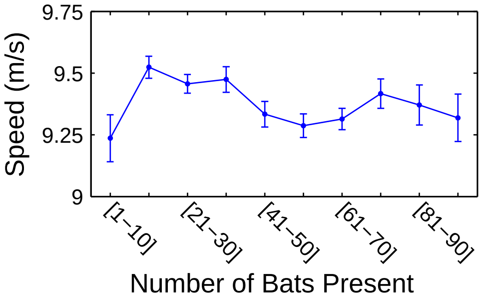


Figure 4. Average speed of bats with 95% confidence intervals, computed using 7,016 flight trajectories.

Our second task was to extend our preliminary analysis [15] and investigate the typical distance between bats as they fly in a column. For every time step, we calculated the distances between all possible pairs of bats and identified each bat's nearest neighbor. By examining the sets of 3D positions defined above, we found that, as the number of bats present increased, the average distance between nearest neighbors converged to approximately 0.5 m (Figure 5). This is a very tight estimate because we have so many measurements; for example, the 95% confidence interval for the set of 3D positions containing between 81 and 90 bats (11,640 measurements) was only 0.4 cm.

Our third task was to study the relative positions of the bats with respect to each other. For this task, we chose to use all 3D positions where at least 60 bats were present simultaneously, for a total of 75,369 measurements. We used the forward velocity of each bat and a vertical vector to establish an orthonormal 3D coordinate frame. We identified each bat's nearest neighbor and computed the bearing (θ) and elevation (ϕ) angles between its velocity and the vector pointing to its nearest neighbor (Figure 6). The distribution of these angles is shown as a two dimensional histogram (Figure 7).

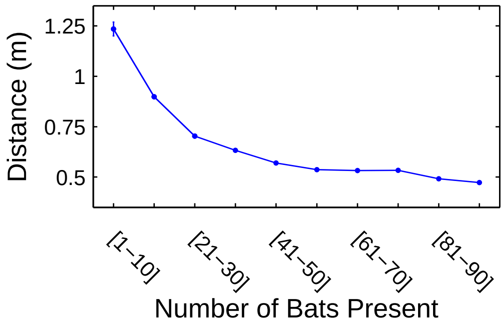


Figure 5. Average distance between nearest neighbors. Confidence intervals (e.g. 0.4 cm for the set of 3D positions containing between 21 and 30 bats) fall inside of the markers for all but the first data point.

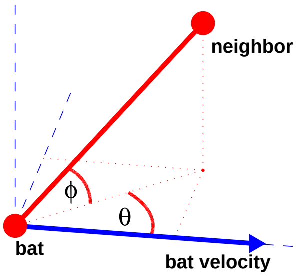


Figure 6. Relationship, computed in spherical coordinates θ and ϕ, between the velocity of a bat and the position of its nearest neighbor.

We found a non-uniform structure in the histogram with respect to the elevation angle ϕ. The area near the poles of the histogram contains fewer samples than the area near the equator (Figure 7). This reveals that the bats typically do not fly directly above or below each other.

With respect to the bearing angle θ, no strong pattern was observed. This result is in direct contrast to Partridge *et al.* [10] and Ballerini *et al.* [1] who reported crystalline structures in schools of fish and flocks of starlings, respectively.

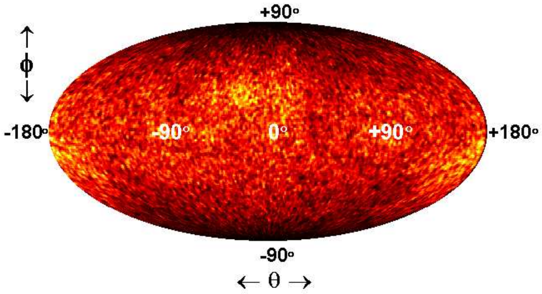


Figure 7. Histogram of angles between bat's velocity and vector to nearest neighbor in spherical coordinates.

4. Conclusions

To effectively explore the behavior of animals that move in three dimensions, such as bats, birds, insects, or fish, it is essential to obtain their 3D positions and trajectories. In the present study, we have analyzed 3D trajectories of Brazilian free-tailed bats in flight, using automatic reconstruction and tracking algorithms based on recorded data from three calibrated, synchronized thermal infrared cameras. Because the methods we discussed are automatic, we were able to base our conclusions on tens of thousands of measurements.

The novel contribution of our paper is to the understanding of the behavior of Brazilian free-tailed bats in their natural environment. We are the first to report estimates of flight speed and distance between individuals based on thousands of three-dimensional trajectories. We are also the first to reveal a non-uniform structure in the way emerging bats position themselves with respect to one another.

Other contributions of this paper include the methods of analysis, which can be applied in the future studies of large data sets of video of other animals or objects that move in three dimensions. For each object, we examined the angle between its movement direction and the vector to its nearest neighbor. The visualization of these angles as a two dimensional histogram has the potential to reveal significant structure in large groups. We have also studied how flight characteristics such as speed and distance between neighbors change as a function of the number of objects in the field of view.

5. Acknowledgements

This material is based in part upon work supported by the National Science Foundation under Grant Nos. 0326483 and 0910908 and the Air Force Office of Scientific Research under Grant FA9550-07-1-0540. We would like to thank Ty Hedrick [13] for help with camera calibration and Louise Allen for help with data collection.

References

[1] M. Ballerini, N. Cabibbo, R. Candelier, A. Cavagna, E. Cisbani, I. Giardina, V. Lecomte, A. Orlandi, G. Parisi, A. Procaccini, M. Viale, and V. Zdravkovic. Interaction ruling animal collective behavior depends on topological rather than metric distance: Evidence from a field study. *Proceedings of the National Academy of Sciences*, 105(4):1232–1237, January 2008.

[2] M. Betke, D. E. Hirsh, N. C. Makris, G. F. McCracken, M. Procopio, N. I. Hristov, S. Tang, A. Bagchi, J. D. Reichard, J. W. Horn, S. Crampton, C. J. Cleveland, and T. H. Kunz. Thermal imaging reveals significantly smaller Brazilian free-tailed bat colonies than previously estimated. *J Mammal*, 89(1):18–24, 2008.

[3] B. Bruderer and A. G. Popa-Lisseanu. Radar data on wing-beat frequencies and flight speeds of two bat species. *Acta Chiropterologica*, 7(1), 73-82, 2005.

[4] D. C. Constantine. 1967. Activity patterns of the Mexican free-tailed bat. *University of New Mexico Publications in Biology*, 7: 1–79.

[5] R. Davis, C. Herreid II, and H. Short. 1962. Mexican free-tailed bats in Texas. *Ecol Monogr*, 32: 311–346.

[6] R. I. Hartley and A. Zisserman. *Multiple View Geometry in Computer Vision*. Cambridge Uni. Press, 2004.

[7] B. Hayward and R. Davis. Flight speeds in western bats. *J Mammal*, 45(2):236–242, 1964.

[8] M. L. Kennedy and G. A. Engrebretson. Flight speeds of the cave bat. *Proc Oklahoma Acad Sci*, 54:12, 1974.

[9] D. W. Morrison. Flight speeds of some tropical forest bats. *Am Midl Nat*, 104(1):189–192, 1980.

[10] B. L. Partridge, T. Pitcher, M. Cullen, and J. Wilson. The three-dimensional structure of fish schools. *Behavioral Ecology and Sociobiology*, 6(4):277–288, 1980.

[11] A. J. Robertson. A set of greedy randomized adaptive local search procedure (GRASP) implementations for the multidimensional assignment problem. *Comput Optim Appl*, 19(2):145–164, 2001.

[12] H. Salcedo, M. Fenton, M. Hickey, and R. Blake. Energetic consequences of flight speeds of foraging red and hoary bats (*Lasiurus borealis* and *Lasiurus cinereus*; Chiroptera: Vespertilionidae). *Journal of Experimental Biology*, 198(11):2245–2251, 1995.

[13] T. L. Hedrick. Software techniques for two- and three-dimensional kinematic measurements of biological and biomimetic systems. *Bioinspir Biomim* 3(3), 2008. 6 pp.

[14] T. C. Williams, L. C. Ireland, and J. M. Williams. High altitude flights of the free-tailed bat, *Tadarida brasiliensis*, observed with radar. *Journal of Mammalogy*, 54(4):807–821, 1973.

[15] Z. Wu, N. I. Hristov, T. L. Hedrick, T. H. Kunz, and M. Betke. Tracking a large number of objects from multiple views. In *Proceedings of the International Conference on Computer Vision (ICCV)*, 2009. 8 pp.

[16] Z. Wu, N. I. Hristov, T. H. Kunz, and M. Betke. Tracking-Reconstruction or Reconstruction-Tracking? Comparison of two multiple hypothesis tracking approaches to interpret 3D object motion from several camera views. In *Proc. IEEE Workshop on Motion and Video Computing (WMVC)*, 2009.