https://doi.org/10.20965/jrm.2021.p0556

Paper:

Three-Dimensional Trajectory Construction and Observation of Group Behavior of Wild Bats During Cave Emergence

Emyo Fujioka*[1], Mika Fukushiro*[2], Kazusa Ushio*[3], Kyosuke Kohyama*[4], Hitoshi Habe*[5], and Shizuko Hiryu*[3]

*[1]Organization for Research Initiatives and Development, Doshisha University
1-3 Tatara-miyakodani, Kyotanabe, Kyoto 610-0321, Japan
E-mail: efujioka@mail.doshisha.ac.jp
*[2]Graduate School of Life and Medical Sciences, Doshisha University
1-3 Tatara-miyakodani, Kyotanabe, Kyoto 610-0321, Japan
*[3]Faculty of Life and Medical Sciences, Doshisha University
1-3 Tatara-miyakodani, Kyotanabe, Kyoto 610-0321, Japan
*[4]Graduate School of Science and Engineering, Kindai University
3-4-1 Kowakae, Higashiosaka, Osaka 577-8502, Japan
*[5]Faculty of Science and Engineering, Kindai University
3-4-1 Kowakae, Higashiosaka, Osaka 577-8502, Japan

[Received January 8, 2021; accepted February 26, 2021]

Echolocating bats perceive the surrounding environment by processing echoes of their ultrasound emissions. Echolocation enables bats to avoid colliding with external objects in complete darkness. In this study, we sought to develop a method for measuring the collective behavior of echolocating bats (*Miniopterus fuliginosus*) emerging from their roost cave using high-sensitivity stereo-camera recording. First, we developed an experimental system to reconstruct the three-dimensional (3D) flight trajectories of bats emerging from the roost for nightly foraging. Next, we developed a method to automatically track the 3D flight paths of individual bats so that quantitative estimation of the population in proportion to the behavioral classification could be conducted. Because the classification of behavior and the estimation of population size are ecologically important indices, the method established in this study will enable quantitative investigation of how individual bats efficiently leave the roost while avoiding colliding with each other during group movement and how the group behavior of bats changes according to weather and environmental conditions. Such high-precision detection and tracking will contribute to the elucidation of the algorithm of group behavior control in creatures that move in groups together in three dimensions, such as birds.

Keywords: echolocation, bat, bio-sonar, collective behavior, trajectory tracking

1. Introduction

Many creatures, such as fish and birds, form groups to avoid attacks from predators, increase the dynamic energy efficiency of migration, and achieve efficient homing [1–3]. Recent research on group behavior has made it possible to measure the group motion of organisms by improving the performance of the measuring equipment used. Research on the mechanisms of collective behavior has also been carried out using measurements of group movement [4–7]. For example, using a bio-logging technique, it is possible to acquire not only position data but also various types of information related to behavioral conditions, such as acceleration of birds flying in the sky [7, 8]. Furthermore, research has been conducted on the interactions between individuals moving in groups using measured data on group behavior [7, 9–11]. It is expected that the elucidation of the mechanisms of group behavior will lead to the conservation of biological resources and the elucidation of ecosystems and will also have applications to human society, such as advancement of automatic driving technology for automobiles.

Bats use echolocation, spontaneously emitting ultrasonic waves and receiving reflected sounds to perceive the surrounding environment [12, 13]. Bats flying in a group are subject to various types of acoustic interference, such as the echolocation pulses and reverberant echoes of other individuals, and yet they are able to conduct aerial feeding in the dark and avoid colliding with other individuals, even in crowded conditions [14]. Research has shown that bats have exceptional sonar ability, and it is expected that better understanding of the mechanism by which bats obtain information about their surroundings will be useful in various engineering applications.

However, little is currently understood about the collec-

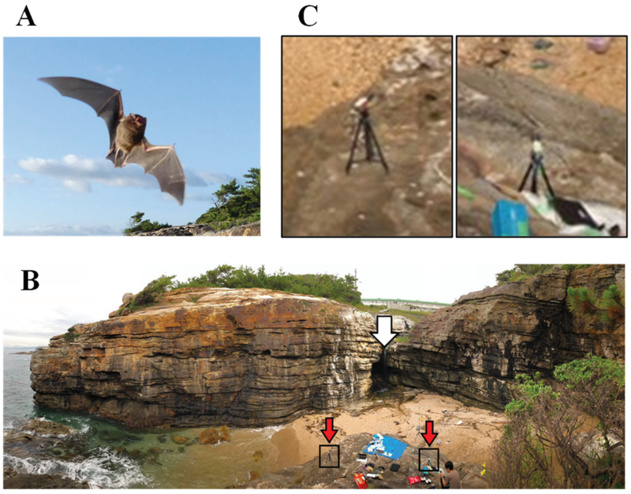

Fig. 1. (A) *Miniopterus fuliginosus*. (B) Photograph of the study site taken in iPhone panorama mode. Open and filled arrows show cave entrance and video cameras, respectively. (C) Enlarged pictures of squared portions in (B).

tive flight and interference avoidance behavior of echolocating bats, because of the technical difficulties associated with measuring their movements. When flying in multiple, the conditions such as the flight routes might have complicated effects on the behavior of the bats, in addition to the factors of acoustic interference. In addition, dense collective behavior is rare among organisms with active sensors, and few quantitative studies on the collective behavior of bats have been conducted.

In this study, we carried out measurements using a stereo camera system to observe the group behavior of bats in the field. The purposes of this study were to construct a system for three-dimensional (3D) measurement of the flight paths of individual bats and to assess the constructed system. It is difficult to measure the movement of small individual bats quantitatively and to analyze huge amounts of data on their movement manually, and these difficulties have been major obstacles in the study of the collective behavior of nocturnal flying bats. Therefore, in this study, we conducted automatic tracking of the flight paths of bats, together with manual analysis of images of the flight paths photographed using a stereo camera.

2. Materials and Methods

2.1. Subject and Study Site

The species observed was the eastern bent-wing bat (*Miniopterus fuliginosus*) (**Fig. 1(A)**). This species is distributed throughout the Japanese archipelago and mainly inhabits caves. In Senjojiki sea erosion cave (**Fig. 1(B)**) in Shirahama-cho, Nishimuro-gun, Wakayama Prefecture, females begin to gather just before breeding, beginning at the end of June, and breeding care is conducted [15]. This cave, utilized as a breeding cave, is reported to shelter approximately 20,000 bats [15]. Each evening during the breeding period, around sunset, bats emerge from the cave in groups. In this study, measurements were taken in front of the cave at approximately 19:00 on July 12 and 15, 2019.

2.2. Stereo Camera Recording

For 3D measurement of the flight paths of the bats, two high-sensitivity cameras (HAS-U2M, digital high-speed cameras manufactured by DITECT in Japan) were placed pointing toward the entrance of the cave (**Fig. 1(C)**). The direct linear transformation (DLT) method was used to estimate the 3D position coordinates calculated by camera calibration from known 3D coordinates (calibration points) of images obtained from the two cameras [16, 17]. A total station (NST-C1r, Nikon, Japan) was used to obtain the coordinates of the calibration points. The total station is a surveying instrument that can measure the distance, altitude angle, and azimuth angle to a reflecting prism that can be optionally installed using an irradiating laser. Although the calculation of the calibration point coordinates becomes theoretically possible with six points, the measurement accuracy is improved if many calibration points are installed over a wide area. In this experiment, 18 points were established to cover the whole flight range of the bats caught by the cameras. Because the measurements were carried out at night, the quay wall was irradiated by an infrared ray projector (LIR-CS88, IR LAB, Taiwan), and the bats movements were clearly captured by the cameras. The frame rate and resolution were 60 fps and 2592×2048, respectively. The continuous photographing was limited to approximately 30 min because of the limited capacity of the built-in solid-state disk (SSD) of the personal computer (HP Spectre Notebook, HP, Japan). DIPP-Motion V/3D, which is software for 3D coordinate calculation, was used for manual analysis of the data.

2.3. Positional Error Estimation of Manual Analysis

Figure 2(A) shows the arrangement of the calibration points recorded by the left and right cameras. The calibration was carried out using these 18 points, and their 3D coordinates were calculated. The measurement accuracy of the 3D coordinate values within the measurement region was then examined using these pictures. The coordinate data measured by the total station were used as the actual measured values. The measurement error results at each calibration point are shown in **Fig. 2(B)**. The mean ($\pm$ standard deviation, SD) errors for all measurement points were 4.9 ± 3.4 cm for the X coordinates, 10 ± 7.0 cm for the Y coordinates, and 3.9 ± 3.0 cm for the Z coordinates. The largest linear distance error was 26 cm, which is the same as the typical wing length (approximately 26 cm) of adult bats of this species.

2.4. Automatic Flight Path Tracking and Counting

Because it was difficult to distinguish flying bats from the background, we used image processing to automat-

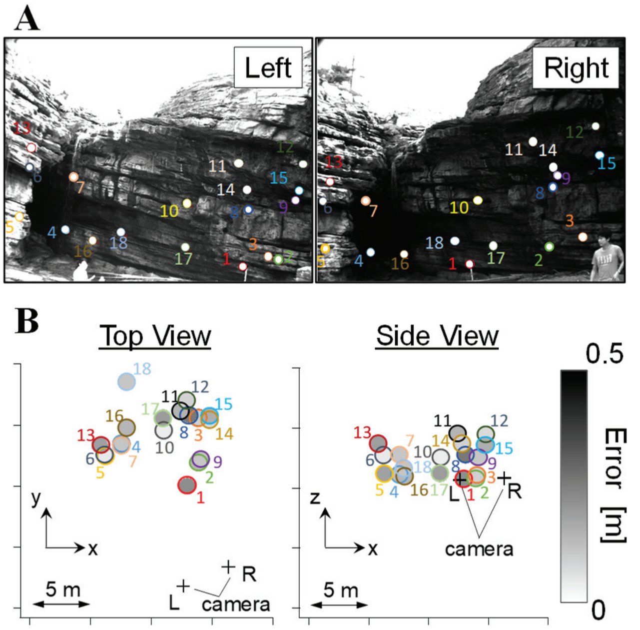

Fig. 2. (A) Photographs taken by the left and right cameras, including calibration points. (B) Color maps of measurement errors of 3D coordinates in manual analysis of observation space from top (left) and side (right) views.

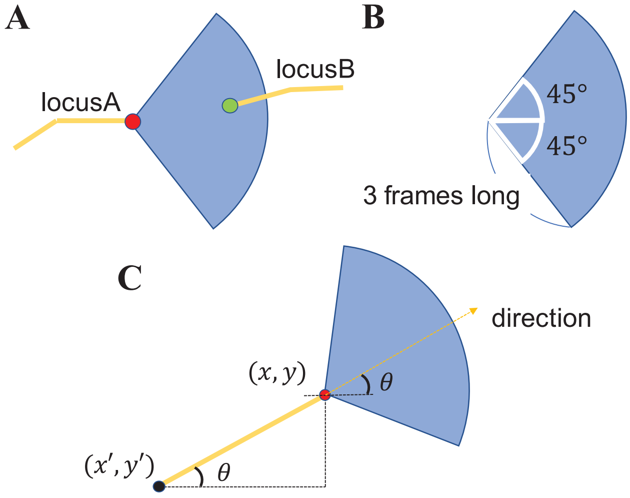

Fig. 3. (A) Fan shapes showing the predicted region of movement in a few frames. After a nearest-neighbor search, locus A and locus B are generated. These are shown by yellow lines. Within the fan-shaped region predicted from the endpoint of locus A, there is a locus B that starts several frames later. In this case, locus A and locus B are considered to be the trajectories of the same individual. (B) The fan shape. (C) Fan-shaped installation direction standard.

ically measure the bats' trajectories and count the number of flying bats. The method first extracted moving objects from a single image using the background subtraction method [18]. By associating the detected moving objects in consecutive image frames, we could suppress falsely detected regions. Finally, the trajectory was used to count the number of bats entering and leaving the cave. Details of the processes used are as follows.

Background subtraction was applied to still images [18], and moving objects were extracted to prevent confusion with the background. The extracted moving objects were divided into connected components [19], and each component was regarded as a candidate point for bat detection. In areas where the background appearance changed dynamically (e.g., water flowing near the entrance of the cave), background subtraction may cause false positives, i.e., some points being wrongly detected as bats. To suppress such false positives, we excluded detected points with a size of less than 5 pixels.

Next, the tracking process was carried out for each detected point. Because it is hard to capture shape and color information for flying bats, tracking becomes difficult in feature point matching and machine learning, which typically rely on shape and/or color information [20]. Therefore, we used the nearest-neighbor search method to associate the detected points in consecutive frames. Our preliminary experiments showed that this simple method yielded good results in complex environments.

Because the above-mentioned background subtraction method results in some false negative (undetected bats), the following method was used for each trajectory identified by the nearest-neighbor search to obtain a more accurate trajectory. The fan-shaped area shown in **Fig. 3(A)** was assumed to be the region in which bats could move. A red point was located at the end point of a trajectory. When the starting point of another trajectory was located within the fan-shaped region, it was regarded as the same bat. This processing approach made it possible to connect points as trajectories and obtain more accurate results.

The radius of the fan shape was determined so that we could associate a trajectory even if we failed to detect a bat in consecutive two frames. This is because the results of our preliminary experiments indicated that detection failures for more than three consecutive frames were rare. The central angle of the fan shape was set to 90° (**Fig. 3(B)**) to encompass changes in the flight directions of the bats. To determine the direction of the fan shape, we used the end point of the trajectory (x', y') and the point one frame ahead (x, y), as shown in **Fig. 3(C)**.

Based on these results, we estimated the number of bats that leave and return from the cave. Focusing on the vicinity of the entrance of the cave, the range for accurate counting was specified as the range shown in **Fig. 4**. Based on the direction in which each individual bat moved within this range, the going out and going in individuals were classified. In this method, because one tracking flight path is counted as one individual, there is a problem with the existence of interrupted flight paths resulting in more counted paths than actual paths. Thus, only a flight path that continued over at least five consecutive frames was considered to correspond to an individual bat to be counted. In this study, since points that could only be detected by one camera cannot be used as a 3D trajectory, two-dimensional (2D) images were used to improve the accuracy of population size estimation.

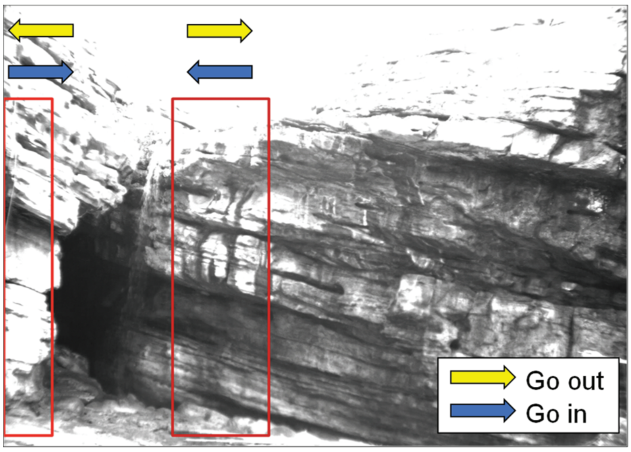

Fig. 4. Illustration of the method for estimating the number of individuals. The two red boxes indicate the ranges for counting. The yellow arrows indicate the direction in which the bats go out the cave, and the blue arrows indicate the direction in which they go in.

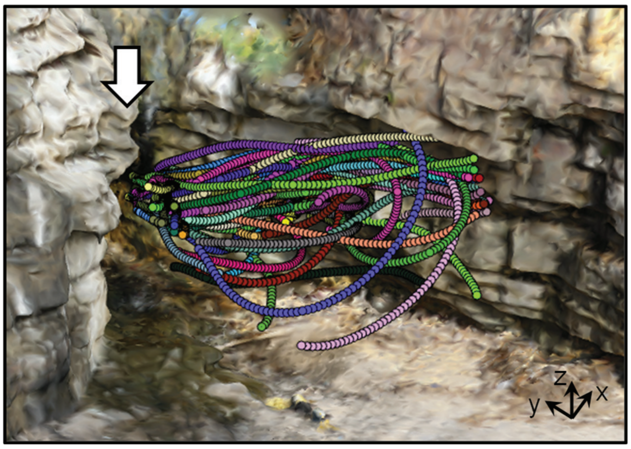

Fig. 5. Manually tracked three-dimensional flight trajectories of the bats for 5 s, starting at 19:23:00. The white arrow indicates the entrance of the roost of the bats. The different colors correspond to the trajectories of different bats.

The flight trajectory of a bat on the 2D images tracked by the above procedure is constructed as a 3D flight trajectory as follows. First, epipolar geometry [21] is used to determine which the same individual from each trajectory is. Strictly speaking, the trajectory of another camera image that appears most often at the detection point of the trajectory is defined as the same individual. Finally, the trajectory determined to be the same individual is converted into a 3D flight path using the DLT method in the same way as the procedure for manual tracking (see Section 2.2).

3. Results and Discussion

3.1. Overview

On both days of data collection, bat activity was observed at approximately 19:00, approximately 10 min before sunset (19:11:14 on July 12 and 19:10:09 on July 15). Recording was performed for 31 min, from 19:17:48 to 19:49:24, on July 12, and for approximately 26 min, from 19:02:54 to 19:28:06, on July 15. Note that, these measurement time includes several minutes of no-data period because of the synchronization error. After the recording periods, the bats continued to leave the nest up to approximately an hour and a half later on both days. Bats left the cave without colliding with each other, and their 3D flight trajectories were constructed from the images of the group behavior (**Fig. 5**). The 3D model of the wharf was reproduced using Agisoft Metashape (Professional Edition, Oak Corporation, Japan), from multiple photographs taken in the field, and this and the flight trajectories of the bats were combined using MATLAB (Mathworks, Japan). This made it possible to visualize the bat's flight patterns, taking into consideration their shapes. This visualization showed that many bats left their roosts and flew along the quays, one after another.

3.2. Behavioral Categorization

Figure 6 shows the trajectories of bats tracked for 5 s on a captured video frame. Reconstructing the flight trails of the bats in all six scenes made it possible to classify them into three behavioral patterns: an individual bat exiting the cave, an individual bat returning to and entering the cave, and an individual bat taking some other action (e.g., moving backward from outside the image, moving to the left of the image, etc.). Most of the bats exited the cave and flew along the cliff to the right of the screen or exited the cave but quickly turned back along the way. It was also found that the number of bats observed increased with the recording time.

3.3. Automatic Flight Path Tracking

Figure 7(A) shows an example of a 2D bat's flight paths calculated by the automatic flight path tracking method developed in this study. We succeeded in omitting false detection of noise due to background subtraction except for the waterfall part, but the trajectory in the waterfall part was almost constructed by the falsely detected points. Therefore, the waterfall part (left side portion in each of **Fig. 7(A)**) was excluded from this analysis. In the future, if there are moving objects in the background of the target object, it would allow us to separate them by incorporating a machine learning process. In this study, there were almost no tracking of incorrect points other than this part because the bats were not dense enough to overlap the size of the fan shape (see **Fig. 3**). Note that, since it could not automatically detect the bats when the brightness of the image was extremely high or low, it is important to shoot with an appropriate brightness.

By comparison with manual analysis of the data, the accuracy of the results of the automatic flight path tracking could be assessed. **Fig. 7(B)** shows the 3D coordinates displayed after associating the 2D flight paths in the left and right images. Distance between each two points reconstructed by the automatic and manual tracking (i.e.,

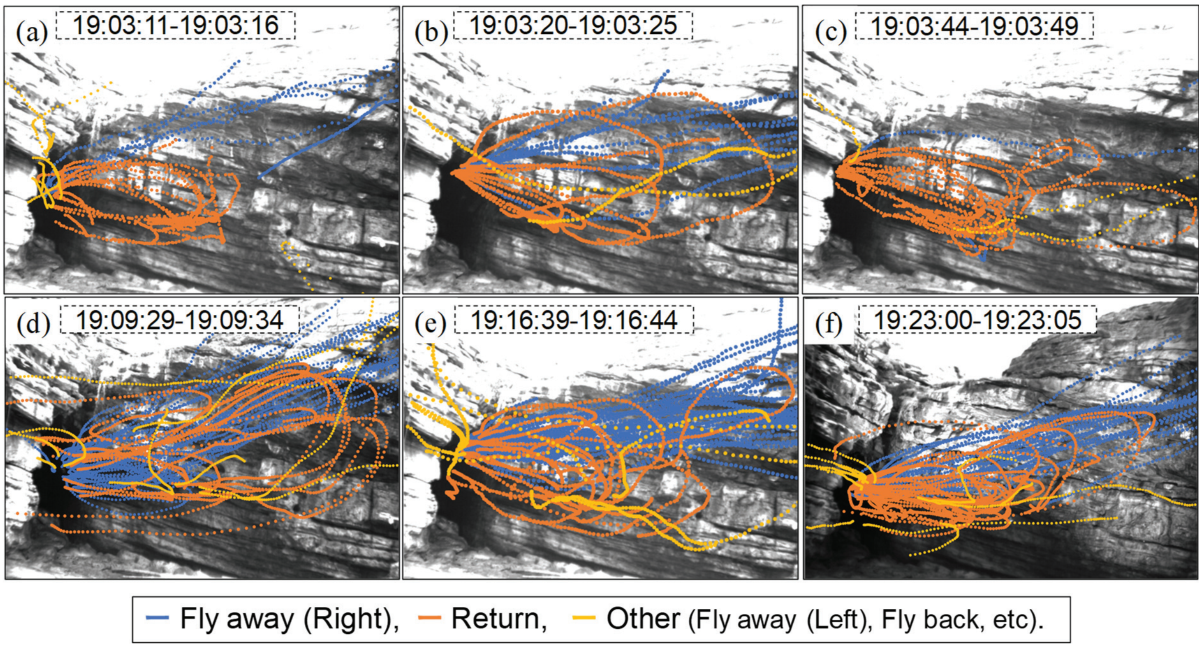

Fig. 6. Manually tracked flight trajectories of individual bats in two-dimensional images. Each shows a trajectory for 5 s. All trajectories shown are based on data collected on July 15, 2019.

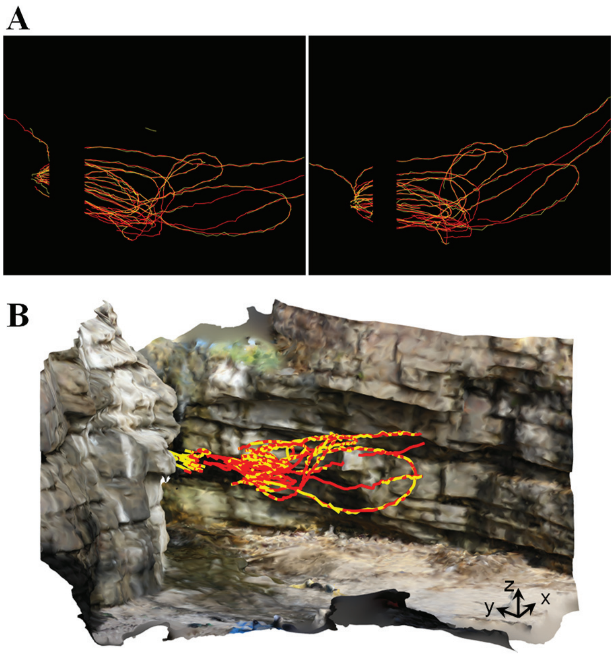

Fig. 7. Tracking results in (A) 2D and (B) 3D images. The yellow lines show the output results, and the red lines show the manual tracking results. All 3D trajectories in (B) were constructed using all of the points in (A).

positional error) was 14±25 cm ($N = 675$). It was confirmed by comparison with the trajectories determined by manual analysis that the 3D transformation was correctly accomplished. It took approximately 5 hours for manual analysis to reconstruct these flight trajectories, but it was shortened to about 5 minutes (approximately 2%) by constructing using automatic analysis method.

Table 1. Evaluation of detection accuracy.

	Precision	Recall	F-measure
Go out	0.94	0.98	0.96
Go in	0.95	0.9	0.92

We then counted the number of bats entering and leaving the cave. This count was conducted manually for comparison of the results with the results of the automatic count. As **Table 1** shows, highly accurate results were obtained for the precision, recall, and F-measure, where precision is the fraction of correctly detected bats among the total detected number, recall is the fraction of correctly detected bats among all bats flying in an image, and the F-measure is the harmonic mean of the precision and the recall. The results show that the 2D and 3D automatic flight path tracking results were approximately correct. In addition, quantitative evaluation of the number of bats behaving according to each behavioral classification category was possible.

The time variation of the number of observed bats was examined using the data measured on July 15. Behavioral classification was performed using the results of the automatic 2D flight path tracking (see **Fig. 4**). The temporal changes in the population size of each behavioral pattern are shown in **Fig. 8**. These results indicate that the number of bats going out the nest increased dynamically and decreased toward the end of the measurement period (20–30 min). Difference between the number of bats counted by manual and automatic methods at each counting period occurred for mainly following reasons:

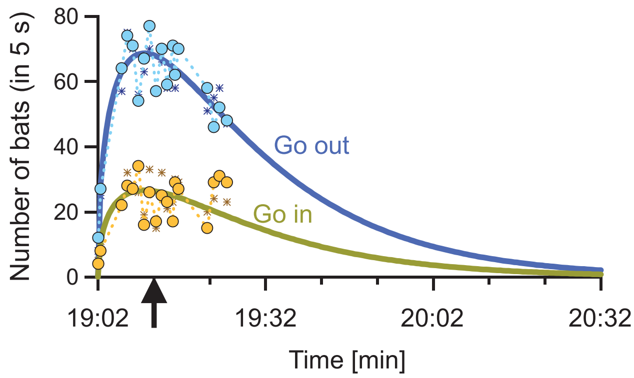

Fig. 8. Population estimation results generated using automatic (circles) and manual (asterisks) tracking data. Automatic and manual detections were performed at a total of 18 locations to collect 5-s videos. The number of bats was counted every 30 seconds except for the no-data period (total 7 min: approximately 3 and 4 min from 19:04 and 19:18, respectively). The cavity time was assumed to converge within approximately 90 min and was fitted to a gamma distribution function using automatically tracked data. The arrow indicates the time of sunset at the study site on the day of observation.

missing detecting the bats, detecting twice for one bat in the target-count area. Based on these results, we estimated the total population by approximating the temporal variation of the number of bats in this case. Time variation of the number of bats leaving from the roost varies based on the various reason (e.g., species, season) [22, 23]. The result of this study shows the number of bats increased drastically and then decreased gradually. Thus, we used gamma distribution function for the approximation in this study. Note that, we disregard the "other" category flight pattern (see **Fig. 6**) for the approximation because the number of this flight pattern was much lower than the other flight patterns. This result indicates that the number of go-out (fly away, return) bats and go-in (return) bats varies at the same rate. As a result of fitting (**Fig. 8**, solid line), the number of individuals going out in 90 min was approximately 29,000, and the number of individuals going in was approximately 11,000. From the difference between these numbers, it was estimated that approximately 18,000 individual bats came out of the cave. A previous study that counted the number of bats emerging from the roost reported a number of approximately 20,000 [15]. This suggests that estimates obtained by the tracking method developed in this study do not significantly deviate from the actual number of bats. However, since the population size estimation is a rough estimate, it is necessary to shoot for a longer time to know the exact size.

In this study, we observed the behavior of bats returning to a cave soon after leaving the cave. This behavior is considered to be light-sampling behavior, which is thought to be the movement of bats from their roost back and forth around the entrance of their roost to check the illumination level outside the roost [24]. The number of returning individuals was highest around sunset, as shown in **Fig. 8**. This suggests that the flight behavior of bats is based on the brightness outside their roost.

In this study, only behavioral classification and population estimation were performed, but using the proposed method, it is possible to quantitatively evaluate various factors, such as more details of population changes and the relationship between population changes and flight control by the bats. In addition to illuminance, temperature, humidity, and weather conditions are also expected to greatly affect the foraging behavior of bats. From quantitative analysis of the group behavior of bats in the wild, the environmental factors that most strongly influence the navigation of bats may also be examined. In addition, while we estimated the number of individuals using 2D images in this study, it will be possible to make more accurate estimates using 3D flight trajectories if the detection accuracy would be increased in the future. Finally, by upgrading automatic flight path tracking technique and measuring group behavior using the stereo camera, various quantitative evaluations of their interaction become possible, and this is expected to be useful for not only the study of bats but also elucidation of group behavior control of animals in 3D space.

4. Conclusions

In this study, methods for measuring and automatically tracking the group behavior of bats were developed. In the 3D measurement of bat trajectories during group flight, the maximum error was successfully suppressed to approximately the wing length of the animal over the whole range photographed. In the automatic tracking, it was verified that it was possible to appropriately track the bats and that most of the automatically detected objects correctly captured were indeed bats. Using the results, we succeeded in quantitative estimation and evaluation of a bat population based on behavioral classification, which is ecologically important information for further investigation of how the collective behavior of bats adapts to weather and environmental conditions. Furthermore, analysis of group behavior may lead to elucidation of group behavior algorithms, as well as greater biological discovery and understanding of bats.

Interactions between individual bats using their 3D trajectories were not analyzed in this study. Bats emit sound for the purpose of echolocation and actively obtain spatial information from the echolocation. Therefore, the main modality of bats for sensing their surroundings differs from those of fishes and birds, which are model animals for group behavior studies. During swarm behavior, bats need to sense the information they need while the sonar sound emitted by other individuals are mixed (**Fig. 9**). Therefore, we expect that echolocating bats have their own rules for collective behavior. The measurement technique established in this study may yield valuable information about the group behavior of not only bats but also other animals that move in groups in 3D space.

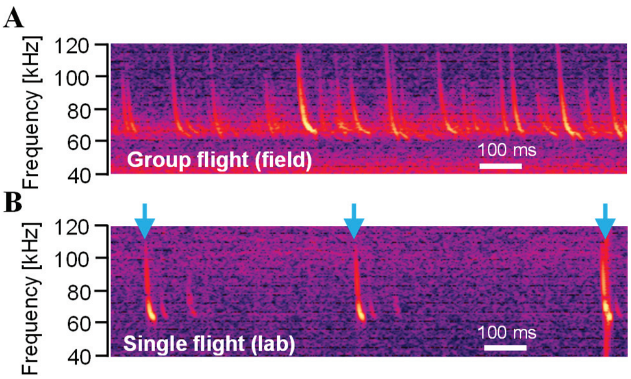

Fig. 9. Spectrogram of echolocation pulses emitted by *Miniopterus fuliginosus* during group ((A), measured at the site of this study) and single flight ((B), measured at the laboratory), respectively. The arrows indicate echolocation pulses. Large number of echolocation sounds from multiple bats intermingled in the flight of multiple bats at the study site, compared with the flight of a single bat recorded in a laboratory flight chamber.

Acknowledgements

We thank Dr. Keisuke Fujii for his valuable comments on the analysis of data. This work was supported by JSPS KAKENHI Grant Numbers JP 18H03786, 16H06542, and 19H04939.

References:

[1] W. R. Siegfried and L. G. Underhill, "Flocking as an anti-predator strategy in doves," Anim. Behav., Vol.23, pp. 504-508, doi: 10.1016/0003-3472(75)90126-8, 1975.

[2] I. L. Bajec and F. H. Heppner, "Organized flight in birds," Anim. Behav., Vol.78, pp. 777-789, doi: 10.1016/j.anbehav.2009.07.007, 2009.

[3] D. Sumpter, J. Buhl, D. Biro, and I. Couzin, "Information transfer in moving animal groups," Theory Biosci., Vol.127, pp. 177-186, doi: 10.1007/s12064-008-0040-1, 2008.

[4] D. J. T. Sumpter, "The principles of collective animal behaviour," Philosophical Trans. of the Royal Society B, Biological Sciences, Vol.361, Issue 1465, pp. 5-22, doi: 10.1098/rstb.2005.1733, 2006.

[5] I. D. Couzin, "Collective cognition in animal groups," Trends Cogn. Sci., Vol.13, Issue 1, pp. 36-43, doi: 10.1016/j.tics.2008.10.002, 2009.

[6] T. Vicsek and A. Zafeiris, "Collective motion," Phys. Rep., Vol.517, Issues 3-4, pp. 71-140, doi: 10.1016/j.physrep.2012.03.004, 2012.

[7] M. Nagy, Z. Ákos, D. Biro, and T. Vicsek, "Hierarchical group dynamics in pigeon flocks," Nature, Vol.464, pp. 890-894, doi: 10.1038/nature08891, 2010.

[8] K. Yoda, "Advances in bio-logging techniques and their application to study navigation in wild seabirds," Advanced Robotics, Vol.33, pp. 108-117, doi: 10.1080/01691864.2018.1553686, 2018.

[9] R. Lukeman, Y.-X. Li, and L. Edelstein-Keshet, "Inferring individual rules from collective behavior," Proc. Natl. Acad. Sci. USA, Vol.107, No.28, pp. 12576-12580, doi: 10.1073/pnas.1001763107, 2010.

[10] Y. Katz, K. Tunstrøm, C. C. Ioannou, C. Huepe, and I. D. Couzin, "Inferring the structure and dynamics of interactions in schooling fish," Proc. Natl. Acad. Sci. USA, Vol.108, pp. 18720-18725, doi: 10.1073/pnas.1107583108, 2011.

[11] M. Moussaïd, D. Helbing, and G. Theraulaz, "How simple rules determine pedestrian behavior and crowd disasters," Proc. Natl. Acad. Sci. USA, Vol.108, No.17, pp. 6884-6888, doi: 10.1073/pnas.1016507108, 2011.

[12] D. R. Griffin, "Listening in the dark: Acoustic Orientation of Bats and Men," Yale University Press, 1958.

[13] J. A. Simmons, M. B. Fenton, and M. J. O'Farrell, "Echolocation and pursuit of prey by bats," Science, Vol.203, pp. 16-21, doi: 10.1126/science.758674, 1979.

[14] K. Hase, Y. Kadoya, Y. Maitani, T. Miyamoto, K. I. Kobayasi, and S. Hiryu, "Bats enhance their call identities to solve the cocktail party problem," Communications Biology, Vol.1, No.39, doi: 10.1038/s42003-018-0045-3, 2018.

[15] R. Inoue, K. Maeda, H. Xu, M. Tsumura, and K. Suzuki, "Migration of Overwinter Colony of Bent-winged Bats, Miniopterus fuliginosus in Simokitayama Mura, Nara-Prefecture (1) Nursery site," Bulletin of Center for Natural Environmental Education, Nara University of Education, Vol.6, pp. 1-5, 2004 (in Japanese).

[16] Y. Ikegami, S. Sakurai, and K. Yabe, "DLT methods," Jpn. J. Sports Sci., Vol.10, pp. 191-195, 1991 (in Japanese).

[17] R. Shapiro, "Direct linear transformation method for three-dimensional cinematography," Res. Quart, Vol.49, Issue 2, pp. 197-205, doi: 10.1080/10671315.1978.10615524, 1978.

[18] Z. Zivkovic and F. Heijden, "Efficient adaptive density estimation per image pixel for the task of background subtraction," Pattern Recognition Letters, Vol.27, Issue 7, pp. 773-780, doi: 10.1016/j.patrec.2005.11.005, 2006.

[19] K. Wu, E. Otoo, and K. Suzuki, "Optimizing two-pass connected-component labeling algorithms," Pattern Anal. Applic., Vol.12, pp. 117-135, doi: 10.1007/s10044-008-0109-y, 2009.

[20] T. Akita, Y. Yamauchi, and H. Fujiyoshi, "Stereo Vision by Combination of Machine-Learning Techniques for Pedestrian Detection at Intersections Utilizing Surround-View Cameras," J. Robot. Mechatron., Vol.32, No.3, pp. 494-502, doi: 10.20965/jrm.2020.p0494, 2020.

[21] Z. Zhang, "Determining the epipolar geometry and its uncertainty: A review," Int. J. Comput. Vis., Vol.27, Issue 2, pp. 161-195, doi: 10.1023/A:1007941100561, 1998.

[22] B. M. Sabol and M. K. Hudson, "Technique using thermal infrared-imaging for estimating populations of gray bats," J. Mammal., Vol.76, Issue 4, pp. 1242-1248, doi: 10.2307/1382618, 1995.

[23] N. I. Hristov, M. Betke, and T. H. Kunz, "Applications of thermal infrared imaging for research in aeroecology," Integr. Comp. Biol., Vol.48, Issue 1, pp. 50-59, doi: 10.1093/icb/icn053, 2008.

[24] H. G. Erkert, "Ecological aspects of bat activity rhythms," T. H. Kunz (Ed.), "Ecology of bats," Springer, pp. 201-242, doi: 10.1007/978-1-4613-3421-7_5, 1982.

Name:
Emyo Fujioka

Affiliation:
Post-doctoral Research Fellow, Organization for Research Initiatives and Development, Doshisha University

Address:
1-3 Tatara-miyakodani, Kyotanabe, Kyoto 610-0321, Japan

Brief Biographical History:

2013-2014 Researcher, JST FIRST Aihara Innovative Mathematical Modelling Project

2014-2016 Assistant Researcher, Doshisha University

2016- Post-doctoral Research Fellow, Doshisha University

Main Works:

• E. Fujioka, I. Aihara, M. Sumiya, K. Aihara, and S. Hiryu, "Echolocating bats use future-target information for optimal foraging," Proc. of the National Academy of Sciences, Vol.113, No.17, pp. 4848-4852, 2016.

Membership in Academic Societies:

• Acoustical Society of America (ASA)
• Acoustical Society of Japan (ASJ)
• The Society for Bioacoustics (SFBA)
• The Marine Acoustic Society of Japan (MASJ)
• Japanese Society of Bio-Logging Science (BLS)

Name:
Mika Fukushiro

Affiliation:
Graduate Student, Graduate School of Life and Medical Sciences, Doshisha University

Address:
1-3 Tatara-miyakodani, Kyotanabe, Kyoto 610-0321, Japan

Brief Biographical History:
2019 Received B.S. in Engineering from Doshisha University
2021 Received M.S. in Engineering from Doshisha University

Name:
Kazusa Ushio

Affiliation:
Undergraduate Student, Faculty of Life and Medical Sciences, Doshisha University

Address:
1-3 Tatara-miyakodani, Kyotanabe, Kyoto 610-0321, Japan

Brief Biographical History:
2021 Received B.S. in Engineering from Doshisha University

Name:
Kyosuke Kohyama

Affiliation:
Graduate Student, Graduate School of Science and Engineering, Kindai University

Address:
3-4-1 Kowakae, Higashiosaka, Osaka 577-8502, Japan

Brief Biographical History:
2019 Received B.S. in Engineering from Doshisha University
2021 Received M.S. in Engineering from Doshisha University

Main Works:
- "Detection and tracking of flying bats by image analysis," Presentation at a Symp. on Sensing via Image Information (SSII), 2019.

Membership in Academic Societies:
- Information Processing Society of Japan (IPSJ)

Name:
Hitoshi Habe

Affiliation:
Associate Professor, Department of Informatics, Faculty of Science and Engineering, Kindai University

Address:
3-4-1 Kowakae, Higashiosaka, Osaka 577-8502, Japan

Brief Biographical History:
1999-2002 Mitsubishi Electric Corp.
2002-2006 Assistant Professor, Kyoto University
2006-2011 Assistant Professor, Nara Institute of Science and Technology
2011-2012 Specially Appointed Lecturer, Osaka University
2012-2018 Lecturer, Kindai University
2018- Associate Professor, Kindai University

Main Works:
- "Multiple Fish Tracking with an NACA Airfoil Model for Collective Behavior Analysis," IPSJ Trans. on Computer Vision and Applications, Vol.8, No.4, pp. 1-7, 2016.

Membership in Academic Societies:
- The Institute of Electrical and Electronics Engineers (IEEE)
- Association for Computing Machinery (ACM)
- The Institute of Electronics, Information and Communication Engineers (IEICE)
- Information Processing Society of Japan (IPSJ)
- The Japanese Society for Artificial Intelligence (JSAI)
- The Institute of Electrical Engineers of Japan (IEEJ)
- The Japanese Society of Fisheries Science (JSFS)

Name:
Shizuko Hiryu

Affiliation:
Professor, Faculty of Life and Medical Sciences, Doshisha University

Address:
1-3 Tatara-miyakodani, Kyotanabe, Kyoto 610-0321, Japan

Brief Biographical History:
1999-2005 IBM Japan
2007-2008 JSPS Research Fellow (PD), The University of Tokyo
2008-2012 Assistant Professor, Doshisha University
2012-2017 Associate Professor, Doshisha University
2014-2018 JST PRESTO Researcher
2017- Professor, Doshisha University

Main Works:
- K. Hase, Y. Kadoya, Y. Maitani, T. Miyamoto, K. I. Kobayasi, and S. Hiryu, "Bats enhance their call identities to solve the cocktail party problem," Communication Biology, Vol.1, Article Number 39, 2018.

Membership in Academic Societies:
- Acoustical Society of America (ASA)
- Acoustical Society of Japan (ASJ)
- Marine Acoustic Society of Japan (MASJ)
- Japan Ethological Society (JES)
- Japanese Society of Bio-Logging Science (BLS)