INTRODUCTION

Recording animals in their natural habitat is important for learning fundamental animal behaviour processes. For animals that perform critical activities in air, such as birds or bats, obtaining such recordings can be challenging, especially when animals are at great altitude. The rise in unmanned aerial vehicles (UAV; such as drones) technology has been useful for many biologists (Anderson & Gaston, 2013; Koh & Wich, 2012; Schiffman, 2014; Weissensteiner, Poelstra, & Wolf, 2015; Zahawi et al., 2015), but the application of UAVs for acoustic recordings has not been extensively studied, likely due to the challenge of the noise profile of UAVs (Intaratep, Alexander, Devenport, Grace, & Dropkin, 2016).

Bats, in particular, are exceptional candidates for UAV recording. Bats fly at altitudes from tens to thousands of metres for navigation and foraging (Gillam et al., 2009; Griffin & Thompson, 1982; McCracken et al., 2008), so recording bats aloft is essential to understand behaviour in their natural environment. Prior attempts to record bats at flight altitude used kites, balloons or towers (Ahlén, 2003; Cryan et al., 2014; Gillam et al., 2009; Griffin & Thompson, 1982; Kalcounis, Hobson, Brigham, & Hecker, 1999; McCracken et al., 2008; Menzel et al., 2005). All of these methods were limited to tether in location and/or altitude, which relies on large recording time windows for opportunistic data collection (Cryan et al., 2014; Gillam et al., 2009; McCracken et al., 2008), and cannot be quickly and easily manoeuvred in 3D space to follow moving animals.

Motivated by the limitations with current technology, we aimed to develop a UAV platform (“The Chirocopter” after the order Chiroptera) to record both the ultrasonic echolocation signals and thermal video

APPLICATION

The Chirocopter: A UAV for recording sound and video of bats at altitude

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Abstract

1. Most recordings of bats are conducted with fixed equipment, which relies on opportunistic data collection. Unmanned aerial vehicles (UAV; such as drones) are considered inappropriate for recording bats due to ultrasound noise constraints.
2. We developed a UAV system that physically isolates UAV noise, so we can record, with 3D manoeuvrability, ultrasonic audio and spatial thermal data of bat flight at altitude.
3. We tested the noise of our UAV with various payloads and microphone configurations to characterize the ultrasonic noise of our system, physically isolate drone noise from the microphone, and maximize UAV flight performance.
4. Over 84 min of recordings, we captured 3,847 echolocation signals from bats with corresponding thermal data of bat flight. Our system provides a feasible mechanism to capture both acoustic and video data of bats aloft at flexible locations and altitudes.
5. We include information on how to extend our method to apply to acoustic recordings in the audible (20 Hz–20 kHz) range for recording sounds of other taxa.

KEYWORDS
bats, thermal data, UAV, ultrasound
data of bats at flight altitude. Specifically, we aimed to create a device that could measure the echolocation signals of bats returning to the roost to determine if bats make altitude-dependent changes in their echolocation signals, and to determine, via spatial thermal data, how bats avoid collisions mid-air in the darkness—all while being manoeuvrable in 3D space. Additionally, from the thermal data, we could assess the impact of the UAV operation on bat activity, an important consideration for any project utilizing UAVs to assess wildlife.

We identified three main challenges with designing such a system: weight constraints, ultrasonic noise from the UAV and flight performance of the UAV. Most noise analysis of UAVs is limited to the human audible range (Intaratep et al., 2016), so we conducted noise analysis of our UAV into the ultrasonic range. We then focused on reducing the propagation path of the UAV noise by careful testing and placement of our microphone recording unit. Finally, we tested the flight performance in concert with the noise reduction to determine a solution that reduced the propagation path of UAV noise to the microphone without compromising flight performance.

2 | MATERIALS AND METHODS

We chose a commercially available model (DJI Spreading Wings S900) with a high payload capacity and flexible design to accommodate the acoustic and thermal data equipment. We used additive manufacturing for custom parts (MakerGear M2) to hold equipment on the UAV. Although there are other commercially available UAVs with high payload capacities, most models are targeted to commercial videographers and only have attachments for cameras below the UAV. Rather, we selected a UAV model that allowed for flexibility in attachment of equipment above or below the UAV. The weight of the UAV is 3.3 kg and the maximal takeoff weight is 8.2 kg (DJI), which allowed an extra 4.9 kg weight on the UAV. Flight time depends on wind condition, payload, battery capacity and flight altitude. We were flying the UAV in darkness in the USA, so we obtained Federal Aviation Administration (FAA) commercial UAV pilot licenses (issued to YF and LNK) and received a 14 CFR §107.29 Daylight Operation waiver (UAV registration number: FA3ANMN7EX, waiver number: 107W-2017-01361). Because the weight of this UAV may require special certification in certain countries, we caution the reader to thoroughly research local UAV regulations and certifications.

On the UAV, we included an ultrasonic microphone (Ultramic, 250; Dododronic), which recorded full spectrum (250 kHz sampling rate) acoustic recordings onto a smartphone (Motorola MotoG). We then tested the performance of our system with a baffle to physically reduce the ultrasonic noise picked up by the microphone. Acoustic testing indicated that a 15.24 cm diameter Styrofoam ball was the best tested baffle shape for reducing UAV noise and reducing the chance of bat echolocation call reflections (see Supporting Information for noise and alternate baffle testing data). Flight testing indicated that positioning the Styrofoam ball on a 50 cm fibreglass pole above the UAV had the least impact on flight performance (see Supporting Information for videos). We also included a small thermal imaging camera (Viento 320; Sierra Olympic) that was manually synchronized to the acoustic recordings, recorded at 30 Hz, and stored the video on a mini digital video recorder (Stuntcams).

Due to the value of the thermal camera on the UAV, and unpredictable winds at our recording location, we also added an emergency parachute (DJI Dropsafe). This could be removed which would make 605 more grams available for payload. Field bat recordings were conducted under New Mexico Department of Game and Fish Authorization Number 3651 issued to LNK.

3 | RESULTS

The final recording platform consisted of five main parts: ultrasound/thermal video recording devices, UAV with control system, UAV safety protection parachute, real-time flight monitoring system and night operation assistant lights (Table 1, Figure 1). UAV noise indicates a noise band between 20 and 60 kHz (Figure 2), which is in the range of bat echolocation calls and thus poses a challenge for bat recordings unless the noise propagation is reduced. By using the Styrofoam ball, we were able to reduce the UAV noise received by the microphone by 11 dB. Maximum flight time in ideal conditions and low payload was 18 min, but with experimental conditions (7 kg, <10 km/h winds, 65 12,000 mAh battery and hover flight), maximum flight time was 12 min. Maximum flight altitude is currently restricted by FAA regulations to 121.92 m, but the theoretical flight height of a UAV is regulated by flight time and flight speed.

The platform was used to record Brazilian free-tailed bat Tadarida brasiliensis flight during morning re-entry (0330-0500) outside of a lava tube cave on private land in Sierra County, New Mexico (Kloepper et al., 2016). During our seven mornings of recordings from May 24–June 5, 2017, we hovered for two replicates (swapping batteries in between) of 1 min each at 5, 10, 20, 30, 40 and 50 m height. At each height, we recorded acoustic and thermal data of bats in flight (Figure 3). From our 84 collective minutes of recording, we extracted 3,847 echolocation calls via visual inspection of spectrogram recordings (5 m: 1,561 calls; 10 m: 1,637 calls; 20 m: 219 calls; 30 m: 237 calls, 40 m: 134 calls, 50 m: 59 calls), with a maximum signal-to-noise ratio (SNR) of 44.33 dB. To demonstrate the ability of our Chirocaptor to record call types at various altitudes, we extracted the three highest SNR signals from each altitude (note the 50 m recordings did not have signals with signal-to-noise ratios over 5 dB, so we omitted this altitude from analysis) and calculated the ~10 dB start frequency, end frequency, bandwidth and duration (Table 2).

4 | DISCUSSION

In this study, we overcame challenges for recording bat activities by using UAV and demonstrated that the system is feasible for recording bat activities, especially bat echolocation calls at flight altitude. To the best of the authors’ knowledge, this is the first published data analysing ultrasonic UAV noise and recording animal vocalizations
TABLE 1 Equipment and parts for Chirocopter

| Equipment and parts | Weight (g) | Price (USD) |
|---------------------|------------|-------------|
| **Aerial system**   |            |             |
| DJI Spreading Wings S900 | 3,300 | 1,199       |
| DJI A2 Flight Control System | 224 | 539        |
| DJI IOSD Mark II | 56         | 89          |
| DJI 5.8 GHz Video Link Kit | 50 | 59          |
| DJI DropSafe Parachute | 605 | 850        |
| Dodotronic ULTRAMIC250K microphone | 50 | 340        |
| Motorola MotoG phone with USB Audio recorder PRO app | 145 | 100       |
| Viento320 Thermal Camera | 245 | 3,019       |
| MiniHD 1080P LCD DVR | 153 | 329        |
| Fibreglass pole with 15.24 cm Styrofoam sphere | 100 | 10        |
| **Tattu plus 12,000 mAh 22.2V 15C 6S1P Lipo Smart Battery Pack with AS150 + XT150 plug** | 1,670 | 264 |
| Central 3D-printed mounting frame for phone and DVR | 114 | 2        |
| Two 3D-printed adapters for mounting thermal camera | 31 | 2        |
| **Nightflight lighting** |            |             |
| Two Lume Cube lights | 212       | 160         |
| One Cree LED strobe light | 4 | 30         |
| Two 3D-printed adapters for mounting Lume Cube light | 13 | 2        |
| **Total weight** | 6,972      |             |
| **Maximum UAV takeoff weight** | 8,200 |             |
| **Ground control and monitoring** |            |             |
| Futuba 14SG 14-channel 2.4 GHz Computer Radio System | 550 |             |
| Airy 7" FPV Monitor | 55        |             |
| Storm 11.1V 2,200 mAh 20C LiPo Battery Pack (T-Join) | 30 |             |
| **Battery charging** |            |             |
| UP120AC duo dual 2 port (2x 12 Amps, 2x 120 Watts, 240 Watts total) | 100 |             |
| **Total cost** | 7,729 |             |

UAV, unmanned aerial vehicle; DVR, digital video recorder.

FIGURE 1 Placement of the ultrasound and video recording equipment on the unmanned aerial vehicle: (1) dodotronic ULTRAMIC250K microphone, (2) 15.24 cm diameter Styrofoam ball, (3) thermal camera pointed upwards, (4) digital video recorder for recording thermal videos and (5) smartphone for recording bat calls

FIGURE 2 Unmanned aerial vehicle (UAV) noise as received by a microphone pointing up (a) without the Styrofoam ball, and (b) with the Styrofoam ball, which reduced the UAV noise by 11 dB

FIGURE 3 Example data recorded by the Chirocopter. (a) Echolocation calls during hover at 40 m height above cave. signal-to-noise ratio is 20 dB. (b) Frame extracted from thermal imaging system during flight. The large white in the foreground is the microphone baffle; small white dots are bats

from a UAV. Compared to prior methods of balloons, kites and towers (Gillam et al., 2009; Griffin & Thompson, 1982; McCracken et al., 2008), the current method allows for flexibility of recording in 3D space. With our flexible recording system, we eliminate the need for
opportunistic data collection. Instead, the recording equipment can move with bats, greatly reducing effort time needed to capture bat signals at altitude. For example, with our system we recorded 3,847 echolocation signals over an 84-min window, for a recording effort of 45.80 calls/min. In comparison, published data of kite effort for *Tadarida brasiliensis* yielded 0.34 “high quality” (undefined) calls/min (Gillam et al., 2009), and 7.42 calls/min (McCracken et al., 2008). Additionally, the Chirocopter can capture thermal data in concert with acoustic data, which has not been accomplished with kites. Towers on wind turbines have been equipped with thermal cameras, but like kites these fixed receivers rely on opportunistic data and yield even lower bat detection rates of 0.013 bats/min (Cryan et al., 2014).

The increase in data provided by a flexible system also increases the probability of obtaining high SNR recordings (signals that are loud compared to background noise). SNR is influenced by ambient noise and the distance and orientation from the bat to the recorder. The Chirocopter’s hover flight noise is constant, so the greatest influence of signal quality is the distance from the bat to the microphone. Due to the effects of frequency-related attenuation (Randall, 2005), higher SNR calls will better represent the true acoustic characteristics emitted by the bats. *Tadarida brasiliensis* are known to produce calls with variable durations and frequencies (Gillam et al., 2009; Simmons et al., 1978), and the signals recorded with our system (Table 2, Figure 3) match prior signal descriptions. With this increase in data provided by our system, we can begin to investigate such questions as: how do bats avoid collisions mid-air while flying at high speeds using sonar, how (if at all) do bats compensate for Doppler shifted echoes when returning to the cave at high speeds, and what is the 3D spatial pattern of bats returning to their roost?

With any drone-based wildlife recording, there are important ethical considerations from noise disturbance or collision (Hodgson & Koh, 2016; Sandbrook, 2015). We obtained FAA remote pilot commercial licenses, a FAA daylight operation waiver, and a New Mexico Department of Game and Fish state permit. With the local operational guidelines, we were limited to flying our drone at altitudes below 121.92 m. We continually monitored the UAV and bats with ground-based thermal data for all UAV flights and were prepared to abort all flights if bats were at collision risk or showed behavioural avoidance >20 m away from the UAV. Interestingly, the bats slowly increased altitude above the UAV when the motor turned on, and did not make sudden evasive manoeuvres. Bats still remained close enough to the UAV to obtain numerous echolocation signals. Additionally, bats descending on the UAV avoided it as they would an object, altering their flight path with a sharp 90° turn a few metres above the UAV (see Supporting Information). No bats collided with the UAV during the duration of our experiment. We therefore conclude that the UAV has minimal impact on bat behaviour, and believe the development of the Chirocopter is important to advancing the understanding of bat behaviour at flight altitude.

To extend this method to audible (20 Hz–20 kHz) recordings, such as bird calls, additional factors would need to be considered (see Supporting Information for details). A larger baffle would help with lower frequency noise, but likely negatively affect flight performance. Alternatives could include different UAV blade material (Intaratep et al., 2016) or attaching a noise damping shroud (Dottererel Technologies, 2016). We encourage the reader desiring application for recordings in the 20 Hz–20 kHz range to research commercially available UAV noise isolation accessories, as technology to use UAVs for audible recordings is rapidly expanding.

### Table 2: Example echolocation signal parameters recorded by the Chirocopter

| Altitude (m) | Signal-to-noise ratio (dB) | Start frequency (kHz) | End frequency (kHz) | Bandwidth (kHz) | Duration (ms) |
|-------------|---------------------------|-----------------------|---------------------|-----------------|---------------|
| 5           | 9.45                      | 46.68                 | 28.37               | 18.32           | 8.92          |
| 5           | 9.70                      | 39.21                 | 27.53               | 11.68           | 7.01          |
| 5           | 8.57                      | 55.42                 | 36.26               | 19.16           | 7.15          |
| 10          | 4.37                      | 51.00                 | 34.89               | 16.11           | 5.78          |
| 10          | 9.00                      | 32.26                 | 27.00               | 5.26            | 6.18          |
| 10          | 44.33                     | 33.15                 | 27.73               | 5.42            | 4.94          |
| 20          | 5.02                      | 41.49                 | 27.26               | 14.23           | 6.79          |
| 20          | 4.63                      | 35.20                 | 29.22               | 5.98            | 6.57          |
| 20          | 8.43                      | 51.18                 | 38.50               | 12.68           | 2.11          |
| 30          | 15.19                     | 53.94                 | 28.99               | 24.95           | 5.38          |
| 30          | 14.05                     | 64.62                 | 46.26               | 18.36           | 2.08          |
| 30          | 15.04                     | 45.95                 | 27.32               | 18.63           | 5.38          |
| 40          | 10.23                     | 50.37                 | 30.38               | 19.79           | 6.70          |
| 40          | 13.62                     | 51.74                 | 30.26               | 21.47           | 5.14          |
| 40          | 10.15                     | 59.87                 | 42.83               | 17.04           | 5.57          |
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AUTHORS’ CONTRIBUTIONS

L.N.K. conceived of the project; Y.F. designed and tested the system; Y.F., M.K. and L.N.K. acquired the data; Y.F. and M.K. analysed the data; L.N.K. interpreted the data; Y.F., M.K. and L.N.K. wrote, revised and approved the manuscript.

DATA ACCESSIBILITY

Data are deposited in Dryad Digital Repository https://doi.org/10.5061/dryad.cf472n3 (Fu, Kinniry, & Kloepper, 2018).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.