Supplementary S1: Fieldwork protocol

Reduction of species identification errors in surveys of marine wildlife abundance utilising unoccupied aerial vehicles (UAVs)

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1 Overview

The objective of this study was to develop practical recommendations for reducing species misidentification probabilities when collecting, processing and analysing image-type data from unoccupied aerial vehicles (UAVs). We conducted trial experiments assessing the effect of reviewer-related variables and image attributes on the accuracy and certainty of identification by trained aerial observers. For that purpose, we required images of known dolphin species, characterised by small body size, morphological resemblance and occurrence in potentially large, mixed groups. In addition, we needed a broad representation of image resolutions, sea states and group sizes for each of the species selected, namely striped dolphins *Stenella coeruleoalba*, short-beaked common dolphins *Delphinus delphis*, and common bottlenose dolphins *Tursiops truncatus*. Data collection was performed during designated shipboard surveys in Italy and Israel, 2017-2020.

2 Drone system and operation details

2.1 Platform specifications

We used multiple quadcopter models developed by DJI Co. (Shenzhen, China). Table S1 presents basic information concerning each model according to the manufacturer's product information found online [https://www.dji.com/]; precise values depend on the mode of operation.

Table S1: Unoccupied aerial vehicle model specifications. Wieght measurements are provided in grams and include the aircraft's battery; diagonal dimensions (D. dim) are measured in millimetres; battery life is provided in minutes; maximum communication distances (Com. dis) are measured in metres; maximum flight, ascent and descent velocities (FLT, ASC and DSC) are measured in metres per second.

Model	Weight	D. dim	Bat. life	Com. dis	FLT	ASC	DSC
Phantom 1	840	410	10-15	300	10	6	6
Mavick Pro	743	335	< 27	4000-7000	18	5	3
Phantom 3 Advanced	1280	350	~ 23	3500-5000	16	5	3
Phantom 4 Advanced	1368	350	~ 30	3500-7000	14-20	5-6	3-4
Phantom 4 Pro	1388	350	~ 30	2000-7000	14-20	5-6	3-4

2.2 Method of operation

Take-off and landing were performed on-board the survey vessel. No specialised launching equipment or other provisions were required except for the surveys conducted in Italy, as described in the following section. We avoided using the UAV's automated homing function due to the research vessel's movement away from the take-off position. Instead, all missions were piloted manually with the obstacle sensing and satellite positioning systems disabled. Designated on-board responsibilities included one person piloting the UAV and another to hand-release and retrieve it during take-off and landing, and to keep sharp lookout for the aircraft; coherent communication between all team members and the operator of the survey vessel was essential for keeping the UAV within visual line of sight and its maximum operating distance.

3 Payloads, sensor, and data collection

3.1 Data overview

We performed focal follow missions in both video and still modes. All footage was stored on the cameras' memory cards and downloaded post-flight. The ground sample distance (GSD) was then calculated for each image based on the corresponding altitude and the camera sensor dimensions and added into the metadata. Similarly, the video recordings included a constant altitude written to the bottom of the footage. We entered those readings into the metadata and trimmed them out from selected frames prior to the subsequent analysis. Notably, videos captured with the Phantom 1 quadcopter did not include this information. Therefore, we segmented those videos into shorter sections during which the flight altitude was maintained and, for each segment, estimated the mean GSD based on the pixel size of observed dolphins. An additional consideration was the altitude above sea level measured at the start of each mission, which typically depended on the UAV's elevation when first switched on, e.g., on the deck of the research vessel. We estimated that altitude based on the height of the research vessel and the person holding the aircraft; we used our estimates to correct the metadata based on the altitude reading before take-off or after landing.

3.2 Payload or sensor description and data collection methods

The only UAV model that carried an additional payload was the Phantom 1 quadcopter, which we mounted with a GoPro Hero3+ Black edition camera (GoPro Inc., San Mateo, CA, USA) using a 3-axis brushless gimbal mount (open hardware). Communication between the aircraft was performed using a 5.8G 32CH 600mW Super Mini A/V FPV Transmitter and a FXT F408 4.3" 32CH FPV Monitor equipped with a 5.8GHz receiver. Finally, we attached two plastic bottles to this UAV model (Figure S1).

Figure S1: Customised DJI Phantom I during take-off.

In order to calculate GSD, only two parameters are typically required - the width of the area (a) captured in metres or centimetres and the width of the image (w) in pixels. If this information is available - a simple division can be performed to calculate the captured area in pixels:

$$\text{GSD } = a/w \tag{Eq. S1}$$

However, while w might be ‘easy’ to determine, a may not be readily available and require further calculation. Therefore, this parameter is calculated using the flight altitude and width field of view ($wFOV$). The latter relates to the size of the image captured, which depends on the camera’s mode of operation:

$$w = (altitude * \tan(wFOV/2)) * 2 \tag{Eq. S2}$$

Finally, the height field of view ($hFOV$) is calculated using the manufacturer’s product information, which typically only provides the diagonal field of view ($DFOV$), the width of sensor (W) and height of sensor (H):

$$\frac{\sqrt{h^2 + w^2}}{\sqrt{H^2 + W^2}} = \frac{\tan\left(\frac{dFOV}{2}\right)}{\tan\left(\frac{DFOV}{2}\right)} \tag{Eq. S3}$$

The width of the image in pixels (w), the height of the image in pixels (h) and the angle between wFOV and dFOV ( ) are also required for determining the horizontal field of view and are calculated using equations S4-5:

$$\tan(\alpha) = h/w \tag{Eq. S4}$$

$$\cos(\alpha) \times dFOV = wFOV \tag{Eq. S5}$$

Table S2 presents all sensor dimensions used for GSD calculations in this study. All parameters are measured in pixels, except DFOV and dFOV which are measured in degrees, and the image dimensions calculated for an altitude of 100 metres, provided in metres and squared meters.

Table S2: Camera sensor specifications.

Model	Sensor area	Image area	H	W	h	w	DFOV	dFOV	Image width m	Image height m	Image area sq.m
GoPro Hero3+ Black	NA	1920 x 1080	NA	NA	1080	1920	NA	115.70000	215.98035	121.48895	26239.226
GoPro Hero3+ Black	NA	3000 x 1688	NA	NA	1688	3000	NA	115.70000	215.98035	121.52495	26247.001
Phantom 4 Pro	5472 x 3648	4863 x 3648	3648	5472	3648	4863	84.0	78.11898	122.27277	91.72343	11215.278
Phantom 4 Pro	5472 x 3648	1920 x 1080	3648	5472	1080	1920	84.0	33.55010	52.25165	29.39155	1535.757
Phantom 4 Pro	5472 x 3648	4096 x 2160	3648	5472	2160	4096	84.0	64.26214	108.36643	57.14636	6192.747
Mavick Pro	4096 x 3000	1920 x 1080	3000	4096	1080	1920	78.8	39.19480	61.54772	34.62059	2130.818
Phantom 4 Advanced	5472 x 3648	4096 x 2160	3648	5472	2160	4096	84.0	64.26214	108.36643	57.14636	6192.747
Phantom 4 Advanced	5472 x 3648	1920 x 1080	3648	5472	1080	1920	84.0	33.55010	52.25165	29.39155	1535.757
Phantom 3 Advanced	5472 x 3648	1920 x 1080	3648	5472	1080	1920	78.8	30.75687	47.73055	26.84843	1281.490
Phantom 3 Advanced	5472 x 3648	1920 x 1080	3648	5472	1080	1920	94.0	39.47847	62.02109	34.88686	2163.721

4 Field operation details

Once launched, the UAV was positioned 100 m directly above the animals and then gradually lowered to an altitude of 20 m; descents were paused at 10 m intervals to stabilise the aircraft as images were captured. Notably, surveys using the Phantom 1 model did not follow this or any other protocol. Nevertheless, we believe that our approach towards this issue, as described in the previous section, was sufficient for our data requirements, particularly since the subsequent analyses in our study referred to image resolutions bins of 1 cm/pixel as opposed to any specific values. Finally, sea states according to the Beaufort scale and ground truth species identifications were documented per encounter by the shipboard surveyors and added into the metadata. A total of 23 dolphin encounters were documented in this study (*S. coeruleoalba*, n = 12; *D. delphis*, n = 5; *T. truncatus*, n = 6). Flights were carried out across various sea conditions and included focal follows in video and still modes. Footage of *S. coeruleoalba* was obtained between July and September 2017, off the coast of Italy, in the northern Ligurian Sea, and surveys for *D. delphis* and *T. truncatus* were conducted between February 2019 and May 2020, off the coast of Israel, in the eastern Levantine Sea. Table S3 summarises all surveys conducted in the course of this study.

Table S3: Survey information.

Survey date	Encounter	Image count	Species	Beaufort sea state (BSS)	Group size	Site
7/7/2017	1	2	Stenella coeruleoalba	BSS-1	30	Italy
29/07/2017	2	3	Stenella coeruleoalba	BSS-0	35	Italy
30/07/2017	3	3	Stenella coeruleoalba	BSS-0	20	Italy
2/8/2017	4	3	Stenella coeruleoalba	BSS-1	60	Italy
23/02/2019	5	7	Tursiops truncatus	BSS-1	6	Israel
23/03/2019	6	9	Tursiops truncatus	BSS-2	1	Israel
22/08/2019	7	9	Delphinus delphis	BSS-2	7	Israel
17/09/2019	8	6	Tursiops truncatus	BSS-1	3	Israel
5/10/2019	9	5	Tursiops truncatus	BSS-0	3	Israel
12/11/2019	10	9	Delphinus delphis	BSS-2	17	Israel
12/11/2019	11	7	Tursiops truncatus	BSS-2	2	Israel
23/11/2019	12	14	Delphinus delphis	BSS-1	14	Israel
25/11/2019	13	6	Delphinus delphis	BSS-1	13	Israel
15/04/2020	14	7	Tursiops truncatus	BSS-1	2	Israel
2/5/2020	15	4	Delphinus delphis	BSS-2	9	Israel

5 Data post-processing

We used a customised software (S. Marco, *unpublished script*) to arrange the images from each encounter via three binning levels: true species identity (ID; *S. coeruleoalba*, *D. delphis* and *T. truncatus*), Beaufort sea state (BSS; 0, 1, 2), and ground sample distance (GSD), or image resolution (cm/pixel; < 1, 1-2, 2-3). From each bin, a maximum of three images with at least one dolphin at the surface was selected per encounter. Images that were not captured at nadir were only used if the animals appeared in the bottom third of the frame. Selected images (n = 94) were uploaded to an online survey platform [https://surveylegend.com/].

6 Permits, regulations, training and logistics

We were not required to obtain an ethics or special flight permit to conduct observational surveys of marine mammals using multi-rotor UAVs in Israel or Italy. Furthermore, we conducted our work outside marine reserves and did not contact the populations under study. Nevertheless, we exercised best practices for minimising UAV disturbance to wildlife and adopted the precautionary principle where we could not make informed decisions concerning the potential implications of our operation.