Morphometric measurements of Omura's whales using consumer grade sUASs: a methodological study

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***Abstract*—Photogrammetry is a powerful tool for taking indirect measurements of free-ranging marine mammals, and small unmanned aircraft systems (sUASs) are expanding the ways in which these images for morphometric analysis can be collected. A sUAS allows for photographs and videos to be captured from highly controllable positions and orientations, largely untethered from the physical location and constraints of the operator. This flexibility allows researchers to study and record agile cetaceans which can exhibit unpredictable swimming behaviors, such as Omura's whales (Balaenoptera omurai). However, purpose built sUASs can be prohibitively expensive, require specialized expertise to operate, and require resources not available to many field biologists. Large multirotor aircrafts can require significant time and space for launch and recovery, and the vehicle can pose a hazard to those operating in its vicinity. By comparison, consumer grade unmanned aerial vehicles (UAVs), or drones, continue to become increasingly inexpensive, reliable, and compact. We tested seven commercially available UAV products from five leading consumer drone manufacturers and gauged their ability to be used at sea and for cetacean photogrammetry. These preliminary experiments informed our selection of equipment which we trialed during a targeted field expedition off the coast of Nosy Be, Madagascar. Over the course of a three week survey, we compared the efficacy of a consumer grade, off-the-shelf UAV with a custom solution of comparable size and price. Both sUASs were successfully able to collect data which translated to animal size measurements. We provide both specific guidelines for selecting, testing, and calibrating consumer grade UAVs to be used on ocean-based expeditions, as well as procedures for conducting morphometric analyses with the resulting data. Our data analysis procedures are based on established methods of morphemic analysis of cetaceans photographed in single still images. Our software is freely available for other to use and modify.**

***Index Terms*—sUAS, UAV, drone, photogrammetry, morphometric, Omura's whale, humpback whale**

I. Introduction

Photogrammetric analysis is often used in the field of cetology to unobtrusively measure large specimens. Marine mammals pose the twin challenges of measuring a large object in a very limiting environment. For that reason, small unmanned aircraft systems (sUASs) are popular as photogrammetry tools. Their maneuverability allows field scientists to view specimens from angles not otherwise possible. Until recently, the equipment required for such data collection was hindered by expensive and fragile setups. Today, mass-market drones have developed enough to supplant these technologies. Consumer demand for user friendly drones has driven down the price of these vehicles while increasing their functionality. Properly calibrated consumer-grade small sUASs equipped with high-resolution cameras can provide meaningful estimates of specimen size [1], and while the comprehensive effects of drone noise have not been determined, it is believed that the volume is not detrimental to baleen or toothed whales even while surfacing [3]. During a 3 week field survey to Nosy Be, Madagascar, we examined the efficacy of the Splash Drone 3, a waterproof sUAS manufactured by Swell Pro alongside a custom built solution. In this paper, we outline a method utilizing the Splash Drone or comparable sUAS in tandem with a Jupyter notebook and open-source image measurement software as a platform for photogrammetric analysis.

A. Consumer Drone Market

In the course of a few decades, drones have become a multibillion-dollar industry with many competitors [6]. Companies such as DJI, Parrot, and Splash Drone now offer consumer products suited to a wide range of applications and skill levels. Pushes to control the market have driven many companies to develop vehicles that are more user-friendly at lower costs. Many are equipped with high-resolution cameras for filming and are ready to fly out of the box. To further assist users trying to capture footage, several of these vehicles also have streams of the drone's video fed back to a screen in the pilot's transmitter. Most UAVs run on Lithium Polymer (LiPo) batteries and have flying times of 15-30 minutes before needing recharging. As an example, the DJI Phantom 4 Pro V2.0 is equipped with a 20-megapixel camera, a transmitter with live video feed from the vehicle, and a flight time of 30 minutes for $1500 USD. An examples of a similar vehicle can be seen in Fig.1. As these systems have become increasingly affordable, they offer a powerful tool for photogrammetry analysis and data collection to the field scientist [2] [1].

Fig. 1: DJI Phantom 3, a popular consumer drone

B. UAVs for Cetacean Photogrammetry

The primary benefit of using drones as a photogrammetric tool is the ability to record data from highly controllable positions that would be otherwise infeasible to access. With a strong GPS signal and favorable weather conditions, a drone can be easily positioned in 3D space and its camera oriented in nearly any desired location. To that end, drones offer a range of utilities and configurations for applications such as photography and aerial mapping [1] [8] [5]. Specially-made gimbals are common on commercial vehicles and are designed to create smooth, controlled footage. Many are equipped with multiple piloting modes to suit different skill levels, allowing relative amateurs to capture viable footage.

The flexibility of recording information from a highly controllable position lends it for use in marine research where maneuvering to reach an animal may be difficult. Many cameras packaged with drones today feature 4K resolution which, at when used to measure whales, can give measurement accuracy within a few centimeters. The small size of many commercial drones also lends to feasible transport, as their weight and volume do not compromise that of other equipment.

C. Consumer Drone Selection

The three main factors to consider when selecting a consumer grade drone for use in cetacean research are how well the sUAS will tolerate the environment, what precision of measurement the system will allow, and to what accuracy the state of the system can be known. Working in a marine environment will subject a sUAS to harsher conditions than it is likely designed to encounter. First and foremost, salt water may cause catastrophic damage to electrical components not conformally coated or otherwise protected. Even operating in the air near saltwater can corrode metal components over the course of a few days of operation. UAVs with user-serviceable motors and electronics can be replaced if corrosion begins to affect flight behavior, and practice replacing these components can be developed prior to operation. Alternatively, some niche UAVs use enclosed chassis which can been entirely submerged. Waterproof UAVs are a clear choice when working in or area water; however, their exposed motors are still susceptible to corrosion will require diligent maintenance. Even if a UAV is not waterproof, ensuring that the chassis will float if it were to land in the water will help guarantee that data can be recovered even if the UAV itself is damaged catastrophically. Equipping a UAV with emergency floatation can be as simple as fixing a short length of pool noodle or other similar buoyant polyethylene foam to the arms of the vehicle.

Toleration of the marine environment is not limited to saltwater resistance. Control over the UAV's failsafe behavior can also be critical to successful ocean operations. A system that will command the vehicle to return to the its launch coordinates when its battery runs low may be a useful behavior on land, but it is not desirable when operating from a moving sea vessel. Understanding if and how such a failsafe can be circumvented is critical. A similar but desirable failsafe behavior can be found sUASs which includes a GPS receiver in the pilot's controller and where the UAV returns to the pilot's actual location upon a failsafe trigger.

Precision in the resulting measurements from a sUAS is primarily driven by image sensor resolution and flying altitude. A higher resolution camera flown closer to a subject will result in more pixels being usable for measurements. Accuracy of the resulting measurements is related to the accuracy at which the distance between the camera and the subject is known. With a UAV flying vertically above a breaching cetacean, the altitude of the UAV above the surface of the water defines this distance. UAVs can use a variety of sensors to measure altitude including barometers, GPS, optical flow sensors, time-of-flight range finders, and sonar range finders. Barometers will relatively precisely measure changes in altitude but can drift over time or with environmental change. GPS altitude information is often more variable and lower precision than a barometer reading, but it can provide a more accurate absolute altitude. Optical flow sensors and sonar range finders both provide unreliable readings over water, which at best are unusable and at worst could cause a UAV to malfunction. LED based time-of-flight sensors can potentially the most precise and accurate altitude measurements, but their functionality can vary highly in changing wind conditions. For the purpose of photogrammetry, the altitude sensor is only as precise as the logging system which records it. Determine how flight information is recorded and/or transmitted during operation in order to assess what flight information will be available for data processing.

II. Survey of Omura's Whales

A. Equipment

We prepared two sUASs for our field survey: a consumer grade solution using a Swell Pro Splash Drone 3 waterproof drone and custom-built system of comparable size and flight capacity. Our primary focus was to collect usable image and sensor data for accurate photogrammetric measurements, but secondarily we aimed to explore the practical differences between using an off-the-shelf drone and a purpose-built UAV on an ocean expedition.

The Splash Drone 3, shown in Fig.2, is a fully waterproof UAV which can be equipped with either a stabilized two or three axis gimbal and a submergible 4K camera sensor. We chose to use a 2-axis gimbal, which only stabilizing the pitch and roll of the camera and mechanically couples the yaw motion of the vehicle to the camera. The 2-axis gimbal is able to keep the camera angled vertically during flight and has the added benefit of matching the yaw position of the vehicle. Since the heading of the camera is coupled to the heading of the vehicle, the camera's heading and the cardinal orientation of the resulting imagery can be determined by reviewing the vehicle's flight history. The Splash Drone 3 is piloted via a handheld controller which doubles as an analog video receiver and display. Vehicle state information (e.g. altitude, distance from launch location, heading, and battery voltage) is displayed as an overlay on the transmitted analog video. Our one addition to the Splash Drone 3 system is a USB 5.8Ghz video receiver and a companion laptop with a daylight readable display. These two additions allow for easy digital recording of the analog video stream and a means for an assistant to the pilot in command to view the UAV's camera view and vehicle state information. At the time of writing, the Splash Drone 3 is available through a variety of online resellers.

Fig. 2: Swell Pro Splash Drone 3 with 2-axis gimbal stabilized 4K camera

We designed our custom sUAS to be similar size and weight to the Splash Drone 3 but built with cetacean photogrammetry in mind. The chassis of our custom UAV is an Aquacopter Bullfrog, a sealed and waterproof quadcopter frame controlled by a Pixhawk autopilot running Arducopter firmware and shown in Fig.3. A GoPro Hero 4 camera with an optically flat lens, capable for recording video at a higher resolution than our Splash Drone 3, is rigidly mounted to the nose of the Bullfrog. A TeraRanger Evo time-of-flight distance sensor is mounted to the chassis to allow for high precision altitude measurements at 2-centimeter resolution. In addition to the vertically mounted GoPro camera, a small front-facing camera transmits an analog video stream to pilot for aid in navigation. The high precision sensors and open hardware in the vehicle allow for more control in data collecting, both in terms of flight characteristics and the resolution of sensor data. However, our Bullfrog is not as user-friendly to operate as our Splash Drone 3 and requires more experience and preparation to operate. The Bullfrog also requires a telemetry connection to laptop to monitor vehicle state and cannot be as be easily operated by a single pilot. Swapping batteries in the Bullfrog requires disconnecting multiple sensor cables and careful maneuvering of the batteries into and out of their mounting position. The analog video stream from the front facing provides some situational awareness, but it does not aid in precisely hovering the UAV directly above a subject.

Fig. 3: Purpose-built UAV in the Aquacopter Bullfrog chassis using a Pixhawk autopilot running Arducopter firmware.

We selected these two UASs for their combined feature set, their transportability, and their cost. Both UAVs are waterproof, allowing us to test both launching and recovering the vehicles from our research vessel as well as from the surface of the water. The physical dimensions of both systems allow them to be transported by air in standard check luggage containers. Their battery requirements are within the Federal Aviation Administration's size limits for lithium batteries carried by persons flying through the United States. Both the Splash Drone 3 and our Bullfrog cost approximately $2000 USD each to purchase and construct respectively.

B. Experiment

Our data samples were collected over a three-week period spanning from October to November of 2018, off the northwest coast of Nosy Be, Madagascar. The purpose of our work in the field was to locate and record information about Omura's whales (Balaenoptera omurai), a species first described in 2003 [11] and first documented around Nosy Be in 2013 [4]. The expedition was headed by Dr. Salvatore Cerchio for the Anderson Cabot Center for Ocean Life, working in cooperation with Point Road Solutions, LLC, which provided

UAS support throughout the trip. Our crew of five crewed the *Yolmi 3*, an 8-meter open shell snorkeling boat seen in Fig.4.

Fig. 4: *Yolmi 3*, the 8-meter open shell boat which we used as a base of our operations for our 3-week survey in Nosy Be

Little is known about Balaenoptera omurai. They are slender baleen whales approximately 10-12 meters in length, with distinctive asymmetrical coloration and pattern similar to that of a Fin whale (*B. physalus*) [11]. Though initially thought to be a pygmy specimen of the Bryde's whale (*B. edeni*), morphological and DNA analysis later ruled out such possibility [11]. The extent of its range is unknown and has been listed as 'data deficient' by the International Union for the Conservation of Nature [9]. Behaviorally, Omura's whales have been seen engaging in lunge feeding, and acoustic analysis suggests that the species is very vocal communicator [4]. The primary goals of our expedition were data collection regarding the population of *B. omurai* as well as morphological data collection from the specimens we were able to locate. A distinguishing feature of *B. omurai's* behavior while tracking the animal is its irregular surfacing patterns. *B. omurai* observed during our survey did not surface for a consistent number of breaths before diving, and seem to move erratically while deeper underwater; when an individual dove, it was very difficult to determine the direction in which it would surface again. In one instance, we were able to capture video of *B. omurai* banking nearly 90 degrees as it was diving. This unpredictability meant that we were never sure how long we had with a specimen and had short windows of time to record video footage and take biopsies. This stands in sharp contrast to humpback whales (*Megaptera novaeangliae*), which share territory in Nosy Be and frequently travel in a straight line when surfacing and diving. Over the course of our studies, we located 17 groups of Omura's whales, with sightings totaling 20 individuals. In addition, we encountered and 20 humpback humpback whales and often practiced our video techniques on them while searching for *B. omurai*. Sightings were recorded on paper and individuals were photographed when possible. During encounters spanning multiple surfacings we were able to fly one or both of our vehicles to record aerial footage.

III. Data Collection Method

Our data collection and photogrammetry workflow can be described in five parts:

1) Capture video of our subject breaching with a camera pointed perpendicular to and from a height of 10 to 35 meters above the surface of the water.
2) Manually find the sections of the recorded video when the subject is surfacing and is entirely in frame.
3) Synchronize the recorded video with the vehicle's flight log
4) Use our software to correct for lens distortion, use the flight log to determine the precise position of the camera, and export calibrated images with known pixel dimensions along the surface of the water.
5) Use Fuji, open source image processing software built on ImageJ, to view the calibrated images and morphometric measurements.

We found this process to be robust to a wide range of sUAS equipment, operating conditions, and levels of operational experience. This method does not require scaling objects to be captured in the same frame as the subject or camera calibration prior to data collection. We found recording high resolution video and later extracting individual frames for analysis resulted in our best overall dataset. Even though both of our UAVs can record still images that are significantly higher in resolution than recorded video on the same camera, the challenges associated capturing still images at precisely the correct time led the videos to be a more reliable dataset. For an accurate distance measurement between the subject and the camera, it is important that the moment of breaching is captured. Capturing still images rather than video proved too imprecise to guarantee clear shots of when the subject surfaces. While video capture was most effective, recording video at a reduced resolution but a higher framerate (1920x1080 at 60FPS compared to 2880x2160 at 24FPS) was not a beneficial tradeoff; the slightly higher pixel count allowed for more precise measurements and the lower framerate proved adequate time resolution.

A. Piloting Procedures

There are six stages of operation to address when using a drone on an ocean field expedition: preparing the UAS for takeoff, launching the UAV, framing the subject in view of the camera, maintaining the UAV's position above the subject, retrieving the UAV, and preparing the UAS for a subsequent launch. Here we will focus on aspects of operation specific to operating a sUAS on a small marine vessel in open water; normal preparations, safety precautions, and operating procedures used on land should continue to apply.

Before launching with the intent to capture data, confirm that the UAV will arm and launch from a moving platform. It is common for consumer drones to require a stable and level surface to launch from to calibrate prior to flying. If this is the case, determine if the prelaunch calibration can be disabled.

Once a cetacean has been spotted within a few hundred meters of our boat, we start recording video and launch our

UAV from either atop our sun canopy or from the surface of the water nearby. The initial goal is to gain enough altitude from which the cetacean will be easy to spot from the transmitted video stream. With the pilot in command (PIC) flying the UAV visually through light of sight, a visual observer (VO) watches the video stream for the subject to enter frame. Once the subject is spotted, the PIC switches views with the visual observer, centering the subject is frame while the VO maintains a visual UAV itself. If possible, the PIC lowers the UAV's altitude down to distance where the subject can take up as much of the frame as possible not leaving the view of the camera. The PIC maintains position above the subject as long as possible, aiming to capture at least one surfacing as shown in Fig.5. If the subject dives but we believe that they will resurface in the area, UAV climbs such that it will be prepared to maneuver when the subject is spotted surfacing. Since both of our UAVs are waterproof and float, we have the added option of landing in the water to conserve battery life while we wait for the subject to resurface. After approximately 20 minutes, the UAV needs to be recollected or landed back on the boat so that a fully charged battery can be swapped in. If the UAV has been directly exposed to any salt water, we rise the exposed components with fresh water.

B. Data Filtering

Filtering recorded data consists of finding every singular moment captured which would be relevant for further analysis. When monitoring cetaceans, this can translate to finding the parts in the recorded video where the subjects are in frame and specifically when they are surfacing.

Using a video player which allows for single frame stepping, such as MPC-HC on Windows, makes finding specific frames containing subjects a straightforward process. For each frame selected for photogrammetric analysis, record the time in the video at which the frame appears. These timestamps will be directly used by our software separate still frames from the video dataset. An example of this timestamp log is included with our program.

C. Producing an Altitude Log

In order to be able to make indirect measurements from camera footage, the position of the camera relative to the subject must be known. In our data collection, we have simplified this problem by orientating the camera on our UAV vertically, pointing straight down to the surface of the water. With a gimballed camera configuration, we can assume that the camera remains in this vertical orientation, decoupled from the pitch and roll of the UAV chassis. With a rigidly mounted camera, the orientation of the vehicle is coupled to the orientation of the camera. Here it is important be able to extract the UAV's pitch and roll angle from the vehicle's flight log so that it can be confirmed that the frames selected for analysis are taken when the camera is orientated vertically. Assuming a vertical camera position reduces the camera position to one variable: height above the surface of the water. The most straightforward method of determining

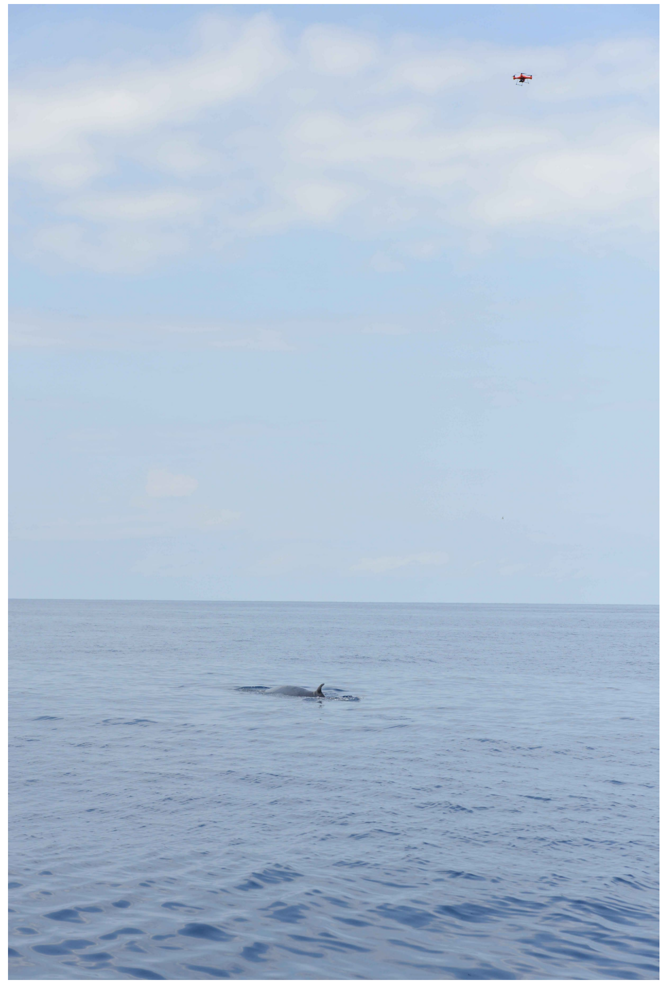

Fig. 5: An image of our Splash Drone 3 positioned above a surfacing cetacean.

the camera's height is to extract altitude information from the UAV's flight log.

Different sUASs store varying amount of flight information and in forms that are not necessarily easy to parse. Ideally, the UAV locally records verbose sensor logs with GPS timestamps. Here, processing the log files consists entirely of removing irrelevant messages and producing a timestamped list of vehicle altitudes. Some sUASs do not store or digitally transmit any sensor data or altitude information, but rather transmit vehicle state information through an analog video signal with an OSD, or onscreen display. An example of the analog video transmitted by our Splash Drone 3 with such an OSD is show in Fig.6. To transform the OSD information into a usable altitude log, we developed a small program which uses optical character recognition (OCR) through OpenCV and Tesseract to capture the displayed altitude information and save the displayed altitude information to a file. If OSD video is recorded on a device with an accurate clock time, then the relative timestamp provided by the OSD can be combined with the file creation or write timestamp to produce log file with absolute timestamps. Having a flight record incremented with absolute timestamps allows for easier synchronization not only with video and images recorded with the UAV but also any other timestamped data or notes taken during the excursion.

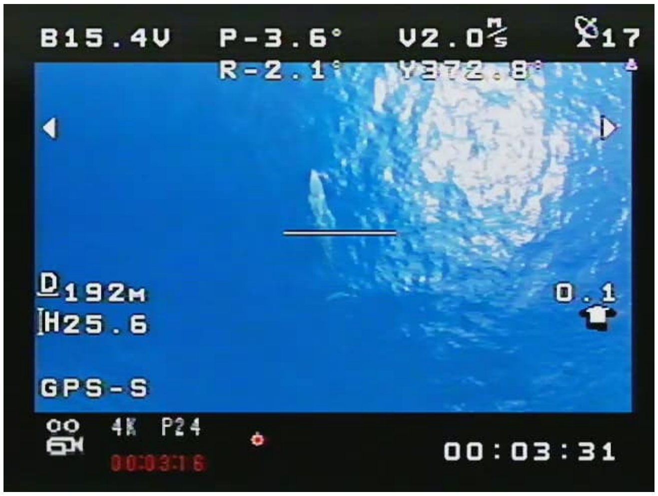

Fig. 6: An example frame captured from the analog video stream of the Splash Drone 3.

D. Flight Log Synchronization

Once produced, altitude logs need to be synchronized with their accompanying high-resolution video. If the altitude log was extracted from a recorded flight log, then a distinct moment which can be matched between the flight log and the video can be used to synchronize the two. In our experience, the moment of vehicle landing often provides the clearest alignment; the frame in which the camera contacts the landing location can be tied to the timestamp when altitude ceases to decrease. Vehicle launch and vehicle arming can also be an inflection points in the flight log that can be seen in the video or image data. If the altitude log was produced from a recorded analog video transmission with an OSD, then any frame of the OSD video can be visually aligned with a frame of the high-resolution video file for image dataset.

If absolute time is recorded in the altitude log, the absolute start time for the video or image file can be calculated. Renaming the video or image to reflect its absolute start or capture time in the form of UNIX Epoch time is a simple and effective means saving the synchronization with the altitude log and any other data collected with accurate timestamps. Some UAV camera setups will provide an absolute time value for the video or image creation; however, in our experience these timestamps are rarely accurate enough to be useful. For example, the Splash Drone 3's camera can use a connected smartphone to set its internal clock, but this time is lost after powering down the vehicle. This means that the camera would have to be recalibrated prior to each flight and doing so was not a practical option. The filesystem of the memory card used in the camera can also affect the file write timestamp resolution: FAT has a maximum resolution of two seconds whereas NTFS has a maximum resolution of 100 nanoseconds [7].

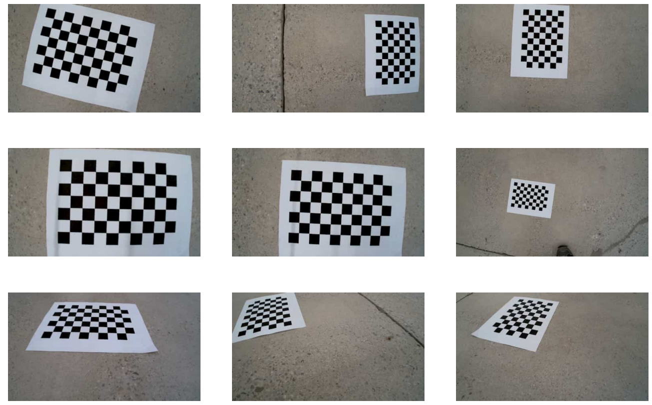

Fig. 7: An example of nine lens calibration checkerboard images.

E. Image Calibration

Most camera lenses, especially those on consumer grade UAVs, distort the image captured by the camera to some degree. For our purposes, this means that the actual distance between two pixels is not consistent across the whole image. Before we can calculate the size that each pixel represents, we need to correct for the distortion which the camera lens creates. We do this using a checkerboard pattern printed on piece of paper and a simple program using OpenCV and written in Python. Using the camera configured as it will be or has been used in the field, we collect approximately ten views of the checkerboard from varying angles, positions, and distances. The entire checkerboard must be frame the calibration to work, but it is equally important to have some views the checkerboard near the edge of the frame where the lens distortion is the strongest. To calibrate our video dataset collected with the Splash Drone 3 set to 4K (2880 x 2160 pixels), we collect our lens calibration data with the same settings; later we select the specific frames from our video to use for calibration procedure. The lens calibration program runs through the selected images or frames and calculates two variables which together describe the focal length, optical center, and amount of distortion measured in the images. Once calculated, these values can be used to undistort or flatten any image captured on the same camera with the same resolution.

The second stage of calibration is determining the ratio between pixel size and the distance between the camera and the subject. In this context, the term "pixel size" is being used to refer to the real world distance covered by a single pixel in a given image. A picture of a ruler measuring one meter across that spans one thousand pixels of the image would have a pixel size of one millimeter. However, if a second image is taken of the same meter long ruler from a farther distance, the ruler will appear smaller in the image and be comprised of less pixels. The scale factor of one pixel to one millimeter does not hold true in this second photo. To calculate the pixel size for a given image, we first determine the ratio between the image pixel size and the camera's distance from the subject using the same checkerboard from the first calibration stage. A single image or video is captured with the camera directly pointed at the checkerboard, as shown in Fig.8 and the distance between the camera the checkerboard is measured. Our program then finds the two farthest corners of the checkerboard (a known distance), takes the measured distance between the camera and the checkerboard, and returns a ratio between pixel size and camera distance which again can be applied to any image captured on the same camera with the same resolution. As a test, Fig.8 is processed by the software to produce a new undistorted and pixel calibrated image, shown in Fig.9.

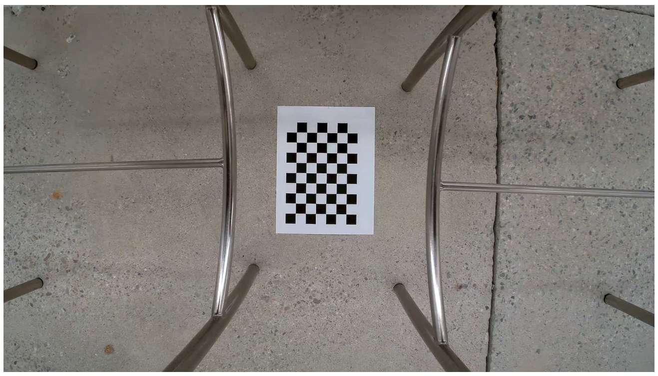

Fig. 8: An image taken at a known distance (805mm) of the calibration checkerboard image.

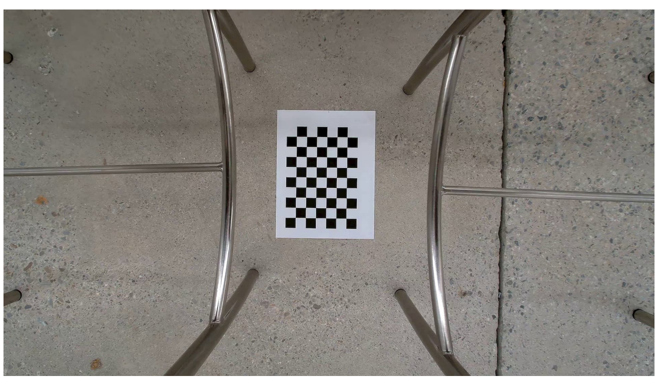

Fig. 9: The same image from Fig.8 after processing to correct for lens distortion.

F. Image Analysis

To analyze the resulting calibrated images, we recommend using image processing such as ImageJ or Fiji. ImageJ is an open source image viewer and analysis program developed at the National Institute of Health and used heavily in microscope image processing [10]. Fiji is built on ImageJ, bundles together many common plugins, and presents a cohesive and user-friendly interface. Our calibrated images are exported as TIFF files with their calculated pixel size information embedded as tags which Fiji will natively read. With a calibrated image open in Fiji, shown in Fig.10, measurements of any subject in view can be made by simply drawing lines or curves on the image. An example of using Fiji to measure an Omura's whale length is shown in Fig.11.

Fig. 10: Image of an Oumra's whale, calibrated for lens distortion

Fig. 11: A length measurement of 10.34-meters taken using Fuji image processing software

IV. Process Review

Three weeks of applying our drone surveying technique in Nosy Be highlighted the strengths and weaknesses of our equipment and our procedures. The user-friendly operation of the Splash Drone 3 made the vehicle more appealing to use which resulted in it collecting the majority of our analyzable images. Even though our Bullfrog UAV could fly more aggressively, the speed at which the Splash Drone 3 could transition from stowed to airborne gave it a meaningful advantage. Additionally, the gimbal stabilized downward facing camera and accompanying video stream proved indispensable in capturing imagery close to a subject. The Bullfrog without downward angled camera video stream had to be flown higher to ensure the subjects would stay in view, and this resulted in lower resolution and less centered images of the subjects. Though we had a means of charging UAV batteries while operating, the charging equipment interrupted regular operation of the boat and was therefore rarely used. The lack of easy charging resulted in the limited number of batteries being used sparingly, and judgment calls being made prior to each launch on whether the use of a battery would be worthwhile. A nonobtrusive means of charging vehicle batteries while operating at sea would lower the perceived cost of each flight and allow for more data to be collected.

The waterproof chassis of the UAVs and the resulting ability to land and launch the vehicles from the water balanced their large size relative to our operating space. When landing directly on boat, as we would have to if our UAVs were not waterproof, all other operations had to pause, and the boat needed to come to a rest. By comparison, the waterproof and buoyant UAVs could land in the water ahead of the boat and the UAV could be grabbed out of the water as we passed without disrupting other operations. Salt water exposure did take its toll of both of UAVs; even with fresh water rinses after each flight and a through washing after each day of operation, motors in both vehicles began to develop resistance to spinning by the end of our three-week survey.

In future surveys, we aim to reduce the hurtles we experienced with our current hardware while continuing to use inexpensive off-the-shelf hardware. From an operational perspective, reducing the physical size of our UAVs would improve every aspect of the sUAS deployment including transportation, set up, ease of use, and safety. Creating a streamlined process to allow battery charging while at sea would allow for more flights per day even with smaller cells. From the perspective of data collection, a major improvement would be the ability to collect GPS timestamped and geolocated video from a single recording device. Such a camera would remove much of the currently required manual work of synchronizing flight data with separately recorded images.

V. Conclusion

Using a commercially available and inexpensive sUAS, we were able to collect image and flight data which together allowed for a variety of morphometric measurements to be made on the 40 individual Omura's and humpback whales we observed. Our software allows for the imagery from consumer grade UAVs to be undistorted and combined with flight log information to produce images of known scale, and our software is freely available for use and modification. The use of drones in our expedition had minimal impact on the other aspects of operation, and we aim to continue to refine our procedures in future surveys.

We are excited to see the continual development of more capable and less intrusive UAVs on the consumer market. Lowering the barrier of entry to using these technologies will allow more researchers to benefit from the data they can provide. The scarcity of *B. omurai* data means that little is known about population size and conservation risk of the species; a low-cost, repeatable sUAS-based documentation approach can provide valuable information on the size and growth of individuals over time when paired with standard documentation procedures such as dorsal photography and biopsy sample. The results of our trip to Nosy Be reiterate that commercial sUASs have a promising future as documentation tools for the study of cetaceans.

Acknowledgment

We would like to thank Halieutic Institute and Marine Sciences at the University of Toliara for their support of our survey work.

References

[1] J. Burnett, et al, "Estimating morphometric attributes of baleen whales with photogrammetry from small UASs: A case study with blue and grey whales," Marine Mammal Science, vol 35, no. 2, p. 109-139, October 2018, Available: Wiley Online Library,

[2] F. Christiansen, et al, "Noninvasive unmanned aerial vehicle provides estimates of the energetic cost of reproduction in humpback whales," Ecosphere, vol 7, no. 10, October 2016, Available: Wiley Online Library: https://esajournals.onlinelibrary.wiley.com/doi/full/10.1002/esc2.1468. [Accessed 22 April 2019]

[3] F. Christiansen, et al, "Noise Levels of Multi-Rotor Unmanned Aerial Vehicles with Implications for Potential Underwater Impacts on Marine Mammals," Frontiers in Marine Science, December 2016, [Online Serial] Available: Frontiers: https://doi.org/10.3389/fmars.2016.00277. [Accessed 22 April 2019]

[4] S. Cerchio, et al, "Omura's whales (Balaenoptera omurai) off northwest Madagascar: ecology, behavior and conservation needs," Royal Society Open Science, September, 2015. Available: Royal Society Publishing, http://royalsocietypublishing.org. [Accessed 19 April 2019].

[5] A. Cunliffe, R. Brazier and K. Anderson, "Ultra-fine grain landscape-scale quantification of dryland vegetation structure with drone-acquired structure-from-motion photogrammetry," Remove Sensing of Environment, vol 183, p. 129-143, September 2016. [Online Serial] Available: Science Direct, https://sciencedirect.com/science/article/pii/S0034425716302206. [Accessed 19 April 2019]

[6] F. Giones and A. Brem, "From toys to tools: The co-evolution of technological and entrepreneurial developments in the drone industry," Business Horizons, vol. 60, no. 6, pp. 875–884, 2017.

[7] J. Kennedy, "File Times - Windows applications," Windows applications — Microsoft Docs. [Online]. Available: https://docs.microsoft.com/en-us/windows/desktop/sysinfo/file-times. [Accessed: 30-Apr-2019].

[8] R. Mlambo, et al, "Structure from Motion (SfM) Photogrammetry with Drone Data: A Low Cost Method for Monitoring Greenhouse Gas Emissions from Forests in Developing Countrires," Forests, vol. 8 no. 3, March 2017. [Online Serial] Available: Forests, https://www.mdpi.com/journal/forests. [Accessed 19 April 2019].

[9] A. Lúcia Cypriano-Souza, et al, "Rare or cryptic? The first report of an Omura's whale (Balaenoptera omurai) in the South Atlantic Ocean," Marine Mammal Science, vol 33, no. 1, August 2016. [Online serial]. Available: Wiley Online Library, https://onlinelibrary.wiley.com/doi/abs/10.1111/mms.12348. [Accessed 29 April 2019]

[10] Schneider, Caroline A., Wayne S. Rasband, and Kevin W. Eliceiri. "NIH Image to ImageJ: 25 years of image analysis." Nature methods 9.7 (2012): 671.

[11] S. Wada, M. Oishi and T. Yamada, "A newly discovered species of living baleen whale," Nature, vol. 426, November 2003. Available: ResearchGate, https://researchgate.net. [Accessed 19 April 2019].