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PERSPECTIVE

Perspectives on the Application of Unmanned Aircraft for Freshwater Fisheries Census

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This work provides an overview of the use of small unmanned aircraft systems for freshwater fisheries survey and fish identification. As an example, a series of river reaches in Mongolia was surveyed for identification and sizing of the endangered Taimen *Hucho taimen*, the world's largest salmonid. Using polarized video imagery, Taimen were positively identified in depths of over 2 m. River reaches were chosen for survey to include likely Taimen holding grounds as well as areas that were unlikely Taimen habitat. Large areas of river reaches were quickly surveyed with video imagery stored for analysis. Using land-based targets for sizing and flying autonomous search patterns, we found that Taimen were easily identifiable based on their swimming patterns and could be remotely sized; furthermore, the fish did not appear to be disturbed by the presence of overhead aircraft. Lessons learned from the experiments and recommendations for future advances are provided. The use of small unmanned aircraft systems for fisheries is shown to be a novel and inexpensive alternative to traditional fisheries survey methods.

Established human aerial census methods provide counts of animals for population-scale estimates of abundance and annual production, but are costly and potentially puts risk on personnel. Biologists have begun to recognize the data-gathering opportunities that remote, small unmanned aerial survey systems offer, particularly as functionality and availability improve over time (e.g., Jones et al. 2006; Anderson and Gaston 2013; Goebel et al. 2015; Christie et al. 2016; Brunner et al. 2017; Pai et al. 2017). The capabilities of small unmanned aircraft systems (sUAS) are now sufficiently cost-effective and diverse enough to allow researchers to tailor systems to specific data acquisition tasks—for example, to distinguish different ages, sexes, size-classes, or individuals (Christie et al. 2016). The application of sUAS for marine fisheries was summarized in a recent National Oceanic and Atmospheric Administration (NOAA) UAS Symposium (October 2016; https://swfsc.noaa.gov/UASsymposium), which demonstrated a wide range of potential and promising marine sUAS applications, including Bluefin Tuna *Thunnus thynnus* census. Remote measurement, condition assessment, and more sophisticated imaging are also possible and under development. One of the most attractive aspects of a functional unmanned aerial system is the ability to obtain information that otherwise would be impossible or prohibitively expensive to collect by using traditional methods (Brook et al. 2015; Koh and Wich 2012; Ventura et al. 2016; Watts et al. 2012; Hodgson et al. 2013).

Kopaska (2014) recognized the potential of sUAS in fisheries management 4 years ago, but since that time, there has been limited peer-reviewed analysis of sUAS in fisheries for detecting vertebrate animals that has been published. Often, publications using sUAS in aquatic ecosystems demonstrate their utility for identifying habitat or particular physical aspects of an ecosystem (e.g., surface water temperatures). In this article, we provide updated perspectives on some of the recent advances in the use of sUAS and their application to animal detections in freshwater. We start with an abbreviated summary of sUAS experiences in the broad area of wildlife management and ecology, documenting several of the advances as well as some of the challenges of that sUAS data collection. We then provide a quantitative example of the use of sUAS for fisheries analysis, demonstrating the ability to census in challenging river environments and providing recommendations on advances in analysis tools to transform simple imagery collected from sUAS into quantitative measurements. We conclude this work with a summary of factors that are important for a successful freshwater fisheries survey as well as recommendations for where advancements are likely to be made.

Table 1 represents a sampling of some of the recent, peer-reviewed sUAS applications, including the type of aircraft used and the target animal taxa. Predictably, terrestrial wildlife analysis is the more popular area of sUAS applications. Animals in terrestrial ecosystems may be easier to identify and less likely to be disturbed by aircraft. Although there is limited peer-reviewed literature describing the detection of freshwater vertebrates with sUAS, online presentations and conference abstracts suggest that this is a growing area.

A number of studies in peer-reviewed publications have employed sUAS to identify the habitat (e.g., nest characteristics or counts) that animals utilize or the characteristics of ecosystems. However, generating counts or densities of animals via the use of sUAS is rare in peer-reviewed literature, and more so for aquatic vertebrates. Published studies that focus on animals from the terrestrial environment show much promise in detecting large animals, stationary animals, or animals that use specific nesting habitat (e.g., birds) during their life cycle. These studies indicate that automated detection technology also shows promise for animal detection and surveys. Karnowski et al. (2016) and Lennox et al. (2017) further provided summaries of the wide range of animal detection and monitoring tools, including recent advances in sUAS technology and other supporting technologies.

A series of non-peer-reviewed presentations and reports demonstrated the application of sUAS for marine fisheries, as summarized in the recent NOAA UAS Symposium (October 2016). Applications range from large ocean surveys for Bluefin Tuna to mapping the spatial distribution of fisheries. For fisheries managers, quantifying the abundance of fish populations is a key goal. Existing in situ methods (e.g., underwater visual surveys, depletion experiments, and mark–recapture) are all expensive and time consuming. Aerial surveys using sUAS are a promising complement—or even a replacement in many instances.

Learning from the lessons and challenges detailed above, sUAS was implemented during a set of field campaigns in Mongolia during 2015 and 2017 to test alternative aerial survey methods for the endangered Taimen *Hucho taimen*, the world's largest salmonid (Holcik et al. 1988). Taimen are listed as "vulnerable" on the International Union for Conservation of Nature's Red List because of an estimated decline of more than 30% in global population over the last 50 years (Hogan and Jensen 2013). Jensen et al. (2009) reported healthy populations surviving in Mongolia, including in the Uur and Eg rivers, tributaries of the Selenge River. In this region, the Taimen's home range and movement patterns have been well studied, with individual fish making seasonal movements of over 100 km (Gilroy et al. 2010; O. Jensen, unpublished data). On the other hand, population densities and census information are much less reliable, with the predominant census estimates derived from mark–recapture studies. Jensen et al. (2009) reported adult Taimen densities of 19 individuals/km with relatively wide uncertainty (95% confidence interval = 13–38 individuals/km) despite intensive tagging effort for this species (612 fish tagged over 4 years, with catch rates averaging 1–2 fish per day). As Taimen populations come

Table 1. A sampling of recent peer-reviewed publications utilizing small unmanned aircraft systems (sUAS) for wildlife observation and monitoring. The majority of applications have focused on terrestrial and marine mammal observation, with no freshwater vertebrate applications to date.

Source	sUAS type	Goals/outcomes	Taxa identified
Koh and Wich (2012)	Fixed wing	Animal detection	Sumatran orangutan *Pongo abelii*, Sumatran elephant *Elephas maximus sumatranus*
Van Gemert et al. (2015)	Fixed wing	Animal detection	Sumatran orangutan, Sumatran elephant, and Sumatran rhinoceros *Dicerorhinus sumatrensis*
Jones et al. (2006)	Fixed wing	Animal detection	American white ibis *Eudocimus albus*, other white wading birds, American alligator *Alligator mississippiensis*, and Florida manatee *Trichechus manatus latirostris*
Vermeulen et al. (2013)	Fixed wing	Survey (per distance)	African bush elephant *Loxodonta africana*
Sarda-Palomera et al. (2012)	Fixed wing	Number and distribution of active nests	Black-headed gull *Chroicocephalus ridibundus*
Hodgson et al. (2013)	Fixed wing	Animal detection	Dugong *Dugong dugon* with some whales, dolphins, turtles, and other fauna
Durban et al. (2015)	Hexacopter	Photogrammetry, identification of individual organisms	Killer whale *Orcinus orca*
Durban et al. (2016)	Hexacopter	Photogrammetry, population determination potential	Blue whale *Balaenoptera musculus*
Sweeney et al. (2016)	Hexacopter	Surveys of life stages (adult, juvenile, and newborn)	Stellar sea lion *Eumetopias jubatus*
Krause et al. (2017)	Hexacopter	Photogrammetric size analysis	Leopard seal *Hydrurga leptonyx*
Chabot et al. (2015)	Fixed wing	Nest census	Common tern *Sterna hirundo*
Koski et al. (2009)	Fixed wing	Cetacean detection	Simulated whales

under threat from angling, climate change, and hydropower development (Hogan and Jensen 2013), the estimation of population density and subsequent changes in density is becoming a critical monitoring requirement.

To overcome the sole reliance on angler surveys or mark–recapture studies, the use of small, airborne imaging platforms to conduct direct counts of fish is quickly becoming a reality. To test the appropriateness of and develop repeatable techniques for an sUAS Taimen census, a series of autonomous and piloted sUAS videography imaging missions were carried out on the Eg and Uur rivers in north-central Mongolia during October 2015 and 2017. The goals of these missions were to (1) test the feasibility of species identification and size estimation from altitudes that were sufficiently high to avoid animal disturbance, (2) estimate detection rates, and (3) develop criteria and tools for the development of computer-aided and pattern recognition tools for automated fish detection and sizing.

METHODS

The study reaches were located on the Eg and Uur rivers in northern Mongolia, the site of a previous study of Taimen population dynamics and movements (Jensen et al. 2009; Gilroy et al. 2010). These are relatively low-gradient rivers with significant meanders. The water clarity in fall (the time of these studies) is excellent, and the mixed sand/gravel bottom is easily visible (on clear days and at or near solar noon) to depths of up to 3 m. Preliminary survey flights were conducted during 2015 in a reach containing at least one radio-tagged Taimen. One Taimen was observed on sUAS video; however, the flight elevations in 2015 were not well controlled, making sizing of the fish impossible. However, the flight elevations ranged from 10 to 20 m, similar to those used in 2017. Based on lessons learned in 2015, sUAS surveys were conducted in 2017 by using a low-cost commercial quadcopter (DJI Phantom 4 Professional) equipped with a gimbaled, f/2. 12-megapixel combination video/still camera. The camera system was operated in 1080p (progressive scan) video mode and was equipped with a polarizing filter. Autonomous flight commands were developed to provide a minimum of 25% overlap between river transects. Manual flights were also conducted to manually verify the presence of a Taimen, which consisted of a pilot (operator) and a videography observer to identify Taimen and to monitor their behavior as the sUAS was maneuvered over and around the fish to determine their sensitivity to overflight. For the actual surveys, commercially available mission planning software (Litchi for DJI, London, UK) was used and programmed through a tablet computer in the field. Base maps were cached on the tablet prior to departure, as no Internet access was available in the field. For the sizing of fish, fixed ground control survey markers (1.52 × 1.52 m) placed at the river's edge were imaged at the flying altitude to provide a visual scale for sizing of fish caught in images.

Overflights were conducted on two subreaches of the Uur River at or near solar noon. These reaches were chosen to have significant contrasts in water depth, stream velocity, and the probability of Taimen in the reach. Although each reach could contain one or more of the other native fish species (Lenok *Brachymystax lenok*, Grayling *Thymallus thymallus*, and Northern Pike *Esox lucius*), the largest salmonid among these (i.e., Lenok) at maturity would still be smaller than a mature Taimen and therefore should be easily differentiated. Northern Pike could approach the size of a mature Taimen; however, their habitats and behaviors are generally quite different. Reach 1 (55°23′56″N, 101°55′55″E) was chosen to represent a low-probability Taimen environment and was characterized by a relatively straight reach with shallow (60–100-cm) depth, a gravel bottom, and uniform but modest (<1-m/s) surface velocities. Reach 2 (50°27′47″N, 101°49′54″E) was a known Taimen holding ground, with much deeper conditions (>3 m), variable substrate (gravel and sand), and a more variable river velocity due to variations in river depth and the presence of a meander bend. Reach 1 was flown at an elevation of 20 m above ground level (which, in these cases, was also the elevation above the water surface) at a maximum forward velocity of 1.7 m/s. The flight line spacing was approximately 30 m, resulting in a video overlap of about 25% for each crossing (i.e., each pass over the river duplicated a 10-m portion of the river). The flights were flown perpendicular to the river flow direction to ensure complete coverage of the entire bank-to-bank reach. Figure 1(A) documents the programmed autonomous flight path of the sUAS; the total area covered by a single flight in Reach 1 was slightly greater than 10,000 m^2 or 1 ha and required a flight time of only 9 min. Each flight covered approximately 100 m of river reach, and given the reported overall river density of 19 Taimen/km (Jensen et al. 2009), upwards of 2 individuals per reach could be considered to be present, assuming a uniform Taimen density.

Figure 1B documents the autonomous flight over reach 2, flown at an elevation of 15 m above ground level and at an airspeed of 1.4 m/s, which covered approximately the same area of river (slightly greater than 1 ha) in 10 min. The flight elevation was lowered slightly to improve the pilot's ability to judge the proximity of the aircraft to the cliff face on the east side of the river, and the flight speed was slightly reduced to ensure consistent image overlap with that used in Reach 1. Flight line separation was not as consistent for Reach 2 due to differences in river morphology and adjacent cliffs but still maintained a maximum separation of about 20 m. Because of the slightly lower flight elevation and closer flight line separation, the overlap to the upstream and downstream side of the camera was maintained at the same overlap as for Reach 1 (~10 m). However, in both cases, it was not anticipated that Taimen would move significant distances during the short flight times and modest flight elevations. Note that in both cases, the reach width was approximately 100 m.

RESULTS

During autonomous flights, live-stream video viewed on the small flight monitors could not be routinely used to identify the presence/absence of Taimen due to both the size of the video screens and the bright outdoor lighting conditions. However, river bottom features (presence/absence of gravel) could easily be detected, as could floating debris on the river. Careful examination of live-stream video during the flight (by experienced and inexperienced viewers) did not detect any Taimen in Reach 1. Figure 2(A) shows a captured image of reach 1 from the river's edge, documenting the ground control target (152 cm), and demonstrates the high clarity of the images and the ease with which features can be discerned. Figure 2(B) documents the water clarity from an elevation of 15 m above Reach 2, which clearly shows river bottom structure in water depths of about 1–2 m.

In contrast, Figure 3 from Reach 2 documents a mature Taimen stationed at the edge of a drop-off. When video imagery was reviewed after the flight, this fish was clearly recognizable from its characteristic swimming behavior. The fish cannot be easily distinguished from nearby macroalgae in still images; however, in the video imagery, the motion displayed by the macroalgae is easily identified as being driven by river currents and not swimming behavior. The first 1.5 min of this video sequence from the flight can be accessed in electronic form (see the Supplemental Materials online), with the observed Taimen appearing about 70 s into the video. Using the ground control panels for scale, this fish measures an average of 105 ± 8 cm (mean ± SD), taken from hand measurement of 10 randomly chosen images during the approximately 20 s that the fish is seen in the video if assumed to be at the surface without refractive influences. If its depth is assumed to be 2 m below the panel elevation on the riverbank (an increase in distance of a factor 17/15), then its true length would be increased by about 1.13 without refraction (119 ± 9 cm). Furthermore, accounting for the refractive index differences between freshwater and air (Kinsler 1945), the true size of the fish is next reduced by the factor $(4/3)^{-1}$. Therefore, the true estimated length of the fish seen in Figure 3 is 89 ± 6 cm. While no anglers were successful in this reach of the river immediately after the sUAS flights, Taimen that were caught in adjacent reaches ranged from 43 to 115 cm.

DISCUSSION

Although the two reaches were chosen with prior knowledge of Taimen behavior to optimize sUAS testing, these reaches can provide "end members" for census studies in the future. In both cases, the river bottom could easily be observed and the large fish present were clearly visible, even in water as deep as 2–3 m. The background contrast with light-colored substrate made initial identification by eye much easier. Water clarity was critical to identification using the sUAS. The turbidity at the time of sampling was low, and the water was sufficiently clear for easy initial identification of fish. Both reaches also demonstrated that surface reflections or distortions driven by surface roughness did not impair the ability to clearly see the river bottom and therefore the presence or absence of large fish. The wind was minimal (<3 m/s) during both flights. High wind conditions would certainly reduce visibility but would also cause challenges for sUAS operations as well (flight control issues, reduced flight time due to battery consumption, etc.); therefore, census surveys are unlikely to ever be conducted in very windy conditions.

The sensitivity of observers to detect Taimen from sUAS videography was also informally tested using both expert fishing guides and non-professional anglers of various experience levels. Subjects were independently asked to view the full flight video in which a Taimen was observed in Reach 2 (note that only the first 1.5 min of the video are shown in the Supplemental Materials) and to record whether a Taimen was recognized and at what time during the video it appeared. Although this was not at all a rigorous or blind test, the simple testing provided insights into the challenges of sUAS census. Each of the fishing guides (n = 2) identified the Taimen shown in Figure 3 immediately and correctly identified the time at which it appeared in the video. By contrast, only three out of five non-professional anglers noted this Taimen.

As only two reaches were surveyed in 2017, it is difficult to assess the potential for "false negatives"—that is, the failure to observe a fish that was indeed present, quantitatively. However, in 2015, a similar sUAS was flown over a reach with a radio-tagged Taimen whose general location (±100 mm) had been identified by radiotracking. Flights over this reach did identify a single large Taimen in video. Because the 2015 flights did not have rigorous altitude control, it was not possible to accurately size this fish. However, this was the only large fish identified in the reach, and its size at tagging in the previous year was consistent with that of a mature Taimen.

Lessons Learned and Moving Forward

Given the results of this preliminary feasibility study, census methods based on statistical spatial subsampling of river

(A)

Figure 1. **(A)** Flight plan for the small unmanned aircraft system, showing the pre-programmed flight patterns and characteristics over Reach 1 (Uur River, Mongolia), which served as the low-probability Taimen environment; and **(B)** small unmanned aircraft system flight plan over Reach 2, which was an anticipated Taimen holding area.

reaches by using sUAS imagery could now be incorporated with other methods of estimating population size. For example, sUAS-based visual surveys could be used to place an empirical "prior" on population density in Bayesian mark–recapture models. Drone setup and flight operations conducted in this study required less than 45 min for each 8–10-min flight, which covered about 1 ha of river reach. These cycle times represent the maximum time needed apart from the time required to charge batteries, which can be accomplished overnight if a sufficient number of batteries is available. As experience is

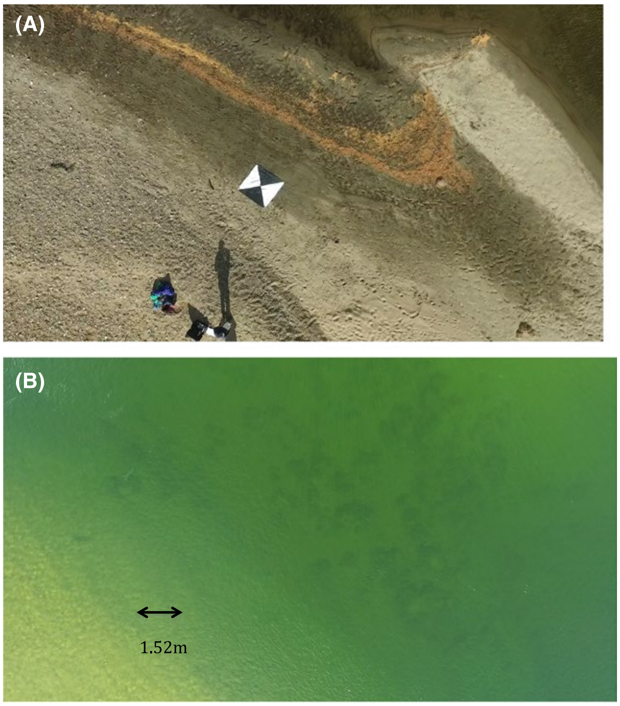

Figure 2. **(A)** Representative river image from Reach 1 (Uur River, Mongolia) documenting the 1.52-m targets for scaling and **(B)** a representative image viewing through the water column between 1 and 2 m in water depth. The scale bar is derived from the known ground control point target size during the survey at 15 m above river level.

Figure 3. Video image capture of a Taimen in the Uur River, Mongolia, from an altitude of 15 m. In the still imagery, the Taimen is challenging to recognize; however, in the video (Supplemental Materials), it is easily recognized and can be clearly seen swimming.

gained in flight operations, mission planning software, pre- and post-checklist speed, and sUAS maintenance (including battery changeover), our team has demonstrated that a river survey mission of 10 min can be accomplished in less than 15 min, making it possible to easily survey 3–4 ha/h at speeds and altitudes that are appropriate for large-fish censuses. For example, all autonomous missions can be planned, tested, and readied for upload in the laboratory or office prior to going into the field, thus reducing the time needed between flights as well as reducing crew stress and, in turn, the potential for errors. This will also reduce the time available for fish movement between flights, thereby reducing double-counting errors (i.e., due to a fish moving between flights and being misidentified as a second fish).

In this example, many conditions were conducive to sUAS detection. Not only was the target species large in size, but it was also relatively stationary. Water clarity was also quite high, making identification of animals at depths of 2–3 m possible. Clear sky conditions were found to be very important, as test flights on overcast days were unable to observe the substrate in water depths greater than approximately 30 cm. In contrast, substrate conditions were less significant than expected, as the swimming motion of the individuals made them quite easy to initially identify. The addition of a polarizing filter did sufficiently reduce glare and glint across the water surface, even in reaches with surface riffles, to permit recognition of the substrate.

The issues raised above begin to focus the range of sUAS for fisheries census. This new "tool in the toolbox" is not a universal one but rather will have a niche of suitable conditions, including fish size, water depth and clarity, wind speed, and sun angles. Clearwater fisheries with limited water depths are prime considerations. Although the work presented here focused on a large, freshwater species, smaller species can be imaged by flying at lower altitudes with knowledge of the field of view and pixel size of the imaging tools to ensure that the species can be seen. Testing can be accomplished by using "dummy" targets with the shape and color of the species of interest. The informal survey taken by experienced and less-experienced anglers suggests that training data sets are helpful to ensure identification, and these same target flights can be used both to train the observers and to test the probability of false negatives. Test flights over known habitat should be conducted at the anticipated flight altitude to determine the species' response to overhead objects. Smaller species may be more likely to react to an overhead, "predator-like" object; thus, it may be necessary to balance flight altitude with image resolution. Flight plans can also be optimized to reduce or eliminate the aircraft's shadow from passing over the target habitats, and given the advances in miniaturization, it is now possible to fly sUAS that more closely resemble a sparrow than an osprey!

The rapid evolution and significant reduction in cost of sUAS that are capable of high-resolution videography suggest that future riverine fish surveys will be able to incorporate them as a robust visual survey tool. Advancements in computer vision and automated pattern recognition software also hold significant promise for automated fish detection and sizing, and these efforts are underway in many areas of wildlife ecology (e.g., Weinstein 2017) and a wide variety of other disciplines. In most countries, the operation of small drones (for example, the U.S. Federal Aviation Administration [FAA] defines "small" as less than 25 kg [55 lb]) for research and commercial use is regulated by the appropriate aviation authorities. In the USA, the FAA governs sUAS operations under the Code of Federal Regulations Title 14, Part 107, released in 2016. These regulations, which have significantly opened up opportunities for legal operation of sUAS for research purposes, can easily be met with modest operator training and allow for the use of a significant new and non-invasive method to improve surveys in river and lake systems.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article. AFS