SYSTEMATIC EVALUATION OF A STOCK UNMANNED AERIAL VEHICLE (UAV) SYSTEM FOR SMALL-SCALE WILDLIFE SURVEY APPLICATIONS

By Dominique Chabot

Department of Natural Resource Sciences
McGill University, Montreal
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ABSTRACT

Unmanned aerial vehicles (UAVs) may soon represent a viable option for use in a variety of wildlife research and management applications. This M.Sc. thesis presents an assessment of a small stock UAV system, the CropCam, as a wildlife research instrument in terms of measured performance in specific trial missions and general capacity to meet certain practical requirements. The UAV proved effective for surveying flocks of snow geese (*Chen caerulescens*), though ineffective for Canada geese (*Branta canadensis*), and carried out censuses without disturbing birds. It was variably successful at detecting black bears (*Ursus americanus*), woodland caribou (*Rangifer tarandus*), white-tailed deer (*Odocoileus virginianus*) and grey wolves (*Canis lupus*) in pseudo-natural enclosures, and factors affecting their visibility were analyzed. The UAV is affordable, portable and relatively easy to use, however it is difficult to master, prone to sustaining damage and functionally restricted by camera performance, range and landing site requirements. Promising results demonstrated in this study combined with rapid ongoing development of UAV markets warrant further exploration of wildlife research and management applications.

RÉSUMÉ

Les drones « UAV » pourraient bientôt représenter une option rentable pour diverses applications reliées à la recherche et la gestion fauniques. La présente thèse de M.Sc. offre l'évaluation d'un système UAV compact de série, le CropCam, en tant qu'instrument d'étude de la faune en termes de mesures de performance au cours d'essais spécifiques ainsi que d'aptitude générale à rencontrer certains critères pratiques. Le drone s'est révélé efficace dans l'exécution d'inventaires d'oies des neiges (*Chen caerulescens*), mais non de bernaches du Canada (*Branta canadensis*), tout en évitant de perturber les oiseaux. Son succès fut variable dans la détection d'ours noirs (*Ursus americanus*), de caribous (*Rangifer tarandus*), de cerfs de Virginie (*Odocoileus virginianus*) et de loups (*Canis lupus*) dans des enclos simili-naturels, et une analyse de facteurs influençant la visibilité de ceux-ci fut réalisée. Le drone est de prix abordable, en plus d'être portatif et relativement commode d'emploi; par contre, il est difficile d'apprentissage, enclin à l'endommagement et limité par les capacités de son appareil photo, sa portée maximale et ses contraintes quant aux sites d'atterrissage. Les résultats prometteurs démontrés dans cette étude ainsi que le développement rapide du marché des drones justifient de plus amples enquêtes sur leur application à la recherche et la gestion fauniques.

PREFACE

This is a manuscript-based thesis containing four chapters. In the first chapter, unmanned aerial vehicles (UAVs) are introduced, their potential applications in wildlife research and management explored, and thesis aims, objectives and proceedings overviewed. The second chapter presents a critical assessment of the UAV system used in this study, the CropCam, as a viable wildlife research tool and draws lessons for future work. The final two chapters focus on the UAV's measured performance in specific trial applications, with the third chapter reporting on surveys of wild geese flocks and the fourth on surveys of wild mammals in pseudo-natural captive settings. The candidate is primary author of all chapters. David M. Bird is secondary author of chapters 2, 3 and 4, and was involved in guidance and fund acquisition throughout the study.

CHAPTER 1 – Unmanned aerial vehicles, their potential wildlife applications and overview of study aim, objectives and proceedings

Introduction to UAVs

The term *unmanned aerial vehicle* (*UAV*) was coined in the 1990's, though the basic concept of these aircraft – aerodynamic flight without a human on board – goes as far back as aviation itself (Newcome 2004). Sometimes also referred to as UASs (unmanned aircraft systems) and formerly as RPVs (remotely piloted vehicles) and surveillance drones, for decades their development was outpaced by the rapid initial proliferation of conventional manned aircraft in military and civilian markets. Nevertheless, like the latter it is successful military applications that spearheaded their eventual coming of age. From the Cold War on, UAVs have been increasingly employed in military operations for spy, reconnaissance and strike missions, reaching an unprecedented rate of growth in post-9/11 operations (Newcome 2004; Wilson 2009).

At present day, UAV may refer to a wide variety of aircraft designs, sizes and specific capabilities. Some of the better-known military UAVs range from the 13.5-m long by 35.4-m wingspan Global Hawk capable of 36 hours of sustained high-altitude flight, to the 1.1-m by 1.3-m hand-launched Raven for short-range reconnaissance missions. UAV may also refer to rotorcraft designs such as helicopters, lighter-than-air designs like airships, or even tiny flapping-wing robots known as MAVs (micro air vehicles). Finally, the term UAV covers a wide range of *levels of autonomy*, from remotely piloted aircraft to fully programmable systems or even those capable of making their own decisions in action. All above classes have benefitted from recent advancements in key technologies including computers, sensors, fabrication materials and processes, energy sources and satellite communication and navigation (Wilson 2009). Such has been the recent rate of development that non-military UAV usages have only begun to surface over the past decade or so. Broadly speaking, UAVs offer the general advantage of being able to carry out high-precision flights in tedious or dangerous missions where human-occupied aircraft may be ineffective, unnecessary, uneconomical or a safety risk.

Much civil-application interest has been invested in the potential for small inexpensive UAVs to aid in agricultural monitoring (Herwitz et al. 2004; Johnson et al. 2004; Lelong et al. 2008), to the extent that a distinct commercial market for agricultural applications is beginning to emerge with such consumer-targeted models as MicroPilot's (Manitoba, Canada) CropCam. Potentially dangerous and/or tedious missions such as forest fire surveillance (Ambrosia et al. 2003; Casbeer et al. 2006; Merino et al. 2006), search and rescue (Goodrich et al. 2008; Murphy et al. 2008) and routine infrastructure monitoring (Hausamann et al. 2005) have also received notable attention. Finally, there is some interest in high-precision biological and environmental measurements including aerobiological sampling above crops (Schmale et al. 2008), rangeland vegetation mapping (Hardin and Jackson 2005), study of volatile pollutant dispersal (Roberts et al. 2008), arctic melt-pond monitoring (Inoue et al. 2008), volcanic gas measurements (McGonigle et al. 2008) and atmospheric wind readings (van den Kroonenberg et al. 2008).

As the civilian UAV market promises to expand into an ever-growing range of applications, its principal obstacle at this time has become integration into civil airspace. While military UAVs have benefitted from *de facto* precedence of military operations in general airspace management, would-be civilian UAVs have an expansive, elaborate, established and saturated civilian manned aircraft market to compete with for limited common airspace. More to their detriment, current civilian regulatory frameworks for official airworthiness certification are not tailored nor amicable towards UAVs due to their novelty and perceived operational risks (Anand 2007). Before widespread civilian use of UAVs becomes a reality, further progress must be accomplished both on the regulatory front and the design and technology front (Peterson 2005; Anand 2007; Loh et al. 2009).

Potential applications in wildlife research and management

In a seemingly endless list of possible civilian applications for UAVs, wildlife research and management are among those which have received minimal attention to date. Similar to some of the aforementioned applications, wildlife-related work also tends to be inherently tedious, remote, risky, delicate and/or highly dependent on precision. In a broad sense, UAVs might be viewed as attractive tools in this field for a variety reasons including affordability, timeliness, convenience, simplicity, versatility, discreetness, precision and accuracy. Thanks to such attributes, UAVs could rival or surpass conventional methods as well as pioneer entirely novel applications.

Potential applications for UAVs in wildlife research and management are multiple. First, they might be conceived as useful instruments for conducting animal population surveys, a pivotal component of wildlife management and one that is heavily dependent on aerial surveys by manned aircraft, though not without unremitting scrutiny and questioning of the method's precision and accuracy (Myers et al. 2008). From smaller-scale surveying of concentrated groups of animals (e.g. bird colonies and flocks, mammal herds) to scouring of larger areas in search of more sparsely distributed subjects, UAVs in some cases might offer numerous advantages over conventional aircraft or other census methods. Small UAVs might prove cheaper and more convenient to operate than manned full-size aircraft as well as achieve a higher level of precision and accuracy, all the while reducing relative disturbance to animal subjects. Moreover, they might represent a simple, effective and economical alternative to tedious and/or time-consuming ground-based census methods where conventional aerial surveys are ineffective or beyond budgetary means.

Second, UAVs might also prove useful in individual-level observation or tracking of animals. Bird nest inspections constitute a prime example of this type of application, as nests are often located in hard-to-reach places (e.g. cliffs, tall trees and buildings) and guarded by parents who can be as sensitive as they can be aggressive towards intrusion, altogether putting both birds and researchers at risk (Antczak et al. 2005; de Villiers et al. 2005; Rosenfield et al. 2007). Inconspicuous and agile UAV rotorcraft or miniature airships equipped with proper sensors might alleviate this exercise for both sides by quickly, safely and unobtrusively carrying out remote nest inspections. Such UAVs could be employed for up-close wild animal observations in general in situations where disturbance represents a potential issue, for instance natural behaviour studies. Additionally, they might be regarded as a more effective and/or economical means of tracking animals equipped with radio transmitters than manned aircraft-, satellite- or ground-based telemetry methods.

Third, UAVs could bring a new level of sophistication to modern studies of wild habitats, already boosted by recent advancements in geographical information systems (GIS) and aerial imagery acquisition by satellite and manned aircraft (Duhaime et al. 1997; McCauley and Jenkins 2005). Such studies are increasingly used to monitor ecosystem health and trends as well as establish links between habitat factors and animal abundance and distribution (Jobin et al. 2007; Barima et al. 2009; Gomez-Rodriguez et al. 2009). In cases where satellites or aircraft are used, small programmable UAVs might acquire the same imagery, perhaps even at a finer resolution, in less time for a fraction of the cost. Where aerial methods are currently impractical or uneconomical, UAVs might affordably spare countless hours of tedious ground-truth labour while achieving enhanced accuracy. Low operational costs combined with high-performance automation could also enable UAVs to precisely repeat surveys multiple times at little additional cost or effort, for example in studies requiring frequent periodic monitoring.

Fourth, there is a potentially large market for effective means of repelling and controlling nuisance birds. These pose a worldwide problem in landfills, agricultural crops and airports, causing billions of dollars in damage, not to mention human fatalities (Allan 2006; Baxter and Robinson 2007; Delwiche et al. 2007; Cook et al. 2008; Kukuda et al. 2008; Werner et al. 2008). While additional technological sophistications (e.g. further miniaturization, enhanced agility, "smart" detection of subjects) may be required before UAVs can truly be effective at repelling nuisance birds, this sort of application may soon be in the range of small fixed-wing or rotorcraft UAVs, or even MAVs used in swarms. Such systems might safely and autonomously patrol airports, crops and landfills for long uninterrupted periods, seeking and repelling pest birds automatically.

To the author's knowledge, the only published work to date on the application of UAVs in wildlife research or management is described in Jones et al. (2006), based on the first component of two Master's thesis research projects (Jones 2003; Lee 2004) conducted at the University of Florida. The first objective consisted of carrying out preliminary tests on the general ability of a small custom-built UAV to detect a variety of wild animals, while the second focused on engineering a UAV system for wildlife survey purposes from scratch. The programmable hand-launched combustion-engine UAV used in the first part (2002-2003) appeared variably successful at capturing aerial videography of American alligator (*Alligator mississippiensis*) decoys, West Indian manatees (*Trichechus manatus*) and a variety of white wading birds. However, in practice the UAV suffered from unreliable engine performance, challenging launches and landings, and inability to georeference video frames for use in GIS. The study provided some valuable insight on key issues that may be encountered in practice when applying UAVs to wildlife research, namely ease, simplicity and reliability of operation, deployment and endurance in remote locations with adverse conditions, and ability to automate certain imagery processing tasks (Jones et al. 2006). Demonstration of promising results in this early study as well as the rapidly evolving nature of the UAV industry warrant continued investigation into potential applications of UAV technology in the fields of wildlife research and management.

Study aim and objectives

The primary aim of this Master's degree research was to pursue and push forward the investigation of unmanned aerial vehicles as viable tools for wildlife research by acquiring and learning to operate a current UAV system and assessing its potential in wildlife survey tasks using systematic and quantitative approaches. The study will serve to provide what may be, to the author's knowledge, the first quantitative data on UAV performance in such surveys, as well as additional practical experience and teachings to base further research upon.

Due to the novelty of the research as well as budget constraints, it was judged sound to restrict the scope of the study to trials of relatively simple and small-scale animal survey-type applications using an affordable UAV system meeting certain basic requirements: approachable and operable by a user possessing no prior special experience, presence of a programmable autopilot and camera system, electric propulsion, portable and hand-launched. Commercially-built ready-to-operate systems were considered rather than custom-built ones as the former increasingly appeared to represent the better overall cost/effort bargain at the time of the study's beginnings in 2007. Among about half a dozen small to large North American companies selling small UAV systems commercially – including Canada-based MicroPilot (Stony Mountain, MB) and Draganfly (Saskatoon, SK) – MicroPilot's CropCam consumer UAV system (detailed below; see Table 1 for breakdown of costs and required accessories) was selected on the basis of competitive price, strong customer support options and immediate domestic availability.

Following preliminary training with the system and familiarization with its capabilities and limitations, specific performance-testing field trials were selected based on logistical feasibility and perceived likelihood to suit the CropCam's basic capacities. These were: 1) detection of active pre-wintering beaver (*Castor canadensis*) food caches in comparison with helicopter and ground-based surveys; 2) censuses of local geese flocks (*Branta canadensis* and *Chen caerulescens*) in comparison with ground counts and; 3) systematic appraisal of the detectability of land mammal species (*Ursus americanus*, *Rangifer tarandus*, *Odocoileus virginanus* and *Canis lupus*) in pseudo-natural enclosures at a local ecomuseum. In addition, as a side-objective throughout all trials and study experiences, the CropCam was to be critically evaluated as a generally capable and viable UAV system for wildlife research, identifying current strengths as well as key areas to improve upon for future work. All trials were performed with the consent of applicable property owners and all observations of live animals under the approval of the McGill University Animal Care Committee (Appendix A).

While the first field trial had to be abandoned in early stages due to complications encountered on site with respect to aircraft deployment (further detailed in the following chapter), the latter two trials constitute chapters 3 and 4 of this thesis, respectively. These are preceded by a brief overview of the CropCam's general specifications and mode of operation below, followed by its global evaluation as a wildlife research UAV in chapter 2.

Overview of the CropCam UAV system

Specifications

Primarily marketed towards agricultural monitoring applications, the CropCam essentially consists of an autopilot and camera system integrated into a stock radio-controlled (R/C) model airplane, altogether weighing approximately 2.75 kg (Figure 1). The airframe used is the Electra Pro by Topmodel CZ (Czech Republic), an electric glider sailplane measuring 1.23 m long by 2.55 m wingspan and equipped with a full set of control surfaces including rudder, elevator, ailerons and flaps. Thrust is provided by a small brushless electric motor at the nose, powered by 4 interchangeable rechargeable lithium-polymer batteries. The fuselage is made of epoxy fiberglass covered with gelcoat, while the wings are made of balsa covered with polystyrene and wrapped in smooth polyvinyl (PVA) sheeting. The airframe is modular (3 wing pieces, fuselage, elevator) and fits into a standard hunting rifle carrying case when disassembled (Figure 1).

Built into the fuselage is MicroPilot's MP2028g programmable autopilot system with an integrated 3-axis accelerometer-gyro system for yaw-pitch-roll sensing along with a pressure altimeter for airspeed and altitude sensing (30 Hz control system response), a GPS receiver and antenna for navigation (1 Hz GPS update), and a radio modem and antenna for communicating with the ground control station (2.4 GHz frequency). The onboard camera system (Figure 1) is comprised of a downward-pointing compact digital still camera (Pentax Optio A-series) housed in a removable protective box fixed under the wing. An infrared remote switch connected to the autopilot system runs into the camera box and serves to trigger the camera's shutter during flight. The aircraft can carry a maximum camera payload of 450 g.

Depending on weather conditions, the CropCam can fly for up to 45 – 55 min at an average airspeed of 60 km/h (45 – 55 km total distance covered) on a single battery charge, at a functional flight altitude range of 120 – 670 m. It is unsafe to operate the aircraft in precipitation or winds exceeding 30 km/h. Basic costs of the system as well as required accessories are listed in Table 1.

Operation

The CropCam operates in conjunction with a suite of custom software by MicroPilot which is installed on the accessory laptop and used to program the autopilot, track and interface with the plane from the ground during flight, and retrieve and view flight log data gathered by the autopilot during flight. Programming and tracking are accomplished with an application named Horizon while flight logs are handled by a separate application named LogViewer.

The CropCam's autopilot executes flight files based on a command-line programming language. The entire repertoire of available commands is quite extensive, though a typical flight usually consists of defining a cruising altitude, then constructing a navigational course composed of a series of waypoints. These can either be entered as absolute GPS coordinates or relative coordinates to the plane's deployment location. Plotting of the course can also be accomplished graphically rather than manually entering commands: a custom map of the area to be overflown is loaded and waypoints placed upon it using point-and-click. Commands must then be added to govern the camera system in order to obtain aerial imagery over the course of the defined trajectory. Through controlling the infrared remote switch that triggers the camera, the system can be programmed to capture single photos at specific waypoints or continuous bursts of photos between successive waypoints. A third option is to use the camera in video mode. Finally, all flight files must contain a number of fail-safe commands to instruct the autopilot on how to behave in the event of various potential malfunctions (e.g. loss of GPS signal, battery failure, etc.).

Once completed, programmed flight files are simulated in Horizon in the same interface environment (detailed below) as is used to track the plane in real time in the field. This routine serves to double-check flights for inadvertent programming errors, to assess their total duration and assure that it is safely within battery capacity, and to make minor course tweaks based on the plane's behaviour in simulation. Finalized flight files are then copied directly to the aircraft's onboard autopilot (capable of carrying one file at a time), via a direct cable connection (faster) or wirelessly via the ground and onboard radio modems (slower). Once the desired flight file is loaded onto the CropCam, the aircraft is ready for deployment.

In most cases the CropCam is launched and made to land at the same location. Suitable deployment sites are constrained foremost by landing requirements: a wide-open field of grass, soft crops or dry mud providing at least 75 – 100 m (depending on wind conditions and skill level of the operator) of unobstructed space. It is also possible to land the CropCam on snow, though there is a risk of getting the internal electronics wet. Onsite setup involves assembling the aircraft (joining airframe modules and wires, inserting batteries and installing camera system) and setting up the ground control station (laptop, radio modem, power supply and R/C radio transmitter). If needed, flight files can be programmed and loaded onto the autopilot on location. The aircraft is then initialized and interfaced with the ground control station using Horizon, and a routine pre-flight checklist is fulfilled to ensure that all components of the system are functioning properly.

Launch is performed by hand as the operator stands holding the plane above head level, manually triggers the motor into full throttle, takes a short running start to build momentum and thrusts the plane forward into the air. The autopilot assumes full control from the moment of takeoff, immediately initiating ascent to the programmed cruising altitude in a straight path for the first 60 m, as a precaution to clear any neighbouring ground obstacles, then in a rising helix pattern for the remainder of the climb. Once target altitude is reached, the aircraft commences the programmed flight, autonomously navigating from waypoint to waypoint.

Throughout the entire flight the aircraft is tracked in real time from the ground control station via radio link with the autopilot (maximum range ≈ 3 km). This is accomplished in Horizon with an interactive virtual-cockpit environment (Figure 3) presenting the operator with a map which dynamically updates the plane's position and heading along the programmed course. Also displayed are the familiar airspeed and altitude dials and artificial horizon, as well as several other virtual instruments which report on parameters such as throttle force, groundspeed, total distance travelled and flight time, GPS position and signal status, battery levels, camera system activity and any system errors or failures.

A number of options are available to the ground operator to manually command or intervene with the CropCam in mid-flight. In Horizon, flight commands can be transmitted in real time from the ground control station to the autopilot, such as modifications to the course, manual triggering of the camera, standard airspace evasive manoeuvres (e.g. perform a right-hand turn) and mission-abort commands (e.g. fly back to launch location, perform an autonomous landing). So long as the plane is within visual range, the ground operator can also completely override the autopilot at any moment and assume full manual control of the aircraft using the R/C radio transmitter.

Once the main course has been completed, the plane is usually programmed to return to the launch site. While the autopilot is capable of autonomous landing, manual landings in R/C mode are most often preferable as they typically require less space and allow precision steering clear of any nearby obstacles (e.g. trees, telephone poles, power lines) which the autopilot is not equipped to detect. In a successful landing, the ground operator guides the plane to a gentle touchdown directly on its belly where impact is cushioned by a suitable ground surface.

Post-flight data retrieval consists of removing the camera from the aircraft and transferring the acquired imagery to computer as well as optionally recovering the log file from the autopilot's flight data recorder using LogViewer. Flight logs keep an exhaustive report on all system parameters during flight at a recording rate of 5 times per second. LogViewer facilitates assessment and analysis of flight data by providing visual representations (Figure 4), for instance graphing parameter fluctuations throughout a flight (e.g. altitude, yaw-pitch-roll, camera system activity) and plotting the exact route followed by the aircraft.

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Table 1 – Cost breakdown of the CropCam UAV system and required extras. Prices are approximate and subject to fluctuation over time. * Required only if operator has no prior R/C flying experience.

Item	**Cost ($CAD)**
CropCam package (includes: aircraft with all onboard components except camera, set of 4 batteries, ground station radio modem and cables, all MicroPilot software and manuals, and 1-year manufacturer's limited warranty and phone support)	$8,000
CropCam 5-day training course	$1,000
Camera (Pentax "Optio A" series) + high-speed memory card	$400
Min. one extra set of batteries (4 x $80)	$320
Battery charger + cell balancer + AC to DC power supply	$380
Laptop (flight programming, live tracking, data log viewing, image post-processing)	$1,500
Portable field power supply (for ground radio modem and laptop)	$85
Min. 5-channel R/C radio transmitter + receiver (for manual R/C control of CropCam)	$320
Field kit (for field setup, repairs and maintenance includes: small screwdrivers + Allen wrenches, X-Acto knife, masking tape, rubber bands, Velcro, CA glue, fast epoxy, lens cleaner + tissue, gas duster, spare wing bolts and R/C plane stand)	$100
*R/C flight simulator software + controller	$280
*R/C trainer plane + accessories	$400
Total	**≈ $12,800**

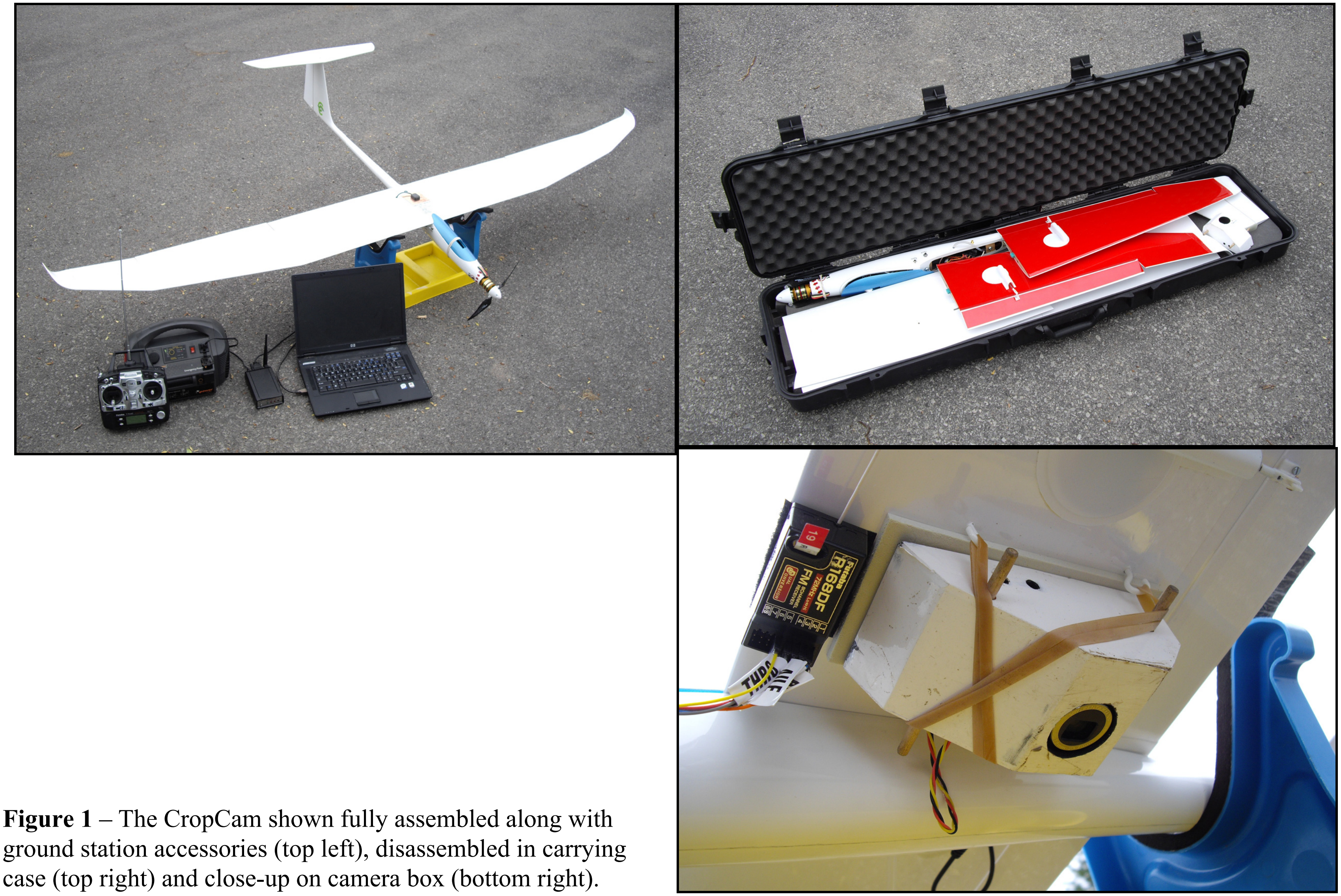

Figure 1 – The CropCam shown fully assembled along with ground station accessories (top left), disassembled in carrying case (top right) and close-up on camera box (bottom right).

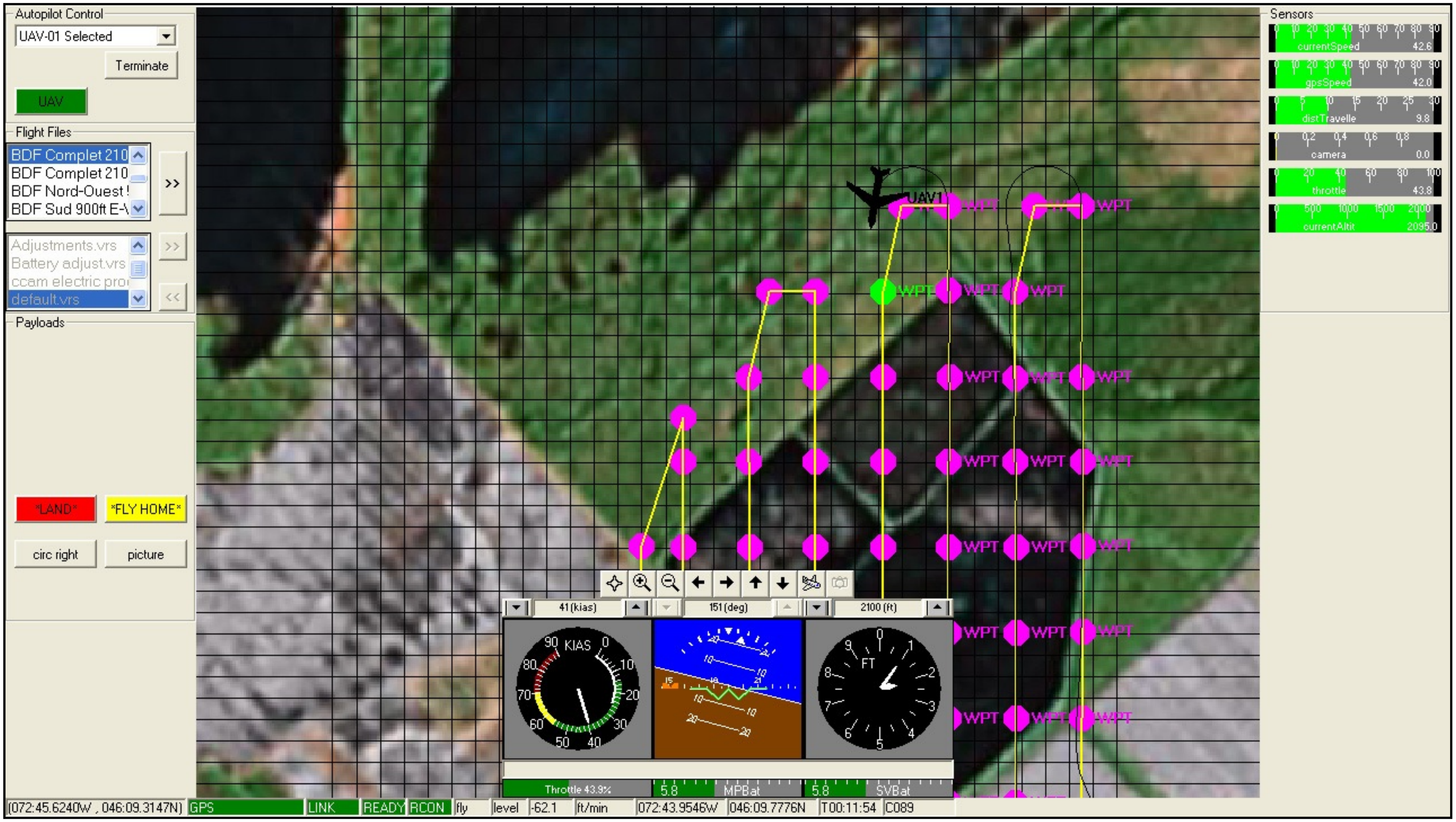

Figure 2 – Screenshot of the Horizon UAV live flight tracking environment.

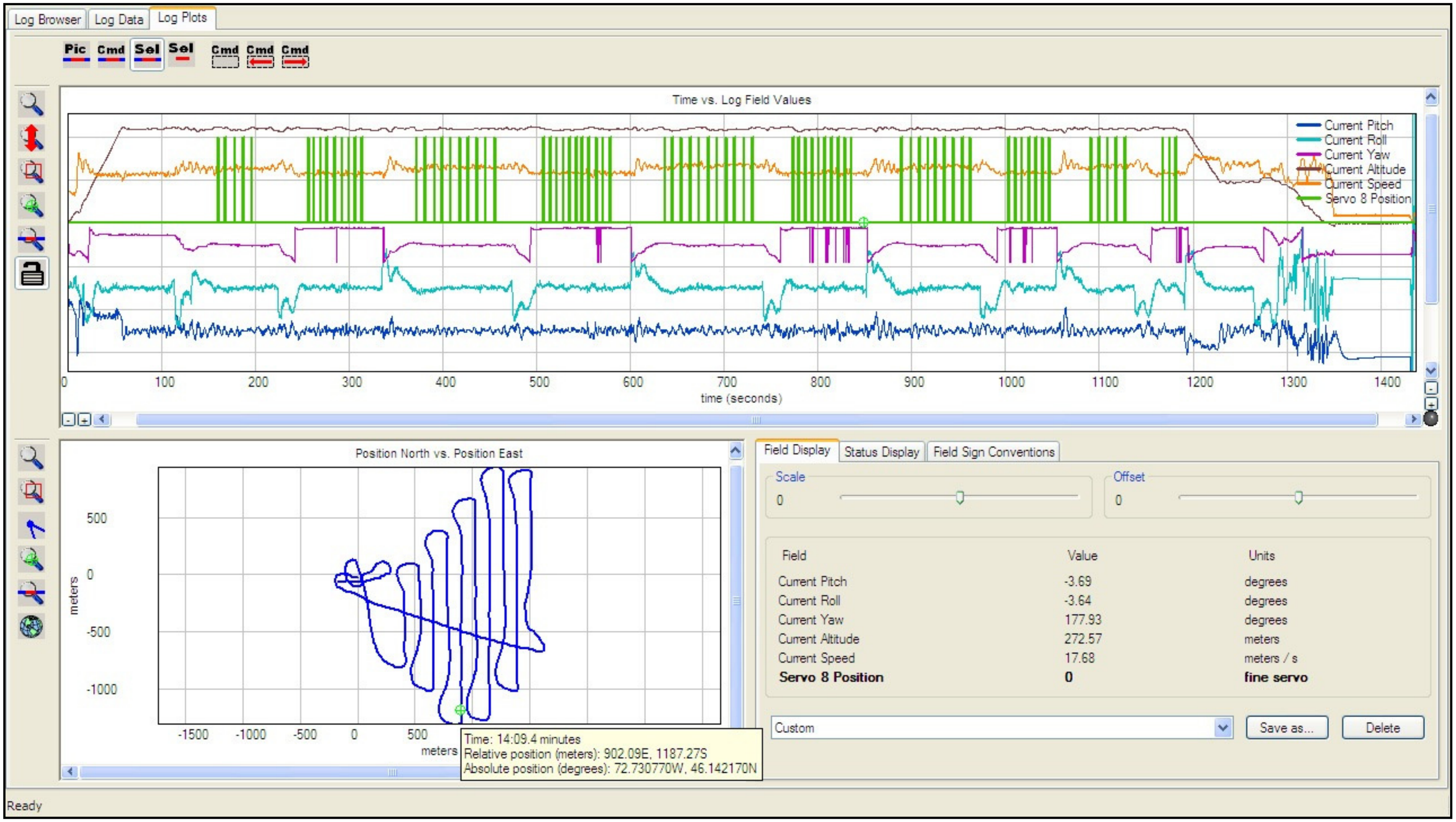

Figure 3 – Screenshot of the LogViewer UAV flight data reader.

CONNECTING STATEMENT

Chapter 1 began with an introduction to unmanned aerial vehicles (UAVs) and an outline of their potential applications in the fields of wildlife research and management. This was followed by a statement of this study's aims and objectives, and finally an overview of specifications and operation of its main instrument of focus: the CropCam UAV system. The second chapter presents a critical experience-based assessment of the CropCam as a generally suited UAV system for wildlife-related research applications, identifying key practical issues and offering recommendations for future UAV implementations in wildlife research.

CHAPTER 2 – Global appraisal of a basic UAV system as a practicable wildlife field research tool

Abstract

Emergent unmanned aerial vehicle (UAV) systems may have much to offer to the fields of wildlife research and management through their sophistication and innovations. Over the course of this 2-year study, the CropCam commercial UAV system was assessed as a generally capable tool for small-scale wildlife research-related tasks based on a number of preconceived criteria as well as novel experiences encountered. Main strengths of the system were found to be affordability, suitable interfacing software, overall reliable autopilot performance, simple transportation, setup and launch, and minimal operational disturbance levels. Main weaknesses were steep training requirements, limited camera system, lack of data post-processing automation, high maintenance requirements, and overall restricted deployment options due to weather factors, ground tracking range and challenging landings. The CropCam's practical scope of wildlife research applications is within short-range missions in non-remote locations where subjects or features of interest are relatively visible, for example certain small-scale wildlife head counts or habitat mapping tasks.

Introduction

The fields of wildlife research and management may stand to profit from the emergence of unmanned aerial vehicles (UAVs) in civilian markets. From large-scale population surveys of wide-ranging animals to up-close inspections of bird nests, cutting-edge UAVs promise to offer many potential advantages compared to other data collection methods: lowered costs, time savings, greater simplicity, enhanced accuracy, reduced disturbance, safety benefits and novel data collection opportunities.

The underlying aim of this thesis study was to acquire a UAV system and assess its value as a wildlife research tool throughout the exploration of a series of practical applications, with a focus on smaller-scale applications as a logical starting point in this novel area of research. In addition to quantitatively evaluating performance in each application, a side-objective of the study was to assess the UAV on the whole as a viable system for wildlife research in general. Based on the typical realities of the field, a set of key criteria can be formulated with respect to what sort of features and characteristics should be sought after in an effective wildlife research UAV. Many of these were previously identified by Jones et al. (2006) in their preliminary assessment of a small combustible-engine UAV for surveying wildlife, the main drawbacks of which were found to be challenging aircraft launches and landings resulting in airframe damage and inability to deploy in certain locations, unreliable engine performance, and inability to georeference imagery.

A UAV system for general small-scale wildlife studies needs to be an economically feasible option relative to other potential data collection methods, all depending on the nature of the research and the basic funding available. The system as a whole should require minimal training to operate and be accessible to field biologists with little or no prior special expertise. This includes user-friendly software for UAV programming and ground control, and easily acquired field operation skills (e.g. setup, deployment, manual control, recovery, etc.). The autopilot system should possess the ability to execute programmed flights with a high degree of customizability with regard to navigational trajectory, flight altitude and camera or sensor control. It should perform reliably and accurately, resulting in safe, stable, precise and repeatable flights.

In order to collect useful data, the UAV must be equipped with an adequate onboard camera or sensor system capable of reliably and consistently gathering imagery of suitable quality and resolution. Moreover, any features that automate or otherwise facilitate post-processing of imagery are desirable. Such procedures may include imagery stitching (e.g. merging successive overlapping still photos), georeferencing (i.e. adding GPS information to imagery for use in GIS) and automatic detection or counting of target subjects (e.g. individual animals, vegetation patches, etc.).

Importantly, a wildlife UAV should meet a number of deployability requirements, as this field of research is inherently unpredictable and opportunistic, and tends to take place in remote areas presenting unfavourable terrain and conditions. Ideally, only a single field operator should be required to deploy the UAV. The entire system should be portable at least to the extent of transportation in a small vehicle (e.g. SUV, ATV, boat), and if possible, even transportation on foot. On-site setup of the aircraft and ground control station should be simple and quick. Launch and recovery of the aircraft should be easy, trouble-free and flexible with respect to deployment site for effective use in many different types of landscapes and terrains. The maximum flight range and duration must be sufficient for the desired scale of data collection and allow for deployment of the aircraft some distance from the study site of interest if suitable deployment sites are sparse. The aircraft should show some degree of tolerance for adverse and unpredicted weather conditions such as wind and precipitation. Ideally, it should create a minimal operational footprint, including inconspicuous appearance and low noise levels, such that surveyed animals are undisturbed by the aircraft.

Finally, the UAV system should be low-maintenance in terms of cost and effort. To begin with, the aircraft should be of durable construction and resistant to damage during normal use. Servicing and repair should necessitate minimal expertise. The airframe should be modular and such that any parts prone to damage or failure are easily and cheaply replaceable.

Presented in this chapter is an appraisal of the CropCam as a generally suited UAV system for wildlife research in relation to the above-mentioned criteria and any other relevant novel experiences encountered over the course of this study. Strengths and weaknesses uncovered through operator experience will be discussed and considerations for future systems provided where pertinent.

Methods

The following assessment is based on 2 years of experience with the CropCam UAV system by a user possessing no prior operation skills and limited knowledge of UAVs, from acquisition through training and into full-scale operation. Over this period, approximately 140 flights were carried out by the UAV, all in the province of Quebec with the exception of 3 flights in Surrey, BC, and one flight in Adirondack Park, NY. Evaluation of the camera system's imagery is based on just under 4000 aerial photos acquired in total, while evaluation of autopilot performance is based on 50 retrieved flight data logs as well as personal observations in the field.

Results and discussion

Getting started

Perceived affordability was one of the main factors that led to the selection of the CropCam for this study. Initial cost of the UAV system plus all necessary extras was under $13,000 CAD or approximately $11,500 USD in 2007. In comparison, the FoldBat UAV system used by Jones et al. (2006) was custom-built in 2000 at a cost of $35,000 USD (approximately $51,000 CAD at the time). The CropCam and associated accessories still retail for about the same price today and the system remains one of the most affordable in the North American commercial UAV market, but it is likely that increasing competition and proliferation of UAVs in civilian markets will lead to further price drops in the near future.

On the whole, the training process required to fully operate the CropCam was manageable, though far from effortless for an operator possessing no prior experience in Radio-Controlled (R/C) flying, which proved to be the most challenging component. The initial 5-day training course provided at MicroPilot's facility in Manitoba focused primarily on the basics of flight programming and aircraft setup and maintenance. While the material covered in the course was useful, it was made clear that supplemental R/C flying skills are a must in order to operate the CropCam, mainly due to the need to perform landings manually.

Acquiring suitable R/C abilities first involved spending a minimum of 40 hours practicing with computer simulation software (Great Planes RealFlight G3.5) and an accessory mock R/C transmitter. Next, an inexpensive electric model glider (Great Planes Spectra Select) loosely resembling the design of the CropCam was purchased as a trainer unit. A model requiring manual assembly of airframe and integration of internal components was selected so as to build experience and familiarity with these tasks for later servicing needs of the CropCam. The trainer plane was successfully flown and recovered 8 times during a one-week period over agricultural fields of the Macdonald Campus Farm (Ste. Anne de Bellevue, QC). However on the 9th flight, the plane's delicate wings folded in mid-air under high winds, causing the 1-kg aircraft to plunge into the ground and disintegrate on impact. Despite the fate of the trainer plane, the R/C piloting proficiency achieved over the course of its usage was judged sufficient to justify initiating use of the CropCam, which features a heavier, more robust airframe unlikely to suffer a similar rupture. R/C piloting of the CropCam proved to be comparable to the trainer plane, however the extra weight made for more challenging landings, requiring significantly more space for the aircraft to decelerate to a safe touchdown speed. A notable advantage of training with the CropCam is the ability to instantly switch to autopilot mode in the event that manual control is compromised. The CropCam flew 20 – 25 practice flights before operator confidence was sufficient to pursue proper field missions.

In total, the training process (MicroPilot course, flight simulator, trainer plane, CropCam practice flights) required for a completely inexperienced operator to gain basic ability to utilize the CropCam is evaluated at 1 – 2 months. While such a timeframe may appear reasonable, it should be noted that the predominant component of training, R/C flying, is a highly specialized skill, the assimilation of which is heavily dependent on the subject's hand-eye coordination, fine motor skills, determination and interest. An ideal UAV for routine application in wildlife research tasks should require no specialized skills whatsoever beyond basic computer competence for system programming and tracking. The autopilot should be capable of safely and reliably handling all elements of flight from launch to landing, thus completely doing away with the need for manual control. If R/C flying is eliminated from the training process, it then becomes justifiable to expect a training period of no longer than a week for such a system. CropCam operation proficiency is very much an ever-evolving prowess, and while it may only take 1 – 2 months to acquire minimum competence, it may take 1 – 2 years to fully master all the tricks of the trade with regard to software and R/C piloting, as will be further discussed below.

Autopilot system: usability and performance

MicroPilot's MP2028g autopilot and associated software is in fact a generic system that can be integrated and tweaked with a wide range of unmanned fixed-wing aircraft of different sizes and characteristics. In all cases, the same software environment and programming language is used to interface with the UAV. It has therefore been developed with user accessibility in mind and on the whole is not exceedingly complicated to grasp for an average computer user.

Flight programming in Horizon, once fully mastered, is very powerful and offers a large set of options. However, it may take quite some experience and additional support before all possibilities and techniques are uncovered by the average user, from plotting flight courses and controlling the camera system to using vital fail-safe commands. New programming approaches and options continued to be brought to light for well over a year into this study. Trajectories, for instance, can be generated either by using the raw programming language or simply by placing waypoints visually on a custom map using point-and-click. While the 5-day training course provided a useful overview of the former's major commands and elements, there was insufficient coverage of the latter technique which, once discovered on the operator's own initiative, ultimately proved far more intuitive and timely for course plotting. Nevertheless, many other routine flight commands – including altitude, camera system, and fail-safe commands – can only be entered using the code-based interface. An ideal user-friendly UAV programming environment should be entirely graphical and should not require the operator to resort to the raw code at any step of programming a routine flight. Moreover, vital fail-safe commands, because of their pre-eminence for safe operation, should be automatically embedded in all flight files rather than requiring manual addition by the programmer.

Programming also revealed itself to necessitate a number of apparent workarounds and "tricks" to achieve full potential, requiring additional support from

MicroPilot on several occasions and at times for procedures that initially appeared simple by intuition. Thus, the overall programming process feels somewhat unrefined, though by no means unworkable. Horizon is, in fact, under ongoing development and the newly released version 3.4 addresses many of the criticisms outlined above with respect to version 3.2 (used in the present study). Due to rapid advancements in UAV programming environments, these are not expected to remain a major limiting factor in the larger perspective of UAV use for wildlife research.

Horizon's virtual cockpit environment for simulating flights and tracking them in real time is very straightforward, functional and interactive, providing at-a-glance feedback on all crucial system parameters as well as on-the-fly autopilot commands and course modifications. The interface is also customizable to a certain degree with regard to map and grid options, and selection and behaviour of displayed sensors and manual commands. This effectively gives the ground operator an overall sense of reassurance about being constantly informed and in control of the system throughout flights, provided the UAV does not travel beyond ground station transmission range (≈ 3 km maximum). Though there is always room for improvement, Horizon is proposed to be an already near-ideal environment for tracking and interfacing with a UAV in routine wildlife research applications.

LogViewer, the application provided to examine flight log files generated by the autopilot, is relatively simple to use and offers a powerful and versatile interface for viewing system parameters in intricate detail or at a glance. Examples of common usages include retrieving precise information on exact flight path, GPS positions, altitude fluctuations and camera system activity. Nonetheless, welcome additions in subsequent incarnations of flight log viewing software would be greater implementation of analytical tools (e.g. quick calculation of parameter averages, minimums and maximums) and automated scripts (e.g. automatic retrieval and consolidation of all information necessary to georeference flight imagery).

Under favourable weather conditions, the autopilot is able to govern the CropCam with considerable precision and stability, although the effect of moderate to high winds will be discussed below in the context of deployability. Not once during the entire study did the aircraft stray from its programmed course. Though no quantitative analysis of autopilot performance was conducted, altitude accuracy was estimated at about 10 m on average based on examination of flight data logs. High degree of flight stability (yaw-pitch-roll) was ascertained through observation of the CropCam from the ground over the course of the entire study, though this information is also available in great detail in the flight logs. By and large, autopilot performance was not deemed a significant obstacle to repeating flights with suitable precision, instead being most hindered by inconsistent camera system performance as will be further discussed below. Finally, there was a general sense that flight stability gradually decreased over time due to accumulating wear and tear on the airframe, the details of which will also be discussed below.

Camera system and imagery processing

An adequate imagery or sensor system is a critical component of an effective UAV for wildlife research as it constitutes the ultimate data collection instrument from which results are drawn. The CropCam's camera system, primarily intended to capture digital still photos, is fairly simple in design and function, and while it proved to be sufficient for certain types of missions, it presents a number of limitations. The aircraft's payload placement (hanging from under the wing) and weight restriction (450 g) limits choice of camera to thin point-and-shoot consumer models which are evidently not designed with this type of specialized application in mind. Furthermore, unless technical modifications to the default setup are carried out, the camera must be compatible with the built-in infrared switch for remote triggering. The camera is fixed in a straight downward orientation and has no pan-tilt mechanism. MicroPilot recommends using Pentax Optio A-series cameras for best results, two of which (the 8-megapixel A10 and 12-megapixel A40) were employed over the course of this study. Due to the light weight of these models (150 g), it is also possible to modify the CropCam's airframe to accommodate a second camera under the opposite wing, for example to shoot photo and video simultaneously, though the extra bulk reduces maximum flight time.

While image quality and spatial resolution is theoretically a simple function of flight altitude and camera focal length, sensor size and pixel count, results in practice are subject to several additional factors. First, the capacity of the camera to maintain focus while in motion imposes a lower altitude limit, estimated at about 80 – 120 m, below which the area photographed moves too fast in relation to the camera for achievement of proper focus. Perhaps more importantly, the need in most cases to have some overlap between successive photos (thus ensuring there are no “gaps” in the imagery) fixes the lower altitude limit at about 120 m. Below this elevation, the camera is unable to shoot at a sufficient rate to capture overlap between photos, the area footprint of which diminishes with decreasing altitude.

Second, photo quality also exhibits varying degrees of inconsistency, which can be exacerbated by weather conditions. Blurry or out-of-focus photos are often the result of the aircraft’s stability being momentarily compromised while shooting, for example by hitting a gust of wind or a thermal. For this reason, windier conditions generally lead to a higher proportion of blurry photos. Focus is also affected by ambient light, such that sunny conditions with clear skies tend to yield higher quality photos than cloudy or overcast conditions. Third, throughout all missions flown by the CropCam over the course of the study, there was a consistent issue with programmed photos being skipped altogether, seemingly at random. In any given flight, anywhere from 0 – 20% of photos would be skipped, averaging about 5 – 10%. Despite numerous consultations with MicroPilot’s support team, the source of the issue could not be identified.

The aforementioned inconsistencies turned out to be the CropCam’s most important shortcoming with respect to accuracy and repeatability of data collection. In practice, the Pentax Optio A40 did not appear to deliver noticeable performance gains over the A10, though the former’s usage was short-lived. A UAV capable of housing a higher-performance camera, or the future advent of higher-performance sub-compact cameras, would likely yield improvements on the majority of the above drawbacks.

When the camera system delivered at its full potential, image quality was nonetheless promising, though certain limits were revealed. In a preliminary trial conducted in Surrey (BC), the CropCam captured shots from an altitude of 120 m of an active bald eagle (*Haliaeetus leucocephalus)* nest containing nestlings atop an electrical tower (Figure 1). While the nest itself and both perched parent eagles were visible in the images, the main of objective of the trial, i.e. to count the nestlings, could not be achieved due to inadequate resolution. The camera system was also successful in detecting a beaver (*Castor canadensis*) food cache (Figure 2) from a 300-m altitude in the Huntington Wildlife Forest (Adirondack Park, NY), as well as Canada geese (*Branta canadensis*), snow geese (*Chen caerulescens*), black bears (*Ursus americanus*), woodland caribou (*Rangifer tarandus*), white-tailed deer (*Odocoileus virginianus*) and grey wolves (*Canis lupus*). Detection of the latter six species will be covered in further detail in the following chapters. On the whole, ability to discern subjects in photos is a function of both their size and contrast with the surrounding ground area.

Finally, post-processing of imagery globally was not as straightforward as was initially expected. In theory, the CropCam's flight log files contain all necessary information (camera shutter timing, GPS headings and positions, altitude and yaw-pitch-roll data) to stitch together and georeference a sequence of partially overlapping photos taken during a flight. A separate application is included in the CropCam software package which is supposed to automate this process, however it could never be made to function properly. Instead, stitching and georeferencing turned out to be a much more approximate and time-consuming procedure. While there are software applications capable of stitching photos together automatically (e.g. Adobe Photoshop, AutoStitch), a quality stitching job requires manual identification of matching points in overlapping photos using a program called PTGui, which can take several hours depending on the total number of photos and desired level of precision. The resulting panorama is then georeferenced by manually pinpointing coordinates taken directly on site with a handheld GPS receiver or from a pre-existing map. The counting of animal subjects in CropCam imagery will be discussed in depth in the following chapters.

Deployability

Portability of the CropCam and its accessories is one of the major strengths of the system. The entire aircraft can be made to fit into a rugged hunting rifle case for easy transport and safe storage. The minimum required suite of field accessories (laptop, radio modem, cables, R/C transmitter, basic repair supplies, up to 4 + sets of batteries for back-to-back flights) can be carried in a medium-size backpack, in addition to the portable power supply equipped with a carrying handle. It is therefore possible, though not undemanding, for a single person to transport the whole system on foot, as well as entirely handle onsite setup and operation. The addition of a field mate overall facilitates and streamlines transport, setup and operation. For long-range travel, the UAV and full set of accessories (add: chargers, spare parts, complete repair kit) can fit into an economy-size vehicle. For multi-day missions in remote areas without a nearby source of electricity, an additional portable gas generator would be required to recharge batteries, power supply and other electronic devices.

The whole setup process can be divided into flight programming and on-site setup. While is it sometimes possible to program flights far in advance of missions, other times certain determining details can only be assessed once immediately on site (e.g. exact location of a group of animals). The time required to program a flight can range from 10 – 30 min depending on course length and complexity. On-site setup is fairly simple and can usually be accomplished in 10 – 15 min with the aircraft ready for launch. Though the CropCam's setup time is already fairly acceptable, improvements are certainly possible with refinements to flight programming and aircraft assembly (e.g. by using snap-on modules).

The method of launching could not be easier: essentially throwing the plane into the air and allowing the autopilot take over from there. However, two launching issues were encountered during the study. First, the 2.75-kg aircraft requires a minimum amount of momentum to initiate takeoff, hence the need to take a short running start before thrusting the plane into flight. Some headwind actually aids in the aircraft's initial climb, and under very low wind conditions it sometimes struggled to ascend, requiring more space to gain safe altitude and on rare occasions coming dangerously close to falling back down. Second, the autopilot's straight-line-ascent safety feature seemed to intermittently stray from calibration, the worst occurrence of which resulted in the plane immediately banking nearly 90 degrees upon takeoff and crashing into a tree directly to the side, effectively terminating launch.

The CropCam's operational footprint is extremely minimal when compared to the full-size manned aircraft often called upon to survey wild animals, where disturbance of subjects can sometimes interfere with the process and/or bias results (Mosbech and Boertmann 1999; Southwell 2005). The small electric motor is barely audible from the ground when the aircraft reaches cruising altitude (120 m and above). Above 300 m, the aircraft becomes completely inaudible and quite difficult to spot from the ground. No animals surveyed over the course of this study appeared to exhibit any reaction to the UAV's presence. These include typically aggressive nesting bald eagles (Buehler 2000) on a tower no more than 90 m below and geese 180 m below to which the plane's appearance might be speculated to resemble a soaring eagle, their main predator on staging grounds (Mowbray et al. 2000; Mowbray et al. 2002). Furthermore, the aircraft carries no fuel, thus eliminating gas emissions as well as risk of combustion and fire in the event of a crash.

Though maximum flight time is formally evaluated at 45 – 55 min, experience with the CropCam led to a precautionary time limit of 30 – 40 min when programming flights. This is because a number of factors can potentially curtail its functional flight time and a certain guaranteed "safety buffer" is of great reassurance to the ground operator. A first example is the occasional need to abort a landing approach, climb back up in altitude and start over, which puts an additional strain on the batteries. Wind can also considerably reduce endurance as well as compromise flight stability, with noticeable effects above 20 km/h and serious risk above 30 km/h. Battery technology has undergone rapid advancement in recent years and will likely continue to deliver increasing stamina in the near future. While the CropCam is fully capable of carrying out missions beyond the ground station's transmission range (max. 3 km), in practice loss of signal link with the aircraft is highly stressful (and ultimately unsafe) for the operator, who loses all means of monitoring or intervening with the system. These constraints effectively limit the CropCam's functional range, precluding missions in locations where deployment sites may be sparse or far from survey areas of interest. Any precipitation also prohibits operation due to risk of short-circuiting the aircraft's internal electronics. An impermeable fuselage as well as a design able bear up against stronger winds would represent desirable features for a wildlife research UAV.

Finally, the CropCam's single most important impediment with regard to deployability is landing, which also constitutes the most daunting aspect of operation and the most difficult to learn. Secure landing requires an expansive open area with a minimum unobstructed approach space of 75 – 100 m. A mild constant headwind is ideal for helping to slow down the plane on approach, while a tailwind has the opposite effect and a crosswind and/or gusts make steering more challenging. Suitable landing surfaces essentially restrict deployment sites to man-made fields or the odd meadow, practically ruling out operation in remote locations (e.g. forests) where many potential wildlife-related applications are expected to be concentrated. Initial difficulties with manual landings led to frequent damage to the airframe on touchdown, and though skills progressively improved with experience, the exercise still felt stressful and not fully mastered even after 2 years.

Overly treacherous landing conditions led to complete abandonment after just one flight of what was to be the CropCam's first trial mission surveying pre-winter beaver activity in the Huntington Wildlife Forest. Substantial time and effort was invested in attempting to devise alternate landing options for the CropCam, including the attachment of skids underneath the airframe to enable touchdown on asphalt, gravel or dirt roads, and the construction of a portable net to catch the plane. Neither of these solutions proved to be reliable. On the whole, this study has clearly highlighted the need for an effectual wildlife research UAV to boast superior ease and versatility of landing. Ideally, landings should be entirely autonomous and able to be safely carried out in confined spaces as well as on a wider variety of surfaces. This might call for a more robust airframe that can withstand rough and imprecise touchdowns, a deployable parachute mechanism, the ability to land on water, or vertical take-off and landing ability, all of which have already been achieved in various other existing UAV systems, though the virtual totality of these are more expensive than the CropCam.

Maintenance and repair

Throughout the study, the CropCam necessitated steady maintenance and repair both in the field and in the workshop. While certain initial repairs were to damage caused by beginner's inexperience, the plane also experienced ongoing wear and tear accumulated during normal use as well as damage due to sporadic mishaps. The operator must possess basic workshop skills to successfully repair, maintain and modify the CropCam.

Nylon wing and rudder bolts weaken and break over time and need regular replacement. The PVA sheeting covering the wings is subject to tears and detachment at the seams which must be mended with CA glue or special adhesive sheeting. Rudder hinges can suffer damage on landing and require repair or replacement. Winglets are prone to snapping off and must be rejoined with epoxy. The carbon fibre plastic propellers can fracture if struck, necessitating replacement ($15 per set). Repeated landing impacts also create and aggravate cracks in the fuselage which must be periodically patched with epoxy. The repeated assembly/disassembly process can cause delicate internal wiring and connectors to break, requiring soldering or replacement. The finely positioned internal autopilot circuit board occasionally needs readjustment. Batteries are susceptible to erratically emerging defects and accidental spoiling, and represent among the most costly components to replace ($80 each). A total of 6 batteries succumbed to such failures over the course of the 2-year study. Also pricey is the replacement of cameras ($300 each), two of which were ruined over this study due to dirt getting into the completely unshielded lens on landings.

A number of one-time repairs and replacements were also necessary. Landing troubles brought about a complete tail fracture requiring major repair, as well as a complete nose fracture and detachment of a flap. The rudder and elevator were both replaced because of excessive wear (replacements donated by MicroPilot). The vulnerable exterior R/C antenna failed, requiring replacement of the entire receiver ($60). Finally, the airframe as a whole was judged to be on its last legs by the end of the study, after approximately 140 total flights, and a complete replacement was ordered from MicroPilot to carry on future work (airframe, autopilot instalment and calibration: $3,544.21).

Altogether, the CropCam is more damage-prone and requires more laborious maintenance than is acceptable for an efficacious wildlife research UAV. A minimum amount of regular service may be inescapable in practice, but a large proportion of the aforementioned damage and wear could be averted with an overall more robust airframe offering better protection for costly onboard parts such as batteries, camera and radio receiver. Moreover, the primary cause of damage, manual aircraft landing, could be attenuated by an autopilot system capable of high-precision, fully autonomous landing.

Conclusion

MicroPilot's CropCam consumer UAV system was evaluated over a span of 2 years as a potential data collection instrument for wildlife aerial surveys. Its main advantages were found to be relative affordability, overall decent interfacing software, generally reliable autopilot performance, good portability, fairly timely setup and launch, and minimal footprint and disturbance levels during operation. Its main disadvantages were steep training requirements, limited camera system in performance and functionality, laborious image post-processing, restricted deployability with regard to sites, weather and tracking range, challenging and costly landings, and high maintenance requirements. In comparison with the FoldBat UAV system used by Jones et al. (2006), the CropCam has more powerful programming options and interfacing software, is lighter and easier to launch, and features a more reliable, easier to operate and greener engine. However, it suffers from similar difficulties with landings and imagery post-processing, and has a more limited camera payload capacity than the FoldBat.

The CropCam has been demonstrated to be suited for relatively short-range missions where adequate deployment sites are present and study subjects or features of interest are fairly visible from above (unconcealed, distinguishable contrast and no smaller than large birds). Examples of suitable practical applications include habitat mapping and small-scale animal head counts or sampling censuses in reasonably accessible areas. However, the UAV is not suited for long-range flights, missions in remote areas with restricted open ground space, or flexible operation in relation to weather conditions.

A number of desirable improvements have been identified for future implementation of UAVs for similar wildlife research endeavours. The airframe should be considerably robust, weather-resistant and composed of easy-to-assemble snap-on modules. The system should possess flexible deployment site options, greater ground control tracking range (e.g. > 5 km) and would benefit from longer flight endurance (e.g. > 1 hr). All aspects of flight should be fully autonomous in all circumstances. Flight programming should be simpler and entirely graphical, and analysis more powerful. Aerial data collection would profit from a high-performance pan-tilt camera system presenting expanded live control features such as streaming video to the ground control station and remote pan-tilt. Finally, there is a need for improved imagery post-processing assistance and automation, in particular with respect to georeferencing.

In the end, it is important to note that this class of product is a prime example of getting what one pays for. There are already UAVs in operation which fulfil all of the above criteria, though they currently either retail at many times the price of the CropCam or are not readily accessible for civilian use. While more advanced systems may already represent an affordable option for certain bigger-budget wildlife research projects, the hope is that increasing consumer-level sophistication and impending expansion of the civilian UAV market will eventually, if not soon, place such systems within the reach of smaller-scale studies where budgets are typically restricted.

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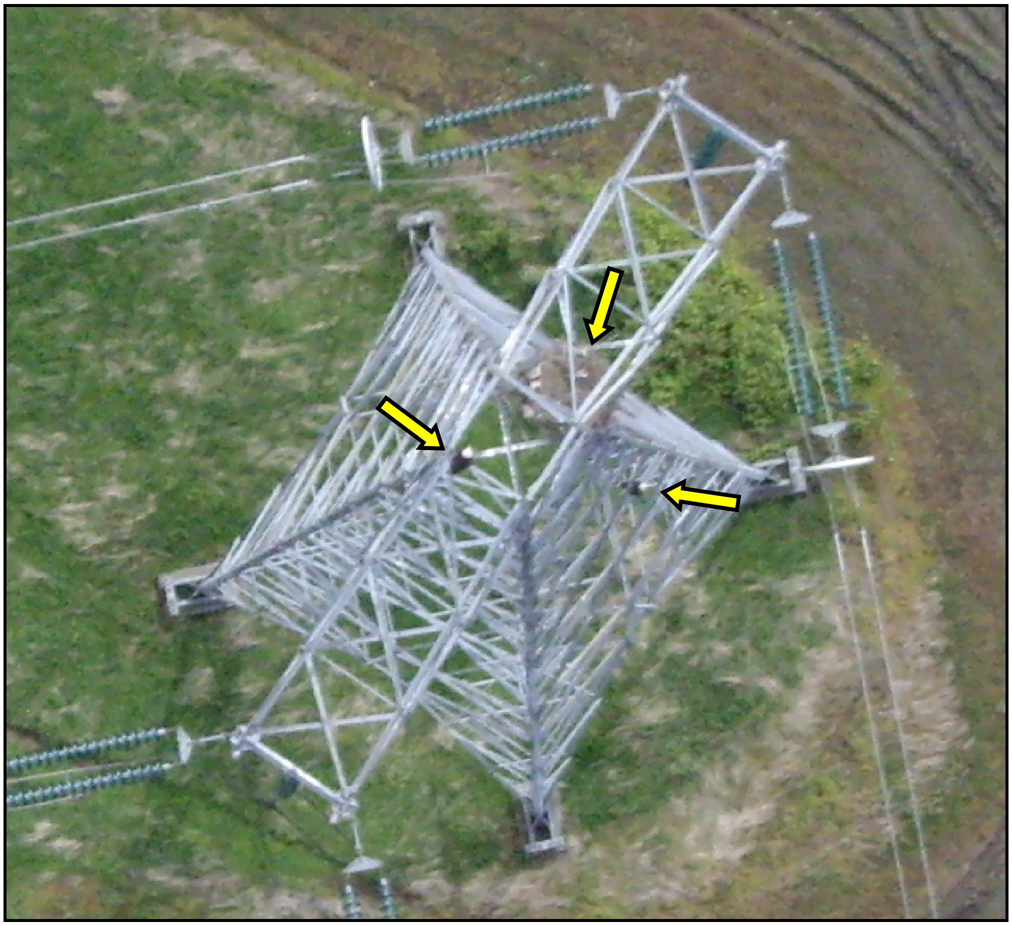

Figure 1 – Sample UAV image of 2 perched bald eagles and nest atop an electrical tower in Surrey, BC.

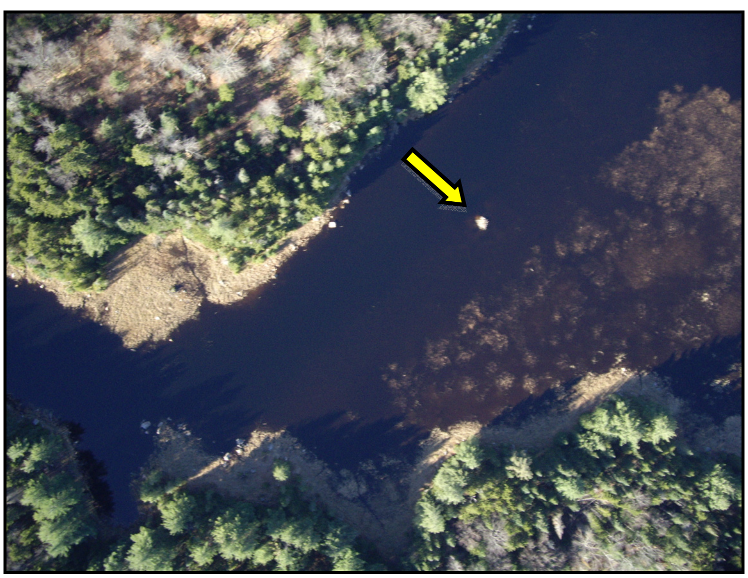

Figure 2 – Sample UAV image of a beaver food cache on Adjidaumo Flow in the Huntington Wildlife Forest of Adirondack Park, NY.

CONNECTING STATEMENT

This study's main instrument of focus, the CropCam UAV system, was detailed in chapter 1 and appraised on the whole in chapter 2 as a capable tool for wildlife-related research tasks. Now adequately acquainted with, the following chapters will focus on the CropCam's measured performance in specific trial missions, beginning with surveys of staging flocks of geese in chapter 3.

CHAPTER 3 – Comparison of a basic UAV system with ground-based visual counts for surveying waterbird flocks

Abstract

Waterbird population surveys, often performed by aircraft, are crucial components of species management and ecosystem monitoring initiatives worldwide. Nevertheless, heavily relied-upon aerial surveys are expensive, can suffer from inaccuracy and/or impose disturbance of potential consequence upon bird subjects. Emergent unmanned aerial vehicles (UAVs) promise to become a new option for performing waterbird surveys, potentially reducing costs, improving accuracy and alleviating disturbance all at once. In this trial, the CropCam UAV system was evaluated for its accuracy and precision in obtaining head counts of staging Canada and snow geese flocks (*Branta canadensis* and *Chen caerulescens*), as compared to ground-based counts. A significant discrepancy was found in the system's performance between the two species. Whereas the relatively inconspicuous appearance of Canada geese in UAV imagery rendered counts generally inaccurate and highly imprecise, it was the opposite for snow geese, which were exceedingly visible in imagery. In addition, the aircraft was found to cause no apparent disturbance upon flocks. Further investigations should be undertaken into using UAVs for waterbird research and management.

Introduction

Population surveys of waterbirds have long been considered an important practice, historically for hunting interests, but nowadays more so for purposes of ecosystem monitoring and species conservation. In the last 50 years, aerial surveys by fixed-wing planes or helicopters have become a hallmark of these surveys since they allow rapid extensive coverage, as well as access to key areas such as wetlands that may be unreachable for ground-based surveys (Kingsford and Porter 2009). Aerial surveys of waterbirds have been used to study breeding parameters such as distribution (Noel et al. 2004), habitat selection (Slattery and Alisauskas 2007) and nesting success (Bromley et al. 1995), monitor migrations (Glahder 1999; Chaulk and Turner 2007; Fleskes and Yee 2007) and assess ecosystem health (Kingsford 1999). In addition, they have played a pivotal role in large-scale estimates of waterbird population sizes and temporal trends in many regions of the world (Kingsford et al. 1999; Bechet et al. 2004; Blohm et al. 2006; Austin et al. 2007).

The principal drawbacks of waterbird aerial surveys are threefold. First, though they may be viewed on the one hand as a cost-efficient survey method in relation to the area covered, the bottom-line cost and effort of conducting aerial surveys remains steep. Aircraft are expensive to purchase, operate or even charter, placing them beyond the reach of budget-constrained research that could potentially benefit from aerial surveys, and ultimately limiting the total coverage or frequency of surveys in studies that already make use of them. Second, low-altitude aircraft are known to provoke disturbance upon birds during surveys (Mosbech and Boertmann 1999; Southwell 2005). Not only can this complicate or bias counts if a flock is flushed by an approaching survey aircraft, but it might impose genuine stress upon birds, potentially interfering with normal behaviour or affecting breeding success (Miller et al. 1994). Third, and perhaps most consequentially, aerial surveys of waterbirds suffer from the same inherent lack of precision and accuracy as most other wildlife aerial surveys. An array of factors – including high aircraft speed, differences in acuity between observers, behaviour of subjects and endless varying influences on their visibility– add up to bring statistical robustness of waterbird aerial surveys into question, as evidenced by the amount of literature on this topic (e.g. Bromley et al. 1995; Gabor et al. 1995; Boyd 2000; Rodgers et al. 2005; Laursen et al. 2008).

These types of surveys are a key area of possible interest for the use of unmanned aerial vehicles (UAVs). Small autonomous UAVs might be able to carry out accurate and closely repeatable aerial photography or videography surveys virtually unnoticed by birds on the ground at a fraction of the cost to operate or charter full-size aircraft. They may prove to be a simple, efficient and inexpensive alternative to manned aircraft for small-scale surveys (or large-scale surveys that can be broken down into smaller increments) or sampling surveys of large populations. In addition, they might represent an attractive new choice for countless censuses that currently cannot afford the option of aerial surveys. Jones et al. (2006) were the first to publish preliminary results on the ability to detect waterbirds using a UAV. Their aircraft's video camera successfully captured imagery of white ibises (*Eudocimus albus*), wood storks (*Mycteria americana*) and a variety of egrets (*Egretta* spp.) in wetland impoundments.

In the present trial, the CropCam UAV system was evaluated for its capacity to detect as well as yield reliable head counts of two locally common species of geese: the Canada goose (*Branta canadensis*) and the snow goose (*Chen caerulescens*). Small flocks (< 500 individuals) of the former were opportunistically surveyed as they made stopovers during spring migration in the agricultural fields of the McGill University Macdonald Campus Farm (Ste. Anne de Bellevue, QC). The latter were surveyed at a major migratory staging ground in the rural farming community of Baie-du-febvre, QC, where hundreds of thousands of geese currently make stopovers each year and aerial population surveys have been conducted annually since 2000 (Bechet et al. 2004). By comparing results with simultaneous ground-based visual counts, the aim was to obtain an empirical estimate of the accuracy and precision (i.e. variability) of UAV surveys for each of the two species.

Methods

Field methodology

Flocks of Canada geese were surveyed, weather permitting, during the period spanning 5 May – 9 May 2008, inclusively. Aerial surveys were carried out by the CropCam while a field assistant simultaneously performed ground counts from an appropriate vantage point using a scope and a handheld mechanical counter. The ground surveyor and UAV operator were equipped with walkie-talkies to synchronize and communicate. An individual survey consisted of the UAV flying a certain number of repeated sweeps (min. 2; restricted by battery capacity), each a series of advancing back-and-forth transects, over a flock of geese at an altitude of 180 m while the ground surveyor completed as many repeated head counts (min. 2) as could be managed during the same span of time. The latter was also charged with recording any new arrivals or departures of individuals over the course of surveys, as well as documenting any perceived reactions of the geese towards the UAV. Six surveys (S1 – S6) were performed in total on 4 separate days between the hours of 10:30 AM and 3:30 PM local time, totalling 23 ground head counts and 20 UAV sweeps. Size and precise location of surveyed flocks varied from day to day, thus UAV flight path and deployment location (min. 200 m from geese) and ground surveyor position had to be adjusted in consequence.

Snow geese surveys were conducted on 20 May 2008. A pair of repeated UAV flights at 180 m were completed back-to-back between 11:00 AM and noon. The aircraft was deployed from a farm field approximately 500 m southeast of the survey site and the flight trajectory (a single sweep of advancing back-and-forth transects) covered 2 discrete flocks of geese, one larger and one smaller. Thus, a total of 2 head counts of each flock could be tallied from the UAV imagery. Since the former flock initially appeared too large to count from the ground, the ground surveyor kept to repeated head counts (4 in total) of the latter flock only, in the same way as described above for Canada geese. A ground count of the larger flock was attempted subsequent to UAV surveys but aborted early on when the flock lifted off and left the area.

UAV imagery processing

For all surveys, the UAV's camera system was programmed to capture sequences of partially overlapping still photos over each transect flown. Photos were viewed in succession and scanned for visible geese using Adobe Photoshop v11.0. Total head counts were tallied on a sweep-by-sweep basis (i.e. one full count per sweep) while being mindful not to double-count subjects in overlapping portions of photos. The sharp colour contrast between individual snow geese and the ground made it possible to use the colour range selection tool to automatically select all geese over an entire photo or specified area within a photo. Then the total number of selected individuals was computed automatically. Canada geese, however, did not sufficiently contrast with the ground to employ this method directly, instead requiring that they first be manually marked to allow automatic selection and count. Moreover, their poor contrast and variation in photo quality made them often difficult to discern with certainty. Therefore, a lower/upper count approach was applied for this species, whereby sure sightings were marked red while unsure sightings, when potential subjects were perceived but unable to be validated with certainty, were marked yellow. Lower counts were tallied from total red marks only, while upper counts additionally included total yellow marks.

Data analysis

Analyses were performed using SPSS Statistics v17.0. A critical significance level of $\alpha = 0.05$ was used for all statistical tests. Within each survey, repeated head counts were pooled for each survey method. Due to small sample sizes, non-parametric tests were used to compare mean counts between survey methods. For Canada geese, counts by the 3 methods (ground count, UAV lower count and UAV upper count; hereafter abbreviated *GRND*, *UAV-L* and *UAV-U*) were first compared within surveys with Kruskal-Wallis one-way analyses of variance. If significant differences were found, pairwise comparisons were performed with Mann-Whitney U tests to determine which methods differed. For snow geese, the 2 methods (*GRND* and *UAV*) were directly compared using a Mann-Whitney U test. For both species, pairwise F-tests were used to compare variances between methods in each survey.

Global comparisons between survey methods across all Canada geese surveys were conducted for head counts and variability in counts. In each survey, pairwise mean count ratios between methods were calculated: *UAV-L*:*GRND*, *UAV-U*:*GRND* and *UAV-L*:*UAV-U*. These ratios were then pooled across all surveys and tested for significant deviation from a 1:1 ratio using one-sample t-tests. For comparison of within-method variability, sums of squares (SS) from each method were pooled across all surveys in order to calculate their total variances (total $\text{Var} = \sum SS / \sum[n-1]$) and compare them with F-tests. This was feasible despite underlying independence of surveys because results for the different methods could be considered to match up within each individual survey, thereby maintaining global parity. Prior to pooling, two randomly chosen ground counts from Survey 2 and one from Survey 5 were removed from the dataset and sums of squares of remaining counts recalculated because total number of ground counts exceeded UAV counts in these surveys, potentially causing bias in the total pool.

Results

Canada geese

Survey results are summarized in Table 1 and mean head count comparisons between methods are illustrated in Figure 1. Mean counts differed significantly between survey methods in 3 out of 6 surveys (S3: $\chi^2_2 = 8.028$, P = 0.018; S4: $\chi^2_2 = 8.056$, P = 0.018; S5: $\chi^2_2 = 6.175$, P = 0.046). The mean *UAV-L* count was inferior to the mean *GRND* count in 5 out of 6 surveys (all but S1), and significantly so in 3 surveys (S3: $U_{4,4} = 0.0$, P = 0.029; S4: $U_{4,4} = 0.0$, P = 0.029; S5: $U_{4,5} = 1.5$, P = 0.032). Moreover, the single highest *UAV-L* head count was inferior to mean *GRND* count in all but S1. Mean *UAV-L* count was also significantly lower than mean *UAV-U* count in 2 surveys (S3: $U_{4,4} = 0.0$, P = 0.029; S4: $U_{4,4} = 0.0$, P = 0.029). Mean *UAV-U* count was higher than mean *GRND* count in 3 surveys (S1, S2 and S5) and lower in the remaining 3, though differences were never significant.

Analysis of mean count ratios between methods across all surveys initially revealed an overall significant difference only between *UAV-L* and *UAV-U* ($t_5 = -3.173$, P = 0.025), however *UAV-L* was significantly lower than both other methods (*GRND*: $t_4 = -3.235$, P = 0.032; *UAV-U*: $t_4 = -3.247$, P = 0.031) if S1 was removed from the dataset. S1 was the only survey in which both UAV counts exceeded the ground count, and it was later realized that certain portions of the flock detected by the UAV were likely out of visual range from the ground surveyor's vantage point during that survey, possibly accounting for the unexpected discrepancy. During the survey, no birds were observed arriving in or leaving from the flock nor were there any major movements within it. Nevertheless, since there is prior evidence of live visual counts increasingly underestimating numbers in relation to photo counts with growing flock size (Boyd 2000), ground surveyor bias cannot be entirely ruled out, hence the presentation of both sets of results above. There was no overall significant difference between *GRND* and *UAV-U* counts with or without S1 in the dataset.

In all surveys except for S1, variance within *GRND* counts was significantly lower than variance within both *UAV-L* (S2: $F_{1,3} = 91.553$, P < 0.01; S3: $F_{3,3} = 34.309$, P < 0.01;

S4: $F_{3,3}$ = 367.831, P < 0.01; S5: $F_{3,4}$ = 94.598, P < 0.01; S6: $F_{3,3}$ = 197.340, P < 0.01) and *UAV-U* (S2: $F_{1,3}$ = 17.191, P < 0.05; S3: $F_{3,3}$ = 88.982, P < 0.01; S4: $F_{3,3}$ = 508.016, P < 0.01; S5: $F_{3,4}$ = 49.671, P < 0.01; S6: $F_{3,3}$ = 137.592, P < 0.01). Variance did not differ significantly between the two UAV count methods in any individual surveys. The same pattern held with global comparisons of variability, as overall *GRND* variance was significantly lower than overall variances for both UAV count methods (*UAV-L*: $F_{14,14}$ = 14.882, P < 0.01; *UAV-U*: $F_{14,14}$ = 9.115, P < 0.01), though the latter did not differ significantly from each other.

Snow geese

Head counts of 5076 and 5620 (mean = 5348; std error = 272.000; std deviation = 384.666) were obtained for the larger flock of geese in the first and second sweep by the UAV, respectively. It should be noted that the camera system missed a programmed photo over the larger flock during the first sweep, thus creating a gap in the imagery that may account for a portion of the discrepancy between the repeated counts. *UAV* head counts for the smaller flock were 1172 and 1250 (mean = 1211; std error = 39.000; std deviation = 55.154), while simultaneously tallied *GRND* counts were 818, 923, 754 and 729 (mean = 806; std error = 43.269; std deviation = 86.537). Comparison of counts between survey methods is illustrated in Figure 2. Though mean *UAV* count was 50% higher than mean *GRND* count, and both *UAV* counts were superior to the single highest *GRND* count by 27% and 35%, respectively, differences were insufficient to obtain a significant result in a non-parametric test with such small sample sizes ($U_{2,4}$ = 0.0, P = 0.133). Likewise, the F-test to compare variances between survey methods was restricted by an extremely large critical value ($F_{3,1}$ = 215.707), therefore no significant difference was found.

Discussion

This trial aimed to assess ability to obtain accurate and precise head counts of Canada geese and snow geese in aerial photographic imagery gathered by the CropCam UAV system. UAV survey results were contrasted with ground-based surveys to evaluate relative count accuracy and variability.

The UAV revealed itself to be largely ineffectual for surveying Canada geese, as conservative (lower) head counts consistently underestimated flock sizes when compared with seemingly precise (evidenced by relatively minimal variability) ground counts, and in several surveys significantly so even despite small sample sizes for repetition of counts. Though upper head counts from the UAV imagery were more on par with ground counts, their differences from lower counts were obtained by making repeated guesses that may be greatly arbitrary with regard to the observer. Furthermore, substantial variability from one sweep to the next was pervasive in both UAV count methods and their global variance was greater than that of ground counts to a level of significance below 1%, thereby seriously compromising the precision of the technique.

The underlying issue affecting UAV counts of Canada geese was their visibility in the imagery. From an altitude of 180 m, they appeared as nondescript darkish specks on the ground (Figure 3). Depending on their posture and crispness of photos, it was sometimes possible to discern more individual detail, such as the contrast between the black head and light-coloured breast. Sightability of individuals was heavily influenced by the ground surface type and to what extent it contrasted with the geese. They were very challenging to detect over shallow water (which appears very dark and often speckled with glare), moderately so over mud and dirt, and easiest over grass and vegetation (the lighter green the better). In all situations, they were even more difficult to spot when photos turned out blurry, which occurred on a frequent basis. Finally, no ground surface provided sufficient contrast with Canada geese to take advantage of automatic selection features which virtually eliminate the need to scan photos and identify individuals manually, thus greatly reducing time and effort required.

While it is possible that lower altitude flight (e.g. 120 – 150 m) might increase visibility of Canada geese in photos, it is doubtful that the improvement would be very significant, and the resulting diminished footprint of individual photos would in turn reduce the efficiency of surveys by requiring that more transects be flown to cover the same ground area. Prior to commencing the trial, two explorative surveys were performed with the camera in video mode, though individuals were found to be even harder to detect using this technique. Potential solutions to poor Canada geese visibility in aerial photos might be to use a considerably higher performance camera capable of superior resolution and focusing ability, or an infrared thermal camera capable of detecting individual heat signatures of geese, though this technique was previously found to be ineffective for wild turkey (*Meleagris gallopavo*) (Locke et al. 2006). More sophisticated image-analysis software might additionally be of aid, as has previously been explored for automating wildlife photographic counts (Laliberte and Ripple 2003).

Contrary to Canada geese, snow geese were revealed to be highly visible in aerial imagery gathered by the CropCam from 180 m in altitude (Figure 3). As with the white wading birds recorded by Jones et al. (2006), this is due to their sharp contrast with the muddy ground, which was sufficient to single them out even in noticeably blurry photos, with the only exception of water surfaces where bright specks of glare could occasionally be confounded with geese. So easy are they to discern that some leeway may even be available to increase flight altitude and therefore improve survey efficiency. Importantly, their pronounced contrast allowed for completely automated selection and counting of individuals in all photos. The accuracy of this feature was judged to be remarkably high following multiple close-up inspections of photos after automatic selection had been applied to scan for any unselected individuals. While unselected individuals were extremely rare, glare on water surfaces would occasionally be selected and require manual exclusion. It is also relevant to note that blue morph snow geese were distinguishable from the rest, which might be of interest for performing accurate estimates of their frequencies in migrating or wintering populations.

The sizable discrepancy (equal to 10% of the mean) between both counts of the larger snow goose flock is likely in large part due to a photo being skipped during the first sweep, resulting in a part of the flock being missing from the imagery. At the time of the trial, the approach used for programming the camera system consisted of taking a predetermined number of photos at regular intervals to ensure a fixed minimum amount of overlap between successive photos. An alternative approach was later discovered that enables photos to be taken in rapid continuous bursts, such that overlap is large enough to avert gaps in the overall imagery even if single photos are skipped. This approach would be advantageous for future surveys of this sort. The reason for disparity between ground counts and UAV counts for the smaller snow goose flock is unclear, though it has previously been reported that live visual estimates of flock sizes might be biased low compared to photographic counts (Boyd 2000). The source of difference between the first and second UAV count is also unclear, though possible causes include new individuals joining the flock without being noticed by the ground surveyor or errors when tallying individuals in overlapping portions of photos.

A final noteworthy finding was the apparent absence of any reaction in both goose species to the UAV flying overhead throughout all surveys. At 180 m in altitude, the CropCam's electric motor is practically inaudible and the aircraft appears very small from the ground. Though geese may not be exceedingly vigilant on staging grounds due to relatively low predation rates (Mowbray et al. 2000; Mowbray et al. 2002), it was speculated that the aircraft might be perceived as a soaring eagle, their primary predator, though this appeared not to be the case. This finding may be of particular interest with regard to snow geese as flocks on the staging grounds in Baie-du-febvre do have a tendency of being flushed by full-size aircraft during surveys, consequently complicating counts (C. Hart, personal communication).

Conclusion

This trial has highlighted both strengths and limitations in the CropCam UAV system's ability to obtain head counts of waterbird flocks. If survey subjects are sufficiently visible from the air, in particular with respect to their colour contrast with the ground, the UAV has the potential to yield highly accurate censuses which additionally can be facilitated and enhanced by computer-automated counting tools. Moreover, surveys may be carried out without causing any disturbance to the birds and repeated multiple times at virtually no additional cost in order to enhance accuracy or monitor changes in flock sizes over time. On the other hand, considerable challenge, inaccuracy and imprecision may be encountered in the case of low-visibility subjects that tend to blend in with the ground surface. It is recommended that further investigations be undertaken into employing the CropCam or other similar UAV systems for surveying snow geese or any other species of colour-contrasting waterbirds.

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Table 1 – Summary of Canada geese survey results. * Denotes significant differences (P < 0.05) between survey methods.

	n	Mean count	Range	Std error	Std deviation
Survey 1					
GRND	2	296.50	27	13.500	19.092
UAV-L	2	366.00	58	29.000	41.012
UAV-U	2	412.00	6	3.000	4.243
Survey 2					
GRND	4	151.75	5	1.109	2.217*ALL
UAV-L	2	137.00	30	15.000	21.213*GRND
UAV-U	2	156.50	13	6.500	9.192*GRND
Survey 3					
GRND	4	95.50*UAV-L	4	0.866	1.732*ALL
UAV-L	4	57.75*ALL	19	5.072	10.145*GRND
UAV-U	4	92.25*UAV-L	35	8.169	16.338*GRND
Survey 4					
GRND	4	101.00*UAV-L	2	0.408	0.816*ALL
UAV-L	4	14.75*ALL	32	7.825	15.650*GRND
UAV-U	4	85.25*UAV-L	43	9.196	18.392*GRND
Survey 5					
GRND	5	88.60*UAV-L	5	0.927	2.074*ALL
UAV-L	4	60.25*GRND	49	10.086	20.172*GRND
UAV-U	4	90.50	31	7.309	14.617*GRND
Survey 6					
GRND	4	89.00	4	0.816	1.633*ALL
UAV-L	4	58.75	49	11.470	22.940*GRND
UAV-U	4	79.75	40	9.577	19.155*GRND

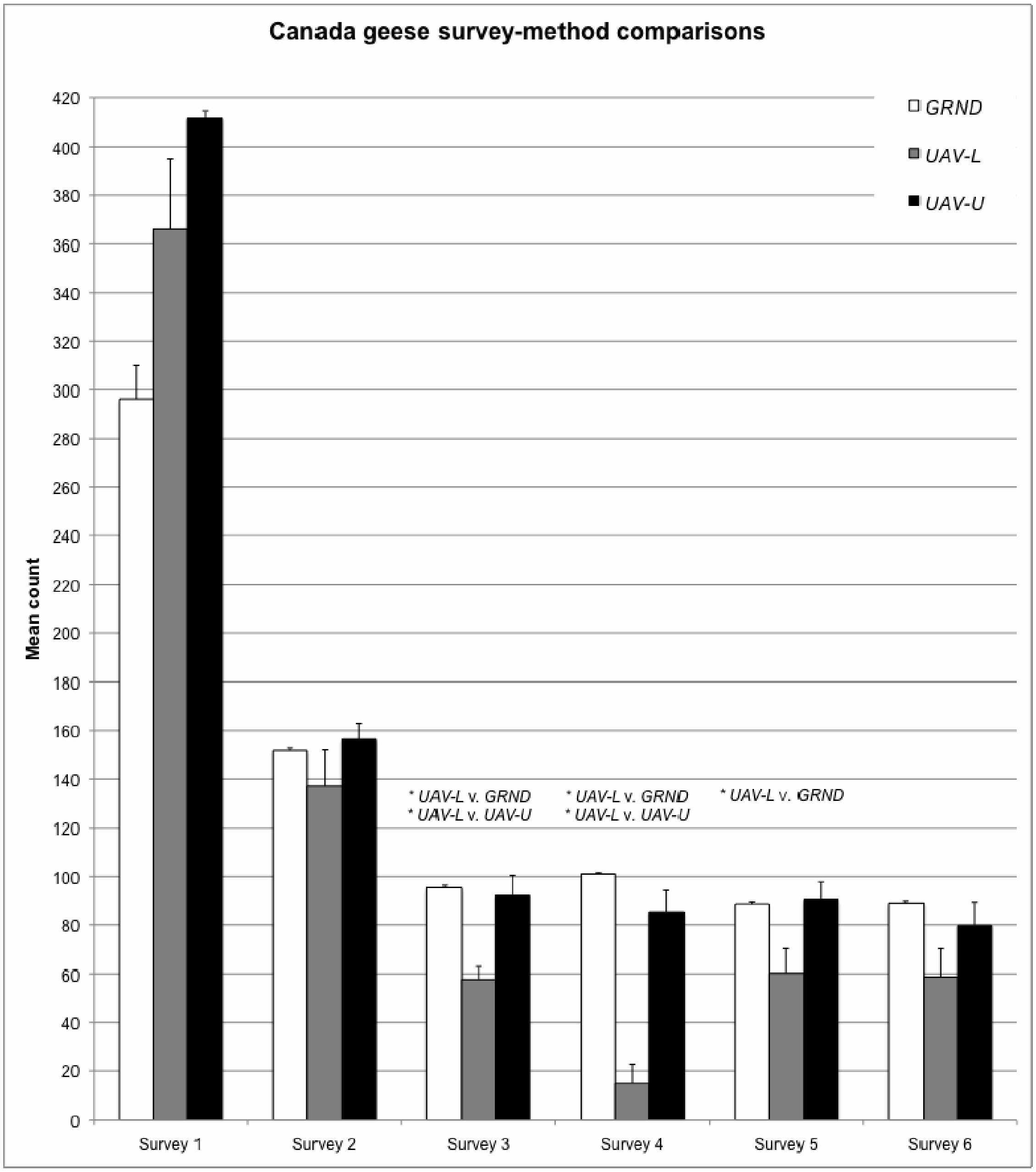

Figure 1 – Comparison of Canada geese mean counts between survey methods. *GRND* = ground count, *UAV-L* = UAV lower count, *UAV-U* = UAV upper count. * Denotes significant differences ($P < 0.05$) between methods.

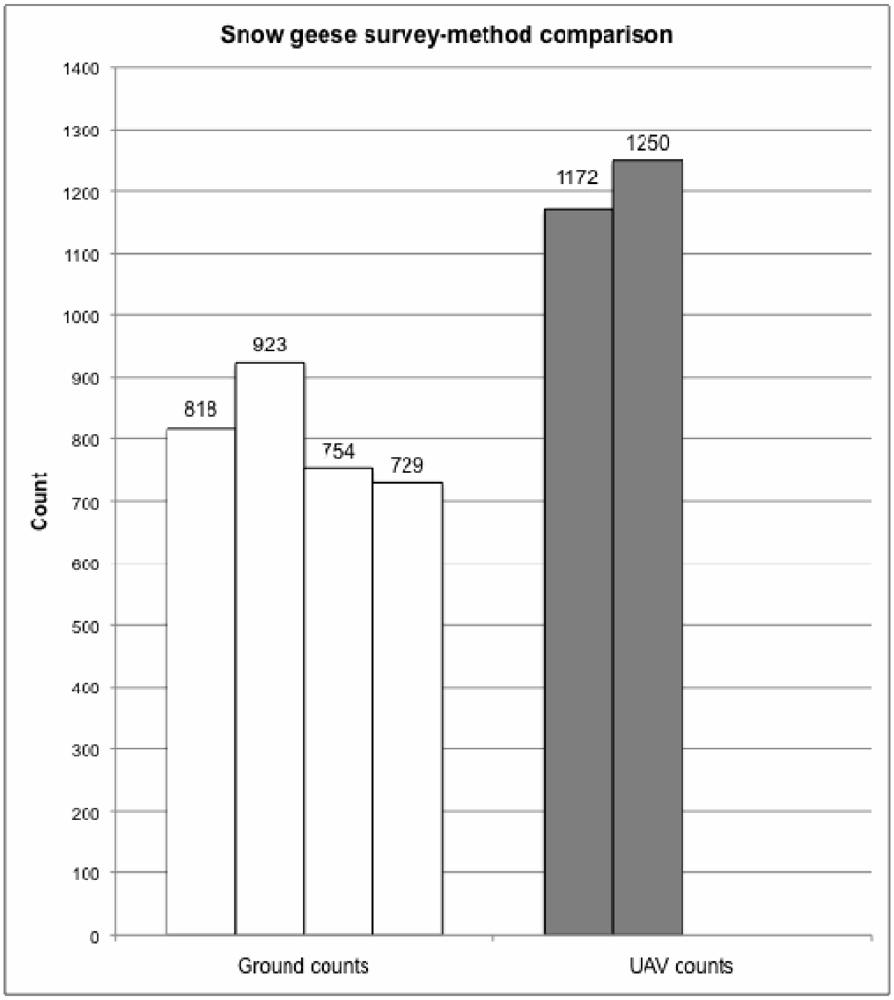

Figure 2 – Comparison of snow geese counts between survey methods.

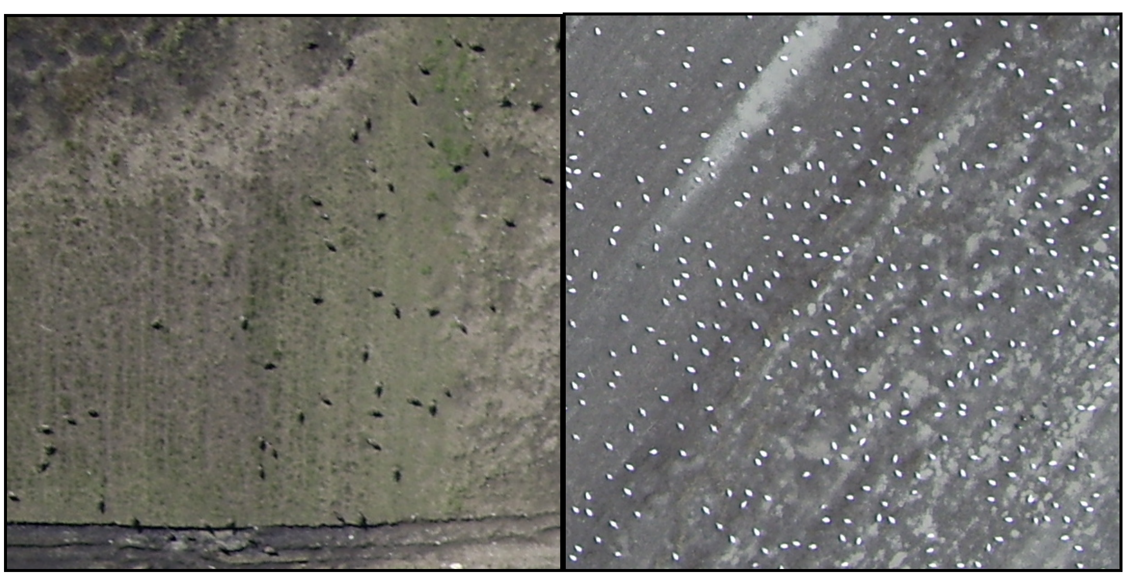

Figure 3 – Sample UAV images of Canada geese (left) and snow geese (right).

CONNECTING STATEMENT

As a first empirical trial of the CropCam UAV system's capabilities in a potential wildlife research application, chapter 3 centred on its performance in obtaining head counts of geese flocks. A second such trial is presented in chapter 4, as the CropCam is systematically evaluated for its ability to detect individual subjects from 4 species of wild land mammals situated within pseudo-natural enclosures.

CHAPTER 4 – Detectability of black bears, grey wolves, white-tailed deer and caribou in pseudo-natural enclosures using a basic UAV system

Abstract

Wildlife population surveys, employing countless different methods to gather information on abundance and distribution, need always have the issue of accuracy at heart. Unmanned aerial vehicles (UAVs) stand poised to develop into an attractive new instrument for a wide variety of animal surveys, thus there will be a need to understand and manage factors which may affect the accuracy of the data they collect. This trial presents a quantitative appraisal of the accuracy of the CropCam commercial UAV system at detecting subjects from 4 different mammal species – black bears (*Ursus americanus*), woodland caribou (*Rangifer tarandus*), white-tailed deer (*Odocoileus virginianus*) and grey wolves (*Canis lupus*) – contained within pseudo-natural enclosures, as well as an analysis of certain basic factors relating to their appearance and behaviour that bear measurable effects on their detectability by the UAV. Attributes favouring detection appeared to be a both large and contrasting body, a low affinity for shaded or concealed areas and frequent local movements. Further investigations are recommended into the feasibility of using UAV systems for wildlife population surveys.

Introduction

The capacity to accurately estimate wild animal populations is a pivotal requirement for sound and effective wildlife management. Countless different techniques are employed in efforts to obtain such estimates, depending on such factors as size, density, range, mobility and stealthiness of study subjects. Methods vary greatly in terms of scale, complexity and cost, from large-scale aerial surveys or radio tracking to smaller scale ground-based trapping or recording of tracks, or even assessment of hunting statistics. In all cases, method accuracy is an important question to consider since results can influence sensitive and consequential management decisions.

Emerging unmanned aerial vehicles (UAVs) may represent a novel avenue for conducting wildlife population surveys at varying scales, either as substitutes or supplements to full-size aircraft, or practical alternatives to various other census methods. Potential advantages offered by UAVs in relation to other survey techniques might include reduced cost, time savings, greater simplicity and improved accuracy. A preliminary qualitative assessment of the ability of a small video camera-equipped UAV to detect various wild animals was carried out by Jones et al. (2006). Their trials demonstrated some promise for eventual wildlife surveys by UAVs, as their aircraft successfully detected West Indian manatees (*Trichechus manatus*), American alligator (*Alligator mississippiensis*) decoys and a variety of white wading birds. In the present study, the CropCam UAV system was empirically evaluated for surveying 4 common land mammal species – American black bears (*Ursus americanus*), woodland caribou (*Rangifer tarandus*), white-tailed deer (*Odocoileus virginianus*) and grey wolves (*Canis lupus*) – in pseudo-natural captive settings at the St-Lawrence Valley Natural History Ecomuseum, an 11.3 ha non-profit educational wildlife park located in Sainte-Anne-de-Bellevue, QC.

Black bears in the wild are monitored for conservation, hunting as well as human-bear conflict purposes (Hristienko and McDonald 2007). Due to their relative sparsity and stealthiness, aerial surveys have generally not been used to census their populations. Leading monitoring techniques instead consist of passive methods such as deploying remote stationary cameras and baited track plates, hair snares and live traps, as well as active scat detection by trained dogs, radio tracking and collection of hunting harvest data (Kohlmann et al. 1999; Zielinski et al. 2005; Long et al. 2007; Matthews et al. 2008). Aerial surveys have been widely used, however, to monitor woodland caribou populations. Much attention has been focused on their recent declines (Courtois et al. 2003; Gunn et al. 2006), with numerous studies assessing potential negative impacts of human development (Vistnes et al. 2001; Noel et al. 2004; Weir et al. 2007) and others investigating more general aspects of their ecology (Fischer and Gates 2005; Fortin et al. 2008). Aerial methods have also been used – in addition to recording of tracks, roadside counts and hunting data – to survey white-tailed deer populations which, in contrast to caribou, have been steadily increasing lately and thus also require management plans (D'Eon 2001; Potvin et al. 2004; Drake et al. 2005; Pettorelli et al. 2007). Finally, a variety of techniques have been used to monitor grey wolves, recently reintroduced in several parts of North America and with a history of conflict with human interests. These include scanning for snow tracks, howling surveys, use of harvest data, radio tracking and aerial surveys (Joly and Messier 2000; Lariviere et al. 2000; Apollonio et al. 2004; Potvin et al. 2005).

In this trial, the aim was to obtain a quantitative appraisal of detectability and visibility of these species when surveyed with the CropCam commercial UAV system. *Detectability* is defined as the overall rate of subject detection in relation to total number of subjects present, which could be calculated precisely thanks to known numbers of animals in the park. In contrast, *visibility* is defined as the relative degree of certainty, or confidence, with which subjects can be recognized in UAV imagery. For example, it could be predicted that detectability will improve with increasing UAV survey altitude as the resulting enlargement of the imagery's area footprint would heighten the probability of spotting subjects. On the other hand, such an improvement could be offset by a concurrent degradation of subject visibility as they progressively appear smaller and become harder to recognize. This offset would gradually increase in magnitude, eventually causing detectability to peak and then begin to drop back down with rising altitude as subjects can no longer be reliably recognized. In addition to assessing visibility and detectability of subjects, this study aimed to record and analyze subject behaviours expected to influence these parameters, including relative mobility and affinity for shade and concealment. Data on these attributes were gathered by performing ground surveys on foot inside the park in synchronization with UAV surveys.

Methods

General

The study was carried out as weather and logistics permitted during the period spanning 5 August – 21 August 2008, inclusively. The four subject species at the St-Lawrence Valley Natural History Ecomuseum have outdoor open-top enclosures within the park, all containing and bordering with trees which provide shade and concealment (Figure 1). At the time of the study, a total of 3 bears (B) occupied a 42 m x 25 m enclosure, 3 caribou (C) occupied a 65 m x 42 m enclosure, 6 deer (D) occupied a 60 m x 60 m enclosure and 2 wolves (W) occupied a 32 m x 28 m enclosure. Aerial surveys by the CropCam and ground surveys by a single field assistant were carried out simultaneously. The ground surveyor and UAV ground operator communicated by walkie-talkie for synchronization. An individual survey consisted of an entire UAV flight, during which the aircraft completed a certain number of repeated transects over the park while the ground surveyor completed a certain number of repeated circuits inside the park. Prior to all surveys, it was confirmed with park staff that all subjects were present in their enclosures. Daily number and timing of surveys were limited by UAV battery capacity and weather conditions. Mornings were generally favoured due to typically calmer winds. A total of 18 surveys was completed on 8 separate days (6 d. x 2 surveys and 2 d. x 3 surveys), totalling 194 UAV transects and 35 ground circuits. All surveys were conducted between the hours of 9:00 AM and 11:30 AM local time, with the exception of one day when 2 surveys were carried out in the afternoon between 1:30 PM and 4:00 PM.

UAV survey

The CropCam was deployed from an alfalfa field situated approximately 200 m northeast of the park and was programmed to execute repeated back-and-forth overlapping passes (i.e. transects) over the park, such that it flew over the enclosures of all 4 subject species in each individual pass. The camera system was set to capture sequences of overlapping photos at its fastest possible rate during transects. The only flight parameter manipulated between individual UAV surveys was altitude (150 m or 275 m), with the aim of always alternating in back-to-back surveys in an attempt to best replicate individual survey conditions between altitudes. Of the 18 total surveys conducted, 10 were flown at 150 m and 8 at 275 m (both 3-survey days had an additional 150 m survey). Initially, the total number of transects able to be performed by the UAV in a single flight (restricted by battery capacity) was underestimated. As a result, 8 transects per survey (≈ 12 min total) were completed for the first 2 surveys, which was subsequently increased to 10 (≈ 15 min total) for the following 3 surveys, and finally fixed at 12 (≈ 18 min total) for all remaining surveys. Insofar as weather and logistics permitted, all surveys on a given day were performed in quickest feasible succession: the amount of time required to land and retrieve the plane, change the batteries, reprogram the autopilot, reinitialize the plane, perform the pre-flight checklist and re-launch. When this process was accomplished without incident, the lapse between the end of the first survey and start the next was under 20 min.

Ground survey

Since it would be unrealistic to liken a ground survey in a wildlife park setting to such surveys in the field, this component of the experiment did not serve to compare total head counts with the UAV per se. Rather, it served to collect data on the species' activities and behaviours that may explain differences in detectability by the UAV. The surveyor repeated a defined circuit inside the park, constrained by the layout of paths, walkways and observation stations accessible to park visitors. The circuit covered every possible viewing point for the bear, caribou and deer enclosures, however the wolves were excluded from the ground survey as it was judged that due to the terrain, too large a proportion of their enclosure (≈ 50%) was impossible to view from the ground to yield reliable data. Observations were noted opportunistically along the circuit, recording individual subjects as soon as they were first sighted. For each sighting, the following parameters were noted: time and location of sighting; subject locomotion (still or in movement); overhead cover (none, partial or complete); and presence/absence of shade. Within a single circuit, re-sightings of same individuals were not recorded. Single ground circuits took on average 8.3 min to perform, never exceeding 11 min and never under 5 min. Initially the number of repeated circuits able to be performed by the ground surveyor over the course of a single flight by the UAV was underestimated. As a result, only one ground circuit was performed during the first survey, which was subsequently increased to 2 for all remaining surveys.

Data handling

UAV imagery for each survey, consisting of a number of disjunct sequences of partially overlapping photos (one sequence per UAV transect completed), was viewed one photo at a time and all visible subjects were marked (including re-sightings in overlapping photos) using Adobe Photoshop v11.0. Since photo quality and visibility of subjects varied, sure sightings were marked red while unsure sightings were marked yellow. For each species, total number of red marks (*r*) and yellow marks (*y*) were tallied in each survey and a final head count (*hc*) established based on the highest number of separate individuals sighted (sure sightings only) during any single transect. From these data, a set of key UAV statistics was computed for each flight (Table 1). Detection rate (*DR*) represents the average number of sure sightings (*r*) per transect (total transects in survey = *tt*), scaled for the total number of individuals in each respective subject species ($N_B = 3$; $N_C = 3$; $N_D = 6$; $N_W = 2$). It can be considered the absolute measure of overall subject detectability. Confidence rate (*CR*) represents the proportion of sure sightings (*r*) among total sightings ($r + y$). It can be considered a measure of the overall visibility of sighted subjects. Census rate (*Census*) is simply the final head count head count (*hc*) expressed as a proportion of total individuals (N) in each species.

Ground data for each survey, consisting of one datasheet per circuit completed, were pooled across circuits. For each species, tallies were kept for total number of subjects sighted (*ts*), total number of subjects in movement (*m*) and total number of subjects in the shade (*s*), under partial overhead concealment (*p*), in combined shade and partial concealment (*sp*), and under complete concealment (*c*). Key statistics for each species were also computed for ground surveys (Table 2). Overhead concealment rate (*OC*) is the proportion of completely concealed subjects among all subjects sighted. Global visibility index (*V-G*) is a measure of the overall visibility of sighted subjects, obtained by assigning sliding-scale values to the different variables predicted to affect subject visibility (*s, p, sp* and *c*). Unconcealed visibility index (*V-U*) is a similar measure which only takes into account unconcealed – and therefore UAV-detectable – subjects. Movement rate (*MR*) is the proportion of subjects in locomotion among all subjects sighted. Finally, Census rate (*Census*) represents the average proportion of total individuals (N) sighted per circuit completed (total circuits = *tc*).

UAV and ground statistics were pooled across all surveys to make global comparisons between species. Within species, UAV statistics were also compared between flight altitudes. An overall improvement of subject detectability with increasing altitude would be indicated by a significantly higher mean *DR*, and possibly an increase in mean *Census*. A concurrent deterioration of subject visibility would be indicated by a significantly lower mean *CR* and, if strong enough, possibly resulting in an unchanged or lower *DR*. Presence of correlations between ground and UAV statistics were investigated for each species (excluding wolves which lacked ground data) to determine if the former are overall accurate predictors of the latter. If subject detectability by the UAV is purely based on overhead concealment rate, a strong negative correlation might be expected between *OC* and *DR.* If other visibility factors such as shade and partial concealment additionally have notable effects on detectability, strong positive correlations might be expected between *V-G* and *DR*, and between *V-U* and *CR*. However, overall reliability of ground statistics at predicting UAV statistics might be weakened by high *MR* and/or low ground *Census*, potentially resulting in failure to reveal existing correlations or, alternatively, signalling erroneous ones. This is because a high movement rate would increase the chance that visibility parameters recorded on the ground will change over the course of surveys as subjects move to different locations. A low census rate would increase the chance that visibility of sighted subjects is not representative of all subjects present.

Data analysis

Analyses were performed using SPSS Statistics v17.0. A critical significance level of $\alpha = 0.05$ was used for all statistical tests. Prior to all analyses, pooled statistics were first evaluated for normal distribution using one-sample Kolmogorov-Smirnov tests in order to assess the need for parametric vs. non-parametric tests.

For comparisons between species, UAV statistics were pooled by flight altitude ($n_{150\ m} = 10$; $n_{275\ m} = 8$) while ground statistics were pooled across all surveys combined ($n = 18$). For normally distributed statistics (*DR*, *CR*, *V-G* and *V-U*), one-way analyses of variance (ANOVA) were used to test for overall differences between the 4 species. Where significant differences were found, least significant difference (LSD) tests revealed which species differed, or Dunnett’s T3 tests in the case of unequal variances.

For non-normally distributed statistics (UAV *Census*, *OC*, *MR* and ground *Census*), Kruskal-Wallis analyses of variance (K-W) were used to test for overall significant differences between species, followed by Mann-Whitney U tests to determine which species differed. To compare each species' UAV statistics between flight altitudes, independent-sample t-tests were used for *DR* and *CR*, while Mann-Whitney U tests were used for *Census*.

Correlation analyses were performed with statistics pooled by altitude as well as pooled across all surveys combined. With altitudes separate, correlations between each species' UAV and ground statistics were evaluated with Pearson's product-moment correlation coefficient, with the exception of *OC* vs. *DR* comparisons in bears which used Spearman's rank correlation coefficient due to the non-normal distribution of OC_B. Partial correlations tests, controlling for effects of altitude, were used for comparisons across all surveys combined.

Results

Species means for UAV statistics at each flight altitude are presented in Table 3 and illustrated in Figure 2. Bears (B) had a significantly higher detection rate (*DR*) than all other species (C, D and W) at both 150 m (ANOVA: $F_{3,36} = 8.761$, P = 0.000; B vs. C: I-J = 0.588, P = 0.000; B vs. D: I-J = 0.465, P = 0.001; B vs. W: I-J = 0.564, P = 0.000) and 275 m (ANOVA: $F_{3,28} = 5.439$, P = 0.004; B vs. C: I-J = 0.645, P = 0.003; B vs. D: I-J = 0.612, P = 0.004; B vs. W: I-J = 0.680, P = 0.002), while caribou, deer and wolves did not differ significantly from each other at either altitude. Bears also had the highest confidence rate (*CR*) at both altitudes, though not significantly above that of other species, which again roughly clustered at both altitudes. Deer had the lowest census rate (*Census*) at both altitudes, significantly lower than bears at 150 m (K-W: $\chi^2_3 = 10.515$, P = 0.015; B vs. D: $U_{10,10} = 9.0$, P = 0.001) and both bears and caribou at 275 m (K-W: $\chi^2_3 = 14.482$, P = 0.002; B vs. D: $U_{8,8} = 8.0$, P = 0.010; C vs. D: $U_{8,8} = 4.0$, P = 0.002). *DR* was notably higher at 275 m than 150 m for all species, and significantly so for bears ($t_{16} = -3.024$, P = 0.008), caribou ($t_{16} = -4.493$, P = 0.000) and wolves ($t_{16} = -2.535$, P = 0.022). *CR* decreased at 275 m for all species to varying degrees, though never significantly.

Census increased at 275 m for all species to varying degrees, though again never significantly.

Species means for ground statistics are presented in Table 4 and illustrated in Figure 3. Overhead concealment rate (*OC*) of bears was almost nil, significantly below that of both other species (K-W: $\chi^2_2 = 27.397$, P = 0.000; B vs. C: $U_{18,18} = 48.0$, P = 0.000; B vs. D: $U_{18,18} = 3.5$, P = 0.000), which did not differ significantly from each other. Bears also had a significantly higher global visibility index (*V-G*) than both other species (ANOVA: $F_{2,51} = 20.377$, P = 0.000; B vs. C: I-J = 0.286, P = 0.003; B vs. D: I-J = 0.424, P = 0.000), which again did not differ significantly from each other. Deer had a significantly lower unconcealed visibility index (*V-U*) than both other species (ANOVA: $F_{2,49} = 10.480$, P = 0.000; D vs. B: I-J = -0.396, P = 0.000; D vs. C: I-J = -0.225, P = 0.015), with no significant difference between the latter. Deer had an extremely low movement rate (*MR*), while that of bears was moderate and that of caribou was relatively high. *MR* differed significantly between all species (K-W: $\chi^2_2 = 32.928$, P = 0.000; B vs. C: $U_{18,18} = 78.000$, P = 0.007; B vs. D: $U_{18,18} = 19.5$, P = 0.000; C vs. D: $U_{18,18} = 13.5$, P = 0.000). Finally, mean ground census rate (*Census*) was relatively high for all species (highest in deer followed by bears and caribou), though differences were not significant.

Correlation coefficients and associated significance levels between ground and UAV statistics are presented in Table 5. Because bears were never observed to be concealed during 150 m surveys, correlation between *OC* and *DR* could not be tested for this altitude. In addition, since overall OC_B was not normally distributed, a partial correlation test combining both altitudes could not be accomplished. No correlation was found between *OC* and *DR* for bears during 275 m surveys, though *V-G* and *DR* showed a significant positive correlation during 275 m surveys and across all surveys combined, and likewise for *V-U* and *CR*. For caribou, the only significant correlations uncovered were a negative one between *OC* and *DR* at 150 m, and a positive one between *V-G* and *DR* at 150 m. For deer, no correlations were found between *OC* and *DR*, however significant positive correlations were found between *V-G* and *DR* at 275 m and across all surveys combined, as well as between *V-U* and *CR* at 150 m and across all surveys combined.

Discussion

This trial aimed to quantitatively evaluate visibility and detectability by the CropCam UAV system of 4 different species of land mammals in pseudo-natural captive settings. Since total number of subjects was known, it was possible to compute exact detection and census rates in UAV imagery. Furthermore, data recorded from the ground on 3 of these species simultaneous to UAV surveys offered potential empirical insight into factors relating to subject behaviour that affect their detectability by the UAV.

Black bears (Figure 4) appeared in the UAV imagery as relatively large, round and conspicuous deep black figures, and they were revealed to be the most visible of all four species with regard to confidence of sightings (*CR*) at both survey altitudes. The overall detectability (*DR*) of bears was also significantly higher than all other species at both altitudes and their UAV census rate (*Census*) was relatively high at both altitudes as well (0.933 and 0.958, respectively). This is likely for the most part due to their extremely low tendency to be completely concealed (*OC*), thus subjects in the enclosure were nearly always all visible from above. In addition, they spent the least time among all species in shade or partial concealment (highest *V-U*). Nevertheless, expected overall negative effects of the latter two parameters on detectability and visibility were still revealed by significant positive *V-G – DR* and *V-U – CR* correlations in individual surveys. These correlations were not significant when considering 150 m surveys alone, however. This may indicate that negative effects of shade and partial concealment on bear visibility only become significant above 150 m, even though their overall detectability remains significantly higher at 275 m in altitude.

Woodland caribou (Figure 4) appeared in the imagery as moderate-size and somewhat elongate light brownish figures, more prone to blending in with surroundings than bears as witnessed by their overall lower confidence of sightings. It was sometimes possible to distinguish their white tail as well as antlers on the lone male in the enclosure.

Caribou were the least detectable of all species in 150 m surveys and the second-least detectable in 275 m surveys, though their detectability was significantly improved with increasing altitude. Their low detectability might be explained by their relatively high rate of complete concealment and their observed tendency to travel along the perimeter of the enclosure, of which 2 out of 4 sides border almost entirely with trees casting foliage over the edge. Nevertheless, this behaviour did not seem to impact their UAV census rate in the same way, as caribou in fact had a perfect census rate of 1.0 across all 275 m surveys. This might be explained by their significantly higher rate of movement (*MR*) compared to both other species, which may increase the chance that all individual subjects in the enclosure will eventually be sighted simultaneously if repeated transects are flown. Expected correlations between ground visibility factors and detectability by the UAV almost all failed to manifest for caribou. This is likely also attributable to their high frequency of movement, which may have rendered their recorded visibility parameters in individual ground surveys unreliable due to high probability of subjects moving from their recorded locations after being sighted.

White-tailed deer (Figure 4) appeared as relatively small and nondescript orangish blotches. Overall confidence of deer sightings was comparable to that of caribou and wolves in 150 m surveys, though it suffered the most important drop among all species ($\approx$ 0.1) when survey altitude was increased to 275 m, suggesting that visibility of deer is the first to begin decreasing considerably with rising survey altitude. Overall detectability of deer at both altitudes was somewhat higher though not significantly above that of caribou and wolves. They were the only species to not show a significantly improved detection rate with increasing altitude, possibly due to the relatively important concurrent deterioration of their visibility. Deer had a notably lower UAV census rate than all other species at both altitudes despite a nearly identical overhead concealment rate to caribou. This is likely explained by the former's extremely low rate of movement compared to the latter: while individual caribou tended to move in and out of concealment throughout surveys, concealed deer tended to stay put, never offering the UAV a glimpse at them. On the whole, deer exhibited a particularly high affinity for shade and concealment as indicated by their low visibility indices (both *V-G* and *V-U*) compared to bears and caribou. Moreover, shade and concealment were shown to have strong effects on their visibility and overall detectability in correlation analyses.

Grey wolves (Figure 4) appeared as small whitish figures, and their legs and tail could sometimes be discerned. When out in the open, they were relatively conspicuous and easy to spot. However, shade and partial concealment seemed to considerably worsen their visibility (though no ground data were available to test this empirically), which might explain why the overall confidence rate of their sightings was roughly on par with caribou and deer. Detection and census rates of wolves were also more or less average among other species. Judging by UAV imagery alone, wolves appeared to have a relatively high movement rate, as they would often be sighted in different locations from one transect to the next.

It should be stressed that results of this trial are not to be taken at face value as definitive indicators of UAV-detectability of these species in the wild. In all likelihood, their constrained enclosures and captive settings in the park alter natural behaviours – for example tendency towards concealment, nature and frequency of movement, and proximity kept with conspecifics – that might influence their detectability in the wild. Furthermore, the park offers but a limited sample of ground landscape types, and all four species occupy vast ranges in the wild which far exceed the operational range of the CropCam. Rather, this trial should be viewed as a preliminary empirical evaluation of general factors relating to appearance and behaviour of wild animals which might affect their ability to be detected by a UAV system such as the CropCam.

With regard to appearance, visibility in photographic surveys by a basic compact camera system like the CropCam's is dependent on both size of animals and their contrast with immediate surroundings. Bears were easiest to spot because of their large size combined with their manifestly deep black colouration which even stood out in shaded areas. Wolves also possess a distinctly contrasting colouration which makes them easy to spot when out in the open (though this would not be the case over snow), however, their small size decreases their visibility when in the shade or partially concealed. Caribou and deer are relatively large animals, though their colouration tends to blend more with surroundings than that of bears and wolves, thus negatively impacting their visibility. With regard to behaviour, animals that tend to seek shade and overhead concealment are likely to be less detectable and consequently undercounted in UAV surveys, though the magnitude of effects is to some degree influenced by fundamental appearance and behaviour. For example, bears in the shade, due to their size and colouration, were easier to spot than caribou or deer in the shade. Caribou, due to their high mobility over the course of repeated UAV transects, were censused with relatively good accuracy despite only moderate overall detectability.

All-around improvements in visibility of animal subjects might be achieved by using higher-performance cameras. Alternatively, use of video cameras or infrared thermal sensors might prove more effective for detecting certain animals. The former were successfully used by Jones et al. (2006) to detect alligator decoys and manatees while the latter have already been employed in deer surveys (Naugle et al. 1996; Drake et al. 2005). Advanced image-analysis software might eventually also aid in detecting animal subjects in photographic and videographic surveys, as has previously been explored (Laliberte and Ripple 2003). Optimal survey altitudes should be determined for different species based on their visibility so as to maximize UAV imagery footprint – and consequently overall survey efficiency and rate of subject detection – without compromising confidence of sightings. With regard to total survey area range, it should be noted that there are already UAVs in operation capable of long range missions (though currently at steep prices) and ongoing advancement in battery technology is likely to deliver continuing improvements to flight endurance of consumer UAV systems.

Conclusion

This trial has produced, to the author's knowledge, the first quantitative estimates of land mammal visibility and detection rates by an unmanned aerial vehicle. The CropCam UAV system was successful to varying degrees at detecting captive black bears, woodland caribou, white-tailed deer and grey wolves in pseudo-natural enclosures, and some basic empirical insight was gathered on factors affecting subject visibility and detectability. In addition, UAV surveys were repeated numerous times at markedly low cost compared to operating or chartering full-size manned aircraft. Further consideration should be granted to emergent UAV systems as eventual substitutes or supplements to full-size aircraft or viable alternatives to various other means for surveying wild animals.

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Table 1 – Key UAV statistics calculated for each species in every survey. *tt* = total transects flown; *r* = total red marks (sure sightings); *y* = total yellow marks (unsure sightings); *hc* = final head count of individual subjects; N = total individual subjects present in enclosure.

Stat	Name	Description	Equation
DR	Detection rate	Average number of sure sightings per transect per individual subject	$= r / (tt \cdot N)$
CR	Confidence rate	Proportion of sure sightings among total sightings	$= r / (r + y)$
Census	Census rate	Proportion of total subjects censused in highest-count transect	$= hc / N$

Table 2 – Key ground statistics calculated for each species in every survey. *tc* = total circuits completed; *ts* = total sightings; *s* = total subjects in shade only; *p* = total subjects under partial concealment only; *sp* = total subjects in concurrent shade and partial concealment; *c* = total completely concealed subjects; *m* = total subjects in movement; N = total individual subjects present in enclosure.

Stat	Name	Description	Equation
OC	Overhead concealment rate	Proportion of sighted subjects under complete concealment	$= c / ts$
V-G	Global visibility index	Overall visibility index of all sighted subjects	$= 1 - \frac{s}{2ts} - \frac{p}{2ts} - \frac{3sp}{4ts} - \frac{c}{ts}$
V-U	Unconcealed visibility index	Visibility index of unconcealed subjects	$= 1 - \frac{s}{2(ts - c)} - \frac{p}{2(ts - c)} - \frac{ps}{(ts - c)}$
MR	Movement rate	Proportion of sighted subjects in movement	$= m / ts$
Census	Census rate	Average proportion of total subjects censused per circuit	$= ts / (tc \cdot N)$

Table 3 – Summary of species means and standard errors at each altitude for UAV statistics: detection rate (*DR*), confidence rate (*CR*) and census rate (*Census*). Unless otherwise indicated, n = 10 for 150 m results and n = 8 for 275 m results. † Denotes significant differences ($P < 0.05$) between altitudes. * Denotes significant differences between species.

	DR		***CR***		***Census***	
	150 m	*275 m*	*150 m*	*275 m*	*150 m*	*275 m*
Bears (B)	0.991 ± 0.093 † *ALL	1.512 ± 0.154 † *ALL	0.873 ± 0.037	0.817 ± 0.046	0.933 ± 0.044 *D	0.958 ± 0.042 *D
Caribou (C)	0.404 ± 0.083 † *B	0.866 ± 0.050 † *B	0.745 ± 0.045 (n = 9)	0.714 ± 0.050	0.767 ± 0.112	1.000 ± 0.000 *D
Deer (D)	0.527 ± 0.101 *B	0.900 ± 0.181 *B	0.758 ± 0.059	0.659 ± 0.084	0.633 ± 0.048 *B	0.688 ± 0.073 *B,C
Wolves (W)	0.427 ± 0.093 † *B	0.832 ± 0.136 † *B	0.742 ± 0.065	0.695 ± 0.063	0.850 ± 0.076	0.875 ± 0.082

Table 4 – Summary of species means and standard errors for ground statistics: overhead concealment rate (*OC*), global visibility index (*V-G*), unconcealed visibility index (*V-U*), movement rate (*MR*) and census rate (*Census*). For all results, n = 18 unless otherwise indicated. * Denotes significant differences ($P < 0.05$) between species.

	OC	***V-G***	***V-U***	***MR***	***Census***
Bears (B)	0.009 ± 0.009 *ALL	0.691 ± 0.045 *ALL	0.616 ± 0.058 *D	0.390 ± 0.060 *ALL	0.917 ± 0.031
Caribou (C)	0.312 ± 0.073 *B	0.404 ± 0.063 *B	0.445 ± 0.078 (n = 16) *D	0.686 ± 0.078 *ALL	0.880 ± 0.038
Deer (D)	0.302 ± 0.043 *B	0.267 ± 0.029 *B	0.220 ± 0.052 *ALL	0.042 ± 0.017 *ALL	0.958 ± 0.017

Table 5 – Summary of correlation coefficients (significance levels in parentheses) between ground and UAV statistics: overhead concealment rate (*OC*) vs. detection rate (*DR*), global visibility index (*V-G*) vs. detection rate (DR) and unconcealed visibility index (*V-U*) vs. confidence rate (*CR*). * Indicates significant correlations (P < 0.05).

	OC* vs. *DR	***V-G* vs. *DR***	***V-U* vs. *CI***
Bears			
150 m	-	0.599 (P = 0.067)	0.237 (P = 0.510)
275 m	0.247 (P = 0.555)	0.742 (P = 0.035)*	0.915 (P = 0.001)*
Alt. combined	-	0.652 (P = 0.005)*	0.527 (P = 0.030)*
Caribou			
150 m	-0.638 (P = 0.047)*	0.849 (P = 0.002)*	0.608 (P = 0.110)
275 m	0.427 (P = 0.291)	0.069 (P = 0.871)	0.291 (P = 0.484)
Alt. combined	-0.466 (P = 0.059)	0.475 (P = 0.054)	0.468 (P = 0.078)
Deer			
150 m	0.173 (P = 0.632)	0.459 (P = 0.182)	0.729 (P = 0.017)*
275 m	-0.439 (P = 0.277)	0.887 (P = 0.003)*	0.705 (P = 0.051)
Alt. combined	-0.118 (P = 0.652)	0.700 (P = 0.002)*	0.714 (P = 0.001)*

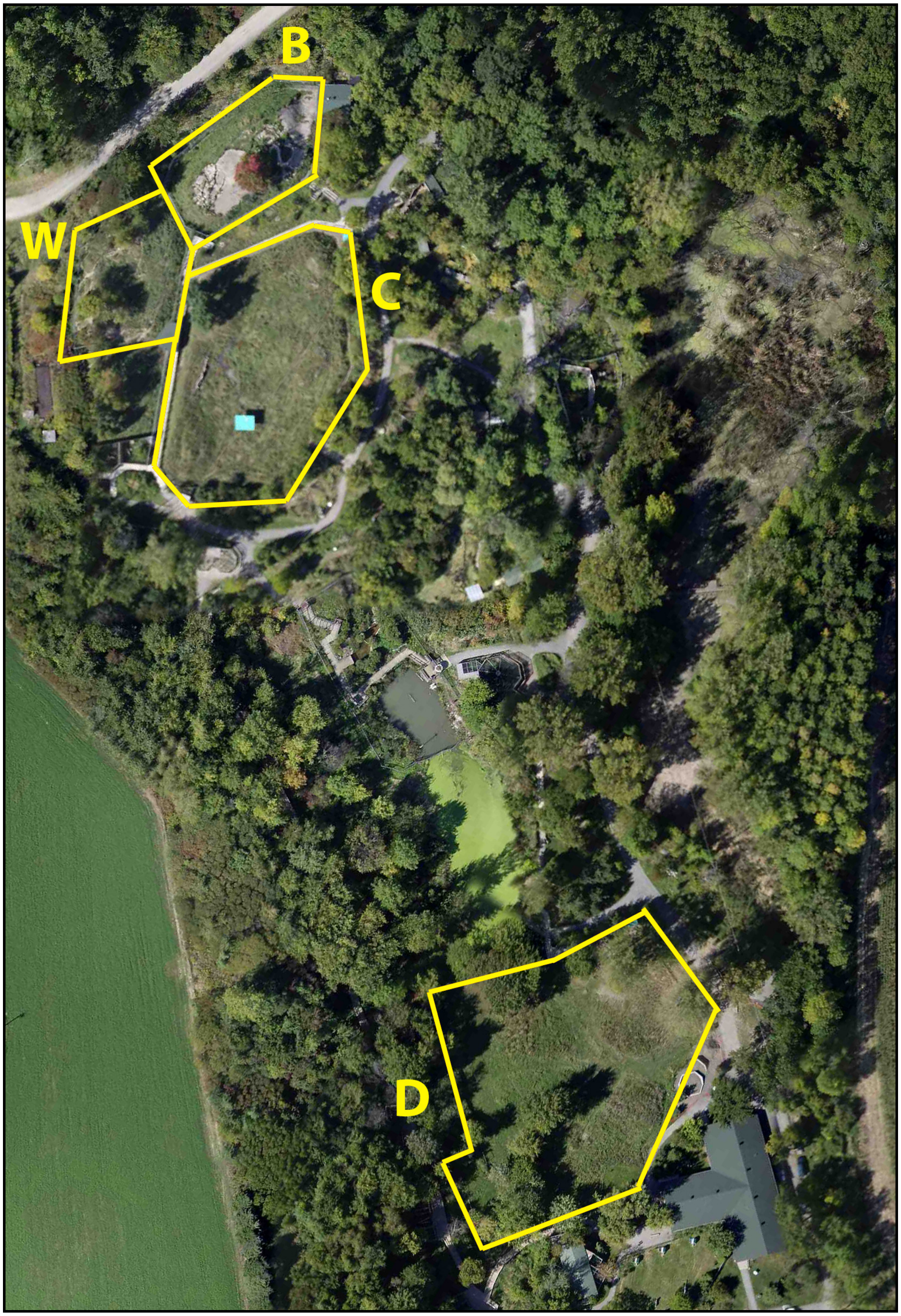

Figure 1 – Layout of black bear (B), woodland caribou (C), white-tailed deer (D) and grey wolf (W) enclosures in the St-Lawrence Valley Natural History Ecomuseum (aerial imagery by CropCam).

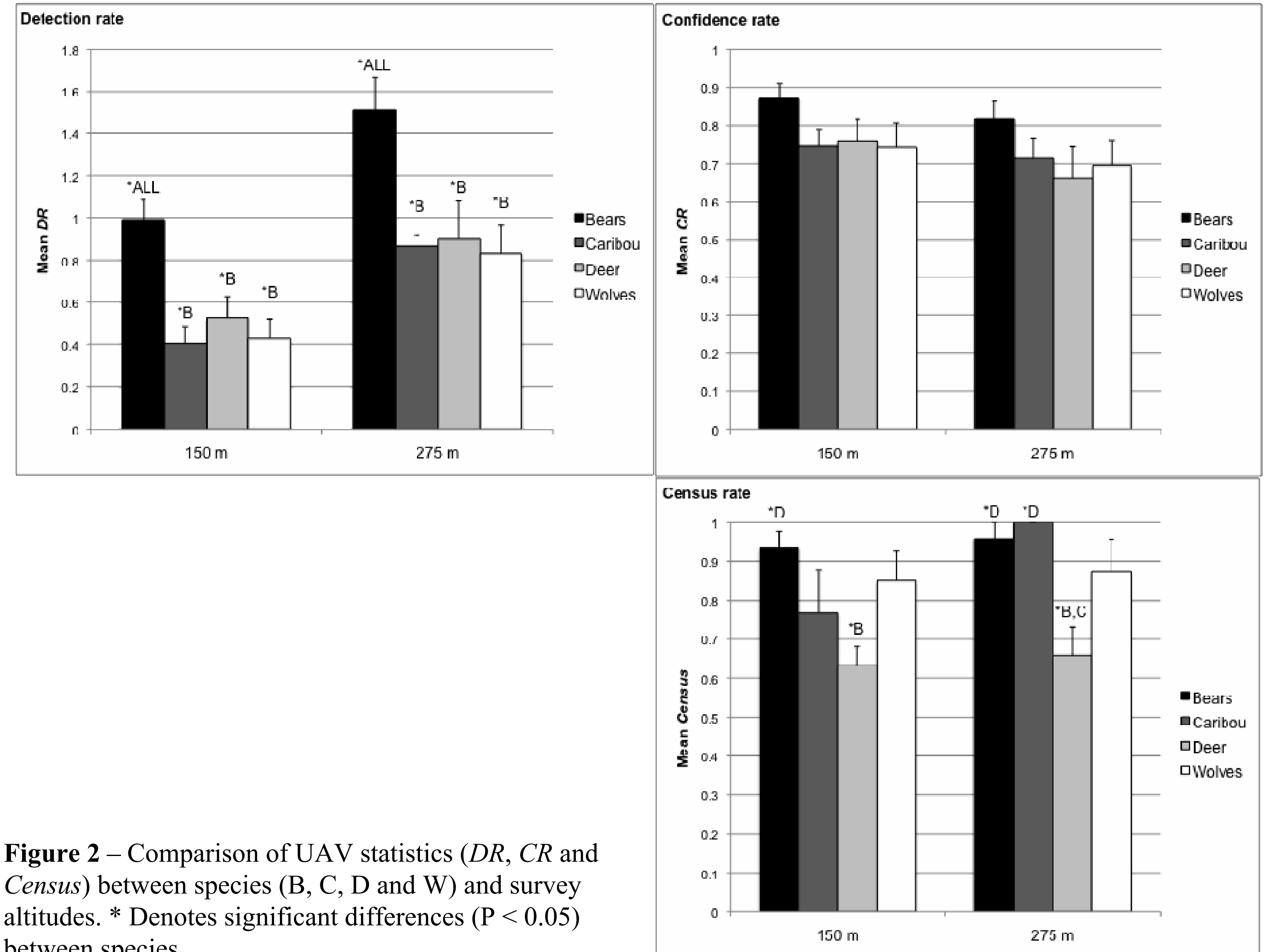

Figure 2 – Comparison of UAV statistics (*DR*, *CR* and *Census*) between species (B, C, D and W) and survey altitudes. * Denotes significant differences (P < 0.05) between species.

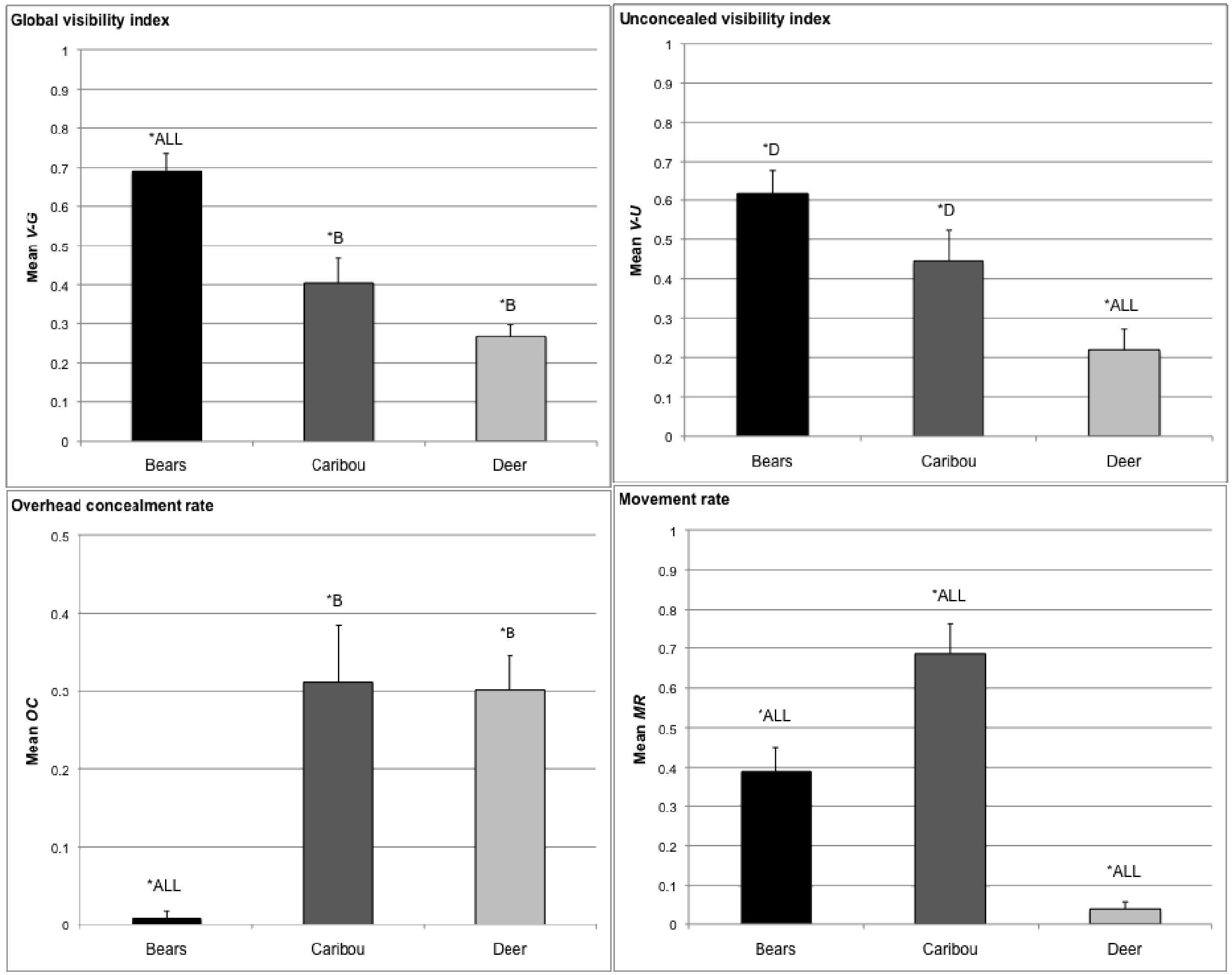

Figure 3 – Comparison of ground statistics (*V-G*, *V-U*, *OC* and *MR*) between species (B, C and D). * Denotes significant differences ($P < 0.05$) between species.

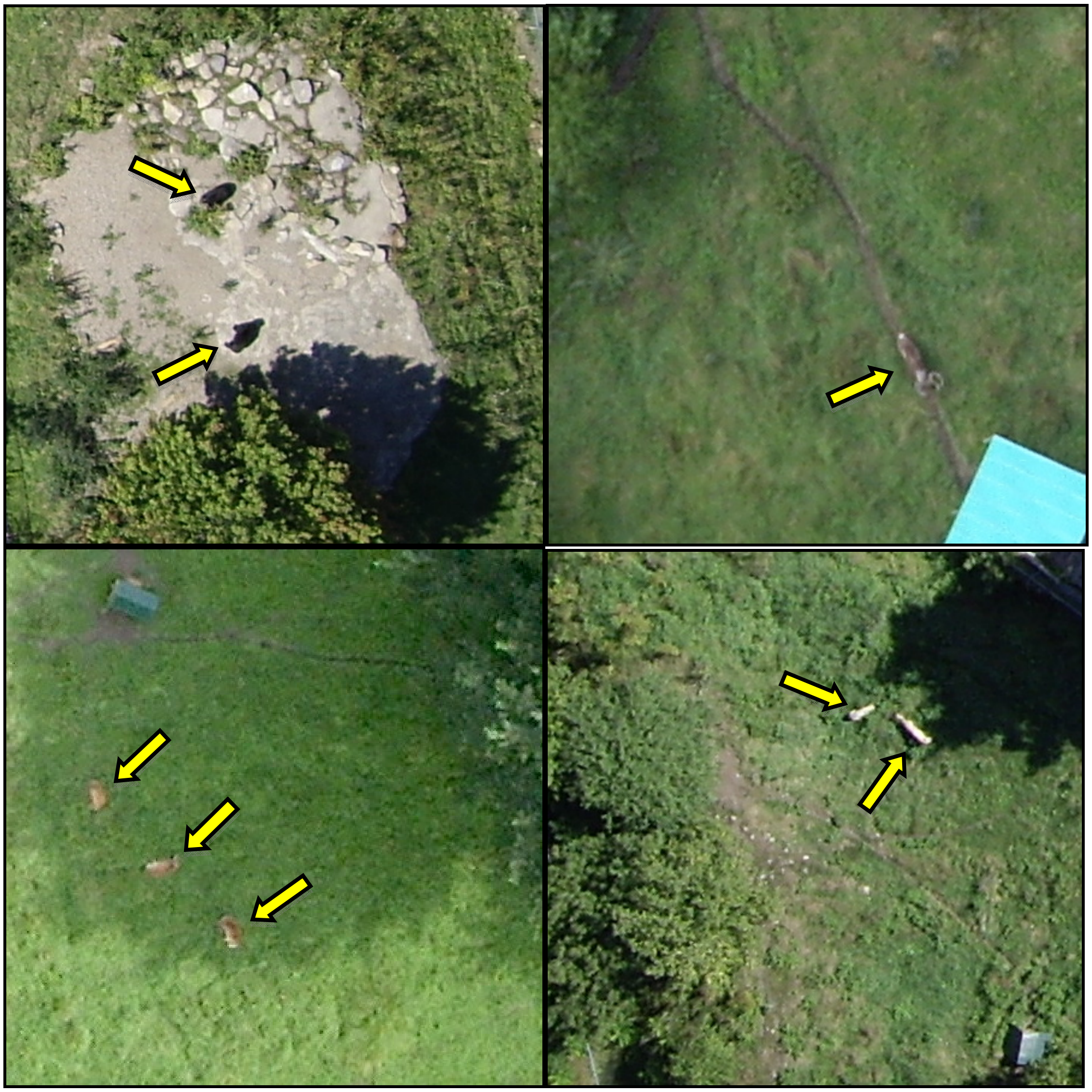

Figure 4 – Sample UAV images of black bears (top left), woodland caribou (top right), white-tailed deer (bottom left) and grey wolves (bottom right) in the St-Lawrence Valley Natural History Ecomuseum.

FINAL SUMMARY AND CONCLUSION

This study engaged in novel investigations of the viability of using unmanned aerial vehicles (UAVs) in wildlife research. Over the course of 2 years, a small stock UAV system, the CropCam, was critically evaluated as a generally proficient tool for wildlife research applications and served to produce, to the author's knowledge, what may be the first quantitative appraisal of a UAV's performance in specific wildlife-related missions. The study brought to light a number of strengths as well as weaknesses in the system's ability to successfully and efficiently accomplish potential wildlife research tasks, and has bolstered the conceptual and practical foundation for carrying out future work in this discipline. Based on the demonstration of promising results in this study in addition to the rapidly advancing pace of UAV technology and markets, it is recommended that further investigations be undertaken into employing UAVs for wildlife research and management applications.

APPENDIX A – Animal use protocol approval certificates

Guidelines for completing the form are available at www.mcgill.ca/research/compliance/animal/forms

McGill University
Animal Use Protocol – Research

For Office Use Only:
Protocol #: 5394
Approval End Date: April 30, 2008
Facility Committee: MAC

Title: The application of UAV technology to bird conservation research - Evaluation of CropCam in censusing raptor nests
(~~must~~ match the title of the funding source application)

☒ **New Application** ☐ **Renewal of Protocol #** _____ ☐ **Pilot** **Category** *(see section 11)*: B

1. Investigator Data:

Principal Investigator: Dr. David M. Bird **Phone #:** (514) 398-7760
Unit/Department: Avian Science and Conservation Centre **Fax#:** (514) 398-7990
Address: 21,111 Lakeshore Road, Ste. Anne de Bellevue, QC **Email:** david.bird@mcgill.ca

2. Emergency Contacts: Two people must be designated to handle emergencies.

Name	Work #	Emergency #
Ian Ritchie	(514) 398-7932	(514) 457-9051
Rodger Titman	(514) 398-7933	(514) 457-6480

3. Funding Source:

External ☒
Source (s): Kenneth M. Molson Foundation
Peer Reviewed for the project proposed in this Animal Use Protocol: ☒YES ☐NO**
Status : ☒ Awarded ☐ Pending
Funding period: 1 Jan. 07 - 31 Dec. 07

Internal ☐
Source (s): __________
Peer Reviewed: ☐ YES ☐ NO**
Status: ☐ Awarded ☐ Pending
Funding period:_____

For Office Use Only:

ACTION	✔	DATE
COs		
DB	✓	May 18'07

APPROVED

** **All projects that have not been peer reviewed for scientific merit by the funding source require 2 Peer Review Forms to be completed e.g. Projects funded from industrial sources. Peer Review Form available at www.mcgill.ca/research/compliance/animal/forms**

Proposed Start Date of Animal Use (d/m/y):	01/05/07	**or ongoing** ☐
Expected Date of Completion of Animal Use (d/m/y):	01/09/07	**or ongoing** ☐

Investigator's Statement: The information in this application is exact and complete. I assure that all care and use of animals in this proposal will be in accordance with the guidelines and policies of the Canadian Council on Animal Care and those of McGill University. I shall request the Animal Care Committee's approval prior to any deviations from this protocol as approved. I understand that this approval is valid for one year and must be approved on an annual basis.

Principal Investigator's signature: [signature] **Date:**

Approved by:

Chair, Facility Animal Care Committee:	[signature]	**Date:** 10 May 2007
University Veterinarian:	[signature]	**Date:** 16 MAY 2007
Chair, Ethics Subcommittee (as per UACC policy):	—	**Date:** —
Approved Animal Use	**Beginning:** MAY 1, 2007	**Ending:** April 30, 2008

☐ This protocol has been approved with the modifications noted in Section 13.

May 2006

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Guidelines for completing the form are available at www.mcgill.ca/researchoffice/compliance/animal/forms

McGill University
Animal Use Protocol – Research

For Office Use Only:
Protocol #: 5394
Approval End Date: April 30, 2009
Facility Committee: MAC

Title: The evaluation of UAV (Unmanned Aerial Vehicle) technology for wildlife aerial survey applications
(must match the title of the funding source application)

☐ **New Application** ☒ **Renewal of Protocol #** 5394 ☐ **Pilot** **Category** *(see section 11)*: B

1. Investigator Data:

Principal Investigator:	David M. Bird	**Phone #:**	(514) 398-7760
Unit/Department:	Avian Science and Conservation Centre	**Fax#:**	(514) 398-7990
Address:	21,111 Lakeshore Road, Ste. Anne de Bellevue, QC	**Email:**	david.bird@mcgill.ca

+K=OK

2. Emergency Contacts: Two people must be designated to handle emergencies.

Name: Ian Ritchie	**Work #:** (514) 398-7932	**Emergency #:**	(514) 457-9051
Name: Rodger Titman	**Work #:** (514) 398-7933	**Emergency #:**	(514) 457-6480

3. Funding Source:

External ☑
Source (s): Molson Foundation
Peer Reviewed for the project proposed in this Animal Use Protocol: ☑ YES ☐ NO**
Status: ☑ Awarded ☐ Pending
Funding period: 01/07 - 00/08

Internal ☐
Source (s): ________
Peer Reviewed: ☐ YES ☐ NO**
Status: ☐ Awarded ☐ Pending
Funding period: _____

For Office Use Only:

ACTION	✔	DATE
CCs		
DB	✓	Apr 16 08

APPROVED

**** All projects that have not been peer reviewed for scientific merit by the funding source require 2 Peer Review Forms to be completed e.g. Projects funded from industrial sources. Peer Review Form available at www.mcgill.ca/researchoffice/compliance/animal/forms**

Proposed Start Date of Animal Use (d/m/y):	01/04/2008	**or ongoing**	☐
Expected Date of Completion of Animal Use (d/m/y):	01/12/2008	**or ongoing**	☐

Investigator's Statement: The information in this application is exact and complete. I assure that all care and use of animals in this proposal will be in accordance with the guidelines and policies of the Canadian Council on Animal Care and those of McGill University. I shall request the Animal Care Committee's approval prior to any deviations from this protocol as approved. I understand that this approval is valid for one year and must be approved on an annual basis. I will ensure that all collaborators and staff are aware of all changes to this protocol.

Principal Investigator's signature:	[signature]	**Date:** Apr 10/08

Approved by:

Chair, Facility Animal Care Committee:	[signature]	**Date:** April 14/08
Animal Compliance Office:	[signature]	**Date:** Apr 16 '08
Chair, Ethics Subcommittee (as per UACC policy):	—	**Date:** —
Approved Animal Use	**Beginning:** May 1, 2008	**Ending:** April 30, 2009

☐ This protocol has been approved with the modifications noted in Section 13.

Renewal next year requires submission of full Animal Use Protocol form

January 2008

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