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ABSTRACT Unmanned aircraft systems (UASs) are proposed as a useful alternative to manned aircraft for some aerial wildlife surveys. We described the components and current capabilities of a small UAS developed specifically for wildlife and ecological surveys that is currently in field use for a variety of applications. We also reviewed government regulations currently affecting the use of UASs in civilian airspace. Information on capabilities and regulations will be valuable for agencies and individuals interested in the potential UASs offer for monitoring wildlife populations and their habitat. Descriptions of current uses and recommendations for future employment will be helpful in implementing this technology efficiently for aerial surveys as the civilian sector begins to adopt UASs for peacetime missions.

KEY WORDS aerial survey, imagery, remote sensing, technology, unmanned aircraft systems.

Aerial surveys using manned aircraft have been conducted on every continent for a variety of purposes. Despite their unquestioned utility, manned aircraft have several disadvantages that have led users to search for supplemental or replacement technology. First, fixed-wing aircraft or helicopters often cost hundreds of dollars per survey hour when personnel, transit (i.e., aircraft movement from a local airport to and from the survey site), and mobilization costs are considered. Second, local conditions at airports, such as low visibility due to fog, or inclement weather, sometimes restrict the use of manned aircraft. A third difficulty associated with manned aerial surveys relates to geospatial accuracy of the acquired data and survey repeatability.

Flying an exact course from one flight to the next in a small fixed-wing manned aircraft or helicopter can be challenging, and even small navigation or piloting errors can be detrimental to accuracy of aerial surveys. When sensors or cameras are used and their exact position and attitude (i.e., orientation with respect to the ground) are not known, data collected on sequential flights using the same flight plan may not actually survey the same area (Pollock and Kendall 1987). Although Global Positioning System (GPS)-linked autopilots might improve flight-path accuracy or repeatability, costs for such systems on manned aircraft (typically >$40,000 exclusive of GPS and installation) discourage their widespread use. In addition, the low speeds and altitudes required for many aerial wildlife surveys confer a high inherent risk to the pilot and passengers. Despite extensive efforts to improve safety, crashes by small aircraft are a leading cause of work-related mortality among wildlife researchers (Wiegman and Taneja 2003).

These concerns, as well as the proven utility of unmanned aircraft systems (UASs) for military operations, have led researchers to explore using UAS technology for ecological surveys. Potential advantages of UASs include lower operating costs and consistency of flight path and image acquisition. These features potentially reduce errors in aerial estimation of wildlife populations often caused by variation in survey path, time over the survey target (i.e., survey effort), and observer fatigue (Conroy et al. 2008). Also, small UASs offer reduced potential for disturbance to wildlife populations. From the late 1990s to the early 2000s, researchers explored the potential of using aerial photography acquired via modified radio-controlled model airplanes for ecological studies (e.g., Nyquist 1997, Quilter and Anderson 2001, Hardin and Jackson 2005). These early efforts showed promise, and subsequent studies evaluated more sophisticated platforms and image-processing techniques (e.g., Maslanik et al. 2002, Abd-Elrahman et al. 2005). Jones et al. (2006) assessed the feasibility of UAS for wildlife research and made several recommendations regarding UAS use for local-area, low-altitude surveys of wildlife populations or vegetation. Jones et al. (2006) recommended that UASs should be small (i.e., capable of manual launch); have an electric motor (as opposed to a gasoline or nitromethane engine); be easy to use, launch, and land without runways on land or water; have low costs; and have the ability to record and store onboard data to prevent data loss or degradation from transmission. As technological developments continued, image georeferencing to produce accurate maps from onboard sensor data was identified as another utility. These more recent technological advances reflect an additional advantage of UASs, the ability to modify platforms and payloads with relative ease compared with manned aircraft.

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Figure 1. University of Florida's Nova 2 unmanned aircraft system ready for deployment. Major components of the system include the 2.5-m-wingspan aircraft, a laptop computer with autopilot and payload software, and communications and manual-control equipment.

Figure 2. Launching University of Florida's Nova unmanned aircraft system (UAS) aircraft from an airboat in the Florida Everglades, 1 May 2008, the first-ever deployment of UAS from an airboat.

Image Georeferencing

Georeferencing confers spatial attributes to each image pixel to link imagery and the map coordinate system. Often, georeferencing is accomplished using ground control points (GCPs) with known image and mapping coordinates; the resulting process is called indirect georeferencing. However, sensors that measure and record the position and attitude of the image acquisition camera can be used to the same effect. Use of these components—GPS receivers and inertial measurement units (IMUs)—can be helpful when ground control is not a viable option (e.g., remote or inaccessible areas). Accuracy of georectified imagery is directly related to accuracy of the onboard sensors, including measurement precision of camera attitude. For example, if the locational precision of the camera is ±10 m, precision of the imagery will be ±10 m (neglecting attitude). A measured camera tilt with precision of ±5° at a flying height of 100 m results in a minimum horizontal position precision for the imagery of ±9 m, with precision decreasing from image center. Creation of geospatially accurate imagery using data from airborne sensors, rather than GCPs, is known as direct georeferencing. Because of its potential advantages in ecological surveys—namely, elimination of the need to physically visit the survey site to locate GCPs, a time-consuming and potentially disruptive process—direct georeferencing is generally preferable, despite increased difficulties associated with sensor component calibration and postflight data processing.

Larger manned survey aircraft and large military UASs can carry highly accurate sensors that enable detailed spatial analysis of collected imagery. Small military UASs have some capabilities useful for scientific research (e.g., durability, portability), but their lightweight sensors are intended for situational awareness or reconnaissance rather than the delivery of high-resolution, geospatially accurate imagery. Partly due to lack of a well developed civilian market, few UASs are available for wildlife research applications. These include the Aerosonde (AAI Corporation, Hunt Valley, MD), used in several atmospheric and oceanographic research efforts (Curry et al. 2004, Ramana et al. 2007); the Manta (Advanced Ceramic Research, Tucson, AZ); and the Puma (Aerovironment, Monrovia, CA). Currently available small UASs do not provide the combination of high spatial accuracy, sensor resolution, and operation from remote areas that lack runways needed for some wildlife research. Users of the available platforms must decide between ease and economy of use, or quality and accuracy of imagery. Our group developed an alternative platform that is easy to use and economical and that produces spatially accurate, high-quality imagery for use in wildlife studies.

METHODS

The University of Florida developed and produced a small UAS (Fig. 1) to collect geospatially accurate imagery over highly repeatable flight paths, enabling positional accuracy previously available only in larger UASs or in manned aircraft with sophisticated guidance systems. The aircraft was constructed of epoxy-impregnated fiberglass with carbon-fiber and aramid-fiber reinforcements that provided durability and allowed for a clean fuselage designed to skid-land on unimproved sites or water, a capability conferred by extensive waterproofing. An electric motor provided reliability, long service life, and quiet operation. Power for propulsion and other onboard systems came from a rechargeable lithium-polymer battery pack. The aircraft had a wingspan of 2.5 m and weighed 6.2 kg, including a maximum payload of 1 kg, which could be carried in a variety of configurations inside the fuselage. Flight endurance was up to 1 hr at cruising speeds of 25–30 m/sec (90–108 km/hr). These dimensions allowed launching where runways or catapults would be impractical or impossible (Fig. 2).

The UAS, known by its Department of Defense designation of Nova 2, used a Procerus Technologies Kestrel™ autopilot (Procerus Technologies, Vineyard, UT). This 17-g device was mounted inside the aircraft and included accelerometers, magnetometers, pressure sensors, and linkage to an onboard differential-capable GPS (D-GPS) antenna for precise navigation along a preprogrammed course. Position data sent to a ground control station enabled monitoring of the aircraft's status

and position, overlain onto digitized aerial maps or Google™ Earth images (Google, Inc., Mountain View, CA). A 2.4-GHz transceiver system provided communication between the aircraft and the ground control station (GCS), enabling changes to flight paths and waypoints in real time. The Nova UAS also could be manually controlled via a module similar to radiotransmitters used for flying model aircraft. This system allowed for communication and control at distances up to 10 km, although satellite communication links or relay-transmission systems used by other UAS autopilot systems can provide greater range at a cost of additional weight and power consumption. The GCS consisted of a laptop computer, transceiver, liquid-crystal display monitor for payload operation, and manual control module. Both GCS and autopilot software incorporated safety procedures that prevent the aircraft from straying out of control or crashing. However, manual control could override the autopilot at any point during the aircraft's flight and was used during takeoff and landing when a human pilot was better equipped to avoid obstacles such as shrubs and rocks on unimproved launching or landing sites.

The payload consisted of an EVolt model 420 digital still camera with a 25 mm f/2.8 pancake lens (Olympus, Tokyo, Japan), an Xsens MTi-G (Xsense, Enschede, The Netherlands) inertial navigation system, and a VIA PICO-ITX P700 computer (VIA Technologies, Inc., Taipei, Taiwan) that controlled the camera using navigation data inputs. The camera and lens were chosen because of their small size (475 g, including lens), resolution (10 megapixel), and firmware compatibility with other UAS subsystems. On-board data storage of up to 160 gigabytes allowed several missions to be flown before transferring data to a ground-based computer. The payload, including mounting hardware and foam to reduce vibration from the aircraft's motor, weighed 996 g. Images were taken using shutter-priority mode at 1/2,000 second to minimize blurring, an important consideration for image processing and georeferencing.

To maximize accuracy of the postflight georeferencing process, it is important to precisely know the spatial relationship between the payload camera and navigation systems and to control the temporal aspects of their operation. The spatial relationship between sensors was established by attaching the various sensors to one physical platform and then measuring their orientation with respect to one another (i.e., degree of tilt) as well as the exact distance between the various components of the navigation system and the center of the camera's lens. Our approach was to initially determine the exact position and orientation of the camera on the ground and then use measurements to the navigation sensors to establish their exact positions. The camera exposure and the navigation data stream were synchronized by a custom-designed timing device with an accuracy of approximately 2 μseconds, providing a time-stamp for establishing a relationship between an image and measurements of the camera's position at that exact time. Given the high shutter speed of the camera during surveys and the stability of the aircraft, the direct georeferencing error due to this synchronization was negligible.

Data and Imagery Analysis

The data processing algorithm used 4 photogrammetric steps to improve georeferencing accuracy: 1) tie point generation, 2) bundle adjustment, 3) terrain model generation, and 4) ortho-mosaicking (Wolf and Dewitt 2000). Generation of tie points involved coordinate identification from navigation data of specific pixels in successive images, thus tying images together using common features. Bundle adjustment was the determination of aircraft position and attitude based on numerous navigation data points and tie point observations. The bundle adjustment process also could provide the coordinates of objects used as tie points; these coordinates were used in the third step to generate an approximate 3-dimensional model of the terrain in images. In the fourth step individual images were corrected for distortions caused by tilt and relief and were combined as a mosaic to create large maps. In combination, these postflight processing techniques allowed accurate georeferencing based on both navigation data and their analysis, rather than by relying solely on highly accurate sensors whose weight would prohibit use in small UASs.

Output imagery is in tagged-image file format (.TIFF), which allowed images to be compatible with common Geographic Information System software. If the target has high contrast compared with its background (such as a white bird over vegetation, or a wildfire), there is no need for further image processing. However, if the target item has low contrast, contrast or histogram manipulation may be required. Contrast or histogram manipulation is available in most image processing software packages. Image texture analysis also is a prospective option for improving the ability to discriminate between spectrally similar plant communities and is increasingly available in image processing programs.

RESULTS

During the iterative development of the Nova 2 UAS, the system and its predecessors were deployed in support of various research projects. Flights in 2005 over the National Bison Range used aerial videography for a population survey of bison (*Bison bison*) and yielded new photogrammetric techniques for the use of video imagery in aerial surveys (Wilkinson et al. 2009). Beginning in 2006, digital still photography was used in the UAS because of its higher resolution, which makes still images preferable over video for most applications. Oberneufmann (2007) used still images of vegetation in wetland impoundments to identify emergent plant species and create bathymetric maps. The procedure for synchronizing the camera shutter and navigation systems tends to be more straightforward for still imagery. Also, the combination of higher resolution images and greater optics quality provides better images when still-imagery payloads are used, compared with video systems of comparable size or weight.

Image resolution is determined by altitude, optics, and contrast between the target and its background. The Nova
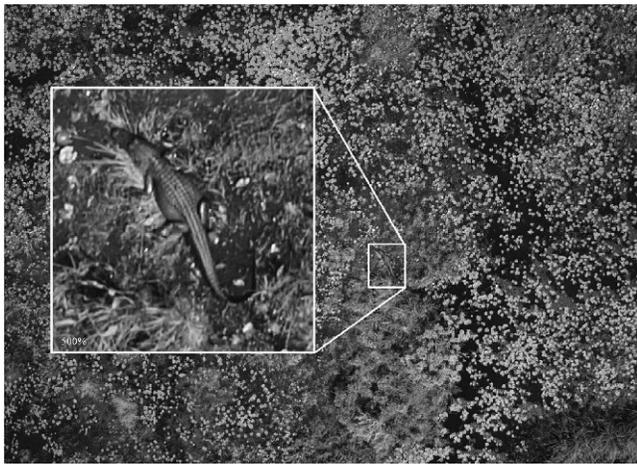
Figure 3. Image taken by University of Florida's Nova 2 unmanned aircraft system (UAS) at an altitude of 75 m, resulting in a pixel resolution of approximately 1 cm. These high-resolution georeferenced images can be used to estimate the size of individual animals such as this American alligator (*Alligator mississippiensis*), shown at 500% magnification in the inset image.

2's payload nominally delivered 2.5-cm image resolution at an altitude of 200 m. The Nova 2's visible-spectrum color imagery (i.e., blue-green-red, between 400-nm and 700-nm wavelength) is suitable for vegetation classification and monitoring, and surveys for non-cryptic wildlife (e.g., Fig. 3). A novel use of imagery collected by UAS is ground-truthing of satellite imagery (Maslanik et al. 2002), the resolution and spatial accuracy of which is lower than that available from many small UASs (e.g., Rango et al. 2006). At these high resolutions, georeferenced imagery can be used to estimate sizes of individual animals (Fig. 3).

In 2007–2008, missions in Florida explored the utility of UASs for shorebird surveys, in particular the endangered red knot (*Calidris canutus*; Brush and Watts 2008). Although aerial identification of the small, well-camouflaged birds was difficult, flights produced promising results with larger, more visible birds such as egrets (*Ardea alba*, *Bubulcus ibis*, and *Egretta* spp.), pelicans (*Pelecanus* spp.), and wood storks (*Mycteria americana*). Navigation data from these and subsequent test flights indicated that the Nova 2 maintains fidelity to a specified flight path with a mean deviation of 1.2 m (SD = 0.92 m) in horizontal position and 2.0 m (SD = 0.92 m) in altitude (Perry 2009). This navigational performance indicates high survey repeatability, particularly useful in areas that cannot be physically visited for plot demarcation. Imagery not subjected to photogrammetric adjustment using navigation and image data displayed edge error of 9.8 m (SD = 4.3 m); however, adjustment reduced error to 0.50 m (SD = 0.31 m), an order-of-magnitude improvement (Perry 2009).

DISCUSSION

Our work with UASs over the past decade indicates that small, autonomously operated aircraft, particularly those designed specifically for research, possess several characteristics that make them suitable for a wide variety of ecological

survey uses. In the future, near-infrared, thermal-infrared, and hyperspectral sensors will expand the ability of UASs to inform ecological questions with spatially explicit data. Certain types of vegetation are more readily differentiated in the near-infrared spectrum compared with the visible spectrum (Estes 1996). Such imagery can be used to monitor insect or disease infestations on vegetation (Hay 1997, Lang 1997, Lelong et al. 2008, Hill et al. 2009). Also, alga distribution in water or chemical contamination can be detected and analyzed (Richardson 1996, Rundquist et al. 1996, Gomarasca and Strobelt 1997). Thermal-infrared radiometers, which identify hot spots in imagery, now are sufficiently lightweight to be used in small UASs for detection, monitoring, and prediction of movement and intensity of wildland fires. This capability may lead to production of more accurate wildfire maps in near real-time with the aid of UASs.

Regulations Affecting UAS Use

For several years, UASs operated in an ambiguous legal environment in the United States. In 2007, the Federal Aviation Administration (FAA) issued a rule clarification concerning the operation of UASs that provided a mechanism for legal operation called a Certificate of Authorization (CoA; FAA 2007). The regulatory process is somewhat complex and is an intermediate step toward adoption of comprehensive UAS regulations in the United States (European and other nations have adopted, or are considering, similar legislation). Current regulations in the United States effectively prohibit commercial UAS operations, including private use of UASs or model aircraft for any purpose other than hobbyist operation. Government users or those affiliated with government entities may operate UASs after completion of the CoA process and approval by the FAA's UAS Program Office.

Small UASs (sUASs) will be regulated by new guidelines specifically created for this smaller size class. Because of their substantially reduced safety risk compared with larger aircraft, sUASs will be allowed to operate with less infrastructure and fewer personnel. These relaxed requirements further enhance the potential logistical, safety, and cost advantages of sUASs. In addition to creating a standardized definition of sUASs (aircraft <25 kg), FAA has drafted a set of sUAS operating guidelines. First, sUASs are restricted to daylight operations over uninhabited areas and within visual line of sight. Second, the crew of a sUAS must consist of a human pilot and ground station operator, both with some degree of specialized training, supplemented by a dedicated spotter to scan the vicinity of operations for other aircraft. Other proposed regulations delineate varying classes of sUASs, defining maximum altitude, speed, and other parameters depending on aircraft weight and the degree of operator training.

Considerations for Potential UAS Users

Compared with manned aircraft, UASs are more limited in range and flight duration but can generate large volumes of imagery and spatial data. These attributes make the clear

articulation of study objectives important in determining whether UASs represent effective and efficient means of collecting survey data. Potential users also should study current and proposed regulations to understand the potential impacts on envisioned uses of UASs. Study sites near airports or populated areas may be too restricted for UAS operations compared with remote sites. Likewise, nocturnal operations are not permitted under current regulations. Because regulations governing UAS use are currently changing, potential users should seek updated information months in advance of their planned research operation from the FAA's UAS Program Office (http://www.faa.gov/uas).

After determining appropriate sampling designs and data requirements, potential users should conduct their own survey of available UASs to determine which systems fulfill their needs and to familiarize themselves with operational and acquisition costs. The latter vary widely, from approximately US$30,000 for UASs with a low-resolution camera payload to >US$1,000,000 for turnkey systems with sophisticated sensors, long flight times, and support equipment. Although production costs of the Nova 2 are difficult to estimate, we believe that a UAS with similar capabilities can be manufactured for approximately US$75,000. This estimate includes sensors and electronics, for which costs can be considerable (e.g., US$8,500 for a Kestrel system and US$10,000 for an IMU in 2010). Cost-per-area estimates for UAS surveys are difficult because of the undeveloped public market for these services and uncertainties about the service life of airframe components. However, assuming a typical mission profile in which 240 ha is surveyed per flight and an airframe cost (minus payload) of US$5,000 amortized over a hypothetical operational life of 100 missions, survey costs for the Nova 2 could be estimated at approximately US$0.21/ha, or approximately US$50/flight hour. This estimate does include amortized acquisition or personnel costs, which represent the primary expense of UAS deployment, because maintenance and operational costs for the UASs are negligible by comparison. Costs of UASs are likely to decrease as technology improves and maturation occurs in the civilian UAS market and its regulation (Cox et al. 2006).

MANAGEMENT IMPLICATIONS

Adaptation and subsequent adoption of UAS technology originally developed for military applications by civilian researchers imitates the development and public acceptance of Geographic Information System (GIS) and GPS technology 2 decades ago. Unmanned aircraft systems and the sensors they carry may be expected to result in a revolution of similar magnitude, once the technology becomes sufficiently simplified and affordable for widespread adoption. As observed for GIS and GPS, UAS manufacturers will probably respond to increasing civilian demand by providing systems appropriate to the needs of researchers and practitioners. Increasing pressure from industry and user groups will simultaneously influence the adoption of legislation to provide a more user-friendly regulatory environment. Potential users of UAS technology are encouraged to begin defining their data and logistics requirements, communicating those broadly, and planning for the incorporation of UASs into long-term research and monitoring. We believe that future market forces will result in UASs that are available and affordable for civilian users.

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