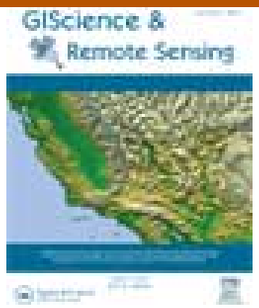

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Small Unmanned Aerial Systems (sUAS) for environmental remote sensing: challenges and opportunities revisited

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Hardin and Jensen (2011) presented six challenges to using small Unmanned Aerial Systems (sUAS) for environmental remote sensing: challenge of the hostile flying environment, challenge of power, challenge of available sensors, challenge of payload weight, challenge of data analysis, and challenge of regulation. Eight years later we revisit each of the challenges in the context of the current sUAS environment. We conclude that technological advances made in the interim (as applied to environmental remote sensing) have either (1) improved practitioner ability to respond to a challenge or (2) decreased the magnitude of the challenge itself. However, relatively short flight time remains a primary challenge to using sUAS in environmental remote sensing.

Keywords: sUAS; sUAS challenges; sUAS power; sUAS payload; sUAS regulations

Introduction

The potential for environmental remote sensing using small Unmanned Aerial Systems (sUAS) was effectively argued by Tomlins (1983) over 30 years ago, reiterated by Laliberte, Rango, and Herrick (2007), Watts, Ambrosia, and Hinkley (2102)), Anderson and Gaston (2013), Colomina and Molina (2014), Everaerts (2008), Pajares (2015), and Salamí, Barrado, and Pastor (2014), and more recently explored by Klemas (2015) and Jensen (2017). In 2011, we agreed with previous researchers that sUAS had significant potential in environmental remote sensing. We also described six challenges to their consistent use in environmental remote sensing (Hardin and Jensen 2011). These included: 1) the hostile sUAS flying environment, 2) the limits of on-board power; 3) the paucity of commercially available lightweight sensors; 4) the difficulties involved in managing and analyzing the large imagery volume generated during a flight; 5) the constraints on payload weights, and 6) the burden imposed on researchers under United States federal regulations designed to ensure the safety of commercial air travel. With the increased research, development and production of commercial drones and sensors, more defined regulatory requirements, and the advent of commercially available pre and post processing software to specifically handle sUAS data, each of the six challenges have been addressed in the preceding years. In fact, sUAS have recently been used in precision agriculture to study viticulture (Matese et al. 2015), to study coastal areas (Green and

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Hagon 2017), in a method to identify green algae (Flynn and Chapra 2014), and in community-based forest monitoring (Paneque-Galvez et al. 2014).

The intent of this paper is not to review all currently available sUAS, sensors available on sUAS, flight planning software, imagery analysis, and regulation. Rather, we revisit the challenges listed by Hardin and Jensen (2011) and describe the current state of affairs for each. We conclude that while the challenges of environmental remote sensing using sUAS have been met to varying degrees, the most serious challenge to consistent use is limited flight times.

The hostile sUAS flying environment

Small Unmanned Aerial Systems, defined by the United States Federal Aviation Administration as unmanned aircraft that weigh less than 55 pounds (24.9 kilograms; FAA 2018), are often required to fly in harsh natural environments, including environments with high wind and obstacles. These environmental conditions have not changed, but modern sUAS are better able to manage them.

Most sUAS documentation provides set limits for environmental operating conditions where the sUAS is safe to fly. Of course, these limits should be observed even if a data-gathering sortie would be precluded. However, even if manufacturer recommendations are satisfied, pilots should recognize their own limitations before flying a sUAS in any situation. For example, assume that manufacturer guidelines state that safe flights can be undertaken at wind speeds below 7 m/sec. However, if the pilot-in-command (PIC) is only comfortable flying under calm wind conditions, then that becomes the defacto criteria used to determine "safe" flying conditions. Interaction between wind and obstacles can constrain flights further. For example, obstacles may present little challenge on a calm day, but can present significant difficulties even if wind speeds are below manufacturer-set limits.

However, in some instances sUAS flights in obstacle-rich locations might be unavoidable; for instance, in urban vegetation studies. To limit the dangers of obstacle collision, some sUAS now have collision technology that can prevent sUAS from striking objects such as buildings, trees, towers, etc. For example, the DJI Phantom 4® quad copter uses machine vision i.e., optical sensors in the front of the aircraft that stop the aircraft from colliding with an object when the aircraft is flying at moderate speeds. This intervention requires no pilot action. The Phantom 4® also displays the distance to an obstacle on the display attached to the remote control. The obstacle sensory range of Phantom 4® is 2–49 feet (0.7 – 15m; DJI 2018) and flight software prohibits the sUAS from approaching these obstacles. The Phantom 4® also has acoustic sensors on the bottom of the aircraft to ensure it does not land on unsafe surfaces. Obstacle avoidance technology is maturing very rapidly. It is likely that nearly all sUAS designed to carry cameras will have obstacle-avoidance technology in the near future.

Operators using fixed wing sUAS must still be very vigilant to changes in wind speed or direction. However, technology available on multicopters can help mitigate the impact of turbulence without needing pilot intervention. Elements of this technology include GPS, inertial measurement units, accelerometers, gyroscopes, and compasses. These make it possible to maintain stable flight even under moderately windy conditions (e.g., 7 meters/second; ~ 25 km/hour). In fact, when flying many multicopters, the pilot can release the controls and the drone will hover in space. This is possible even when wind is present. Most sUAS manufacturers claim that their flying vehicles can operate at 8.3 meters/second (30 km/hour; Von Bueren et al. 2015) but flights may need to be interrupted at considerably lower wind speed. In our experience, wind greater than 7 meters/second (~ 25 km/hour) generally restricts or shortens flights.

While the cruise phase of fixed-wing sUAS flight is usually safe, fixed-wing take-off and landing requires significant pilot skill and favorable conditions. In contrast, current multicopter models automate takeoff and landing for a pilot. For example, many quadcopters will hover a few feet above the ground immediately after takeoff. This permits the pilot to visually verify that the aircraft is operating correctly before beginning data acquisition. To land a quadcopter, the pilot engages a "return to home" function on the control panel that commands the aircraft to land at its takeoff point. Other safety functions include "return to controller," which commands the aircraft to return to controller's location, and "land now," which instructs the aircraft to land immediately. These take-off and landing capabilities come standard with many multicopters, greatly increasing aircraft survival probability. In summary, sUAS still fly in hostile environments. However, most advanced sUAS help mitigate this with advanced flight controls and obstacle avoidance capabilities. We encourage all sUAS users to become familiar with model specific environmental conditions and limits.

The challenge of power

Most sUAS are powered by electric batteries; others are powered by combustion engines using either gasoline or methanol as fuel. Electricity, gasoline, and methanol all have advantages and disadvantages as sources of power for sUAS (Hardin and Hardin 2010). However, because electrical batteries are used to power most multicopter sUAS, this discussion will focus on that source.

Current sUAS manufacturers provide intelligent battery systems that transmit to the pilot indicators of battery power and estimated flight time remaining. Most sUAS batteries provide between 10 to 30 minutes of flight time. For example, a DJI Phantom 4® battery (5400mah @ 15vdc) provides roughly 27 minutes of flight time. However, this is highly variable, and depends on factors such as the absolute aircraft altitude, height of the aircraft above ground level, weight of payload, camera power demands, and wind (e.g., Bhardwaj et al. 2016). The actual amount of flight time for a single sortie may not be sufficient for a given application. If more than one battery is needed, it is simple to swap intelligent batteries and instruct the aircraft to continue data acquisition along the flight line where battery change was needed. Finally, on most sUAS, the single intelligent flight battery powers the aircraft and all peripherals including the camera(s), GNSS receiver, etc. This obviates the need for multiple batteries (and extra battery weight) to power individual systems.

Problems related to battery power constraints are also mitigated by careful mission planning. This can be done using software that provide users pilots very detailed flight plans. In addition, these applications frequently permit autonomous flight i.e. the application controls the aircraft via the aircraft controller with minimal input from the operator after launch. In the planning stage of a mission, the user draws the image area on an aerial photograph in the application. Then, after determining photographic mission parameters (e.g. height of the aircraft Above Ground Level (AGL), photo sidelap, photo endlap, aircraft speed, etc.), the application calculates the precise flight lines needed to complete the mission. We feel that the automated mission planning process provides the most efficient use of flight time and thus maximizes battery power usage. Mission planning software is available from sUAS manufacturers (e.g., DJI GS Pro®) or other application developers (e.g., DroneDeploy®, AgVault®, Pix4DCapture®, etc.).

Given the foregoing, the challenge of power, largely a function of study area size, increases in difficulty as the study area size increases. Under scenarios where the pilot has FAA permission to fly beyond visual line of sight (VLOS) over a large geographic area,

current battery technology and power management would almost certainly be insufficient. It is hoped that improvements in battery development providing batteries with both higher capacity and lower weight will enable much longer flights in the near future. Therefore, while the challenge of power will continue to be an issue, we hope that sUAS power (batteries, fuel, etc) will continue to be addressed by researchers and sUAS companies.

The challenge of sensors and paucity of commercially available sensors

When Hardin and Jensen (2011) was published, sophisticated sensors for sUAS were available only to researchers with both large budgets and an implicit willingness to sacrifice the sensor in a crash. Nowadays, there are a variety of sensors available for sUAS. In addition, flight pilot assists (described above) mean fewer expensive instrument losses. Most rotary wing sUAS come equipped with a relatively good RGB camera capable of acquiring high quality RGB still images (e.g., > 20 megapixels) and videos (e.g., > 4k video).

When a remote sensing project goal is to collect high-resolution still imagery for interpretation or photogrammetry, sUAS with integral RGB cameras can be employed. These RGB cameras usually include CMOS areas between 29 mm^2 and 225 mm^2 and pixel arrays of at least 12 million. Seven of these integrated-camera sUAS are shown in Table 1. While instruments such as small infrared cameras can be mounted on these sUAS, they are not designed for custom payloads. All are available with GPS/GLONASS

Table 1. A sampling of sUAS models suitable for remote sensing.

sUAS Model	CMOS array (megapixels)	CMOS area (mm^2)	Flight time (min)	Weight (kg)	Maximum Payload weight (kg)
Integral Camera					
DJI Mavic Air®	12.4	29	21	0.4	*
DJI Mavic Pro Platinum®	12.4	28	30	0.7	*
DJI Phantom 4 Advanced®	20.0	116	30	1.4	*
DJI Phantom 4 Pro®	20.0	116	30	1.4	*
Yuneec Tornado H920 Plus†††®	16.0	225	25	5.0	*
Yuneec Typhoon H®	12.4	29	25	1.9	*
Yuneec Typhoon H Plus®	20.0	116	25	2.0	*
Custom Instrumentation					
DJI Spreading Wings®	†	†	††	**	7.0
DJI Matrice 600®	†	†	††	**	5.5
DJI Inspire 2®	†	†	††	**	3.4
Yuneec H520®	†	†	††	**	0.5

Notes:
*sUAS with integrated cameras are not designed to carry payloads.
** Total takeoff weight is dependent on payload and battery weight.
† A variety of active and passive instruments (with different weights) may be mounted on custom instrumentation sUAS.
†† Although flight time varies with flight speed, wind speed, and so forth, in these cases, flight time is highly impacted by the payload weight. For sUAS designed to carry custom instrumentation, a hover time around 15 minutes would be normal.

navigation aids, and 22 minute flight times are typical. Absolute maximum ceilings above sea level, and maximum flight heights above-ground vary. Table 1 also shows four sUAS designed for carrying a variety of gimbals and instruments sold by both the vendor and third-parties. Flight time for these custom instrument sUASs are highly dependent on flight profile, environmental factors, and payload weight.

While these types of cameras are sufficient for many applications, some projects require spectral information outside of the visible spectrum. For example, vegetation researchers may require a near-infrared band, while urban researchers require a band that measures thermal energy emitted by impervious surfaces. There are now several companies that currently provide these types of sensors. For example, Sentera® (https://sentera.com/) manufactures and mounts near-infrared cameras on existing sUAS platforms. In Figure 1, a Sentera SingleNDVI® camera is attached to a Phantom 4®. This camera works in tandem with the Phantom 4's stock RGB camera. When the image acquisition button is activated by the PIC or software, the NDVI image is collected simultaneously with the RGB picture. Additionally, Parrot®, Inc. markets the Sequoia® multispectral camera that collects, blue, green, red, red-edge, and near-infrared reflectance data at the instant of exposure. Thermal-infrared sensors (e.g., manufactured by FLIR®, Inc.) and Light Detection and Ranging (LiDAR) sensors are available for use on sUAS. The latter sensor is new to the civilian sUAS sector, and price may be prohibitive.

Most sUAS provide real-time video transmission to the remote control point so the pilot and camera operators can track the flight accurately. As noted by Hardin and Jensen (2011), in-flight video transmission is also useful because it can: 1) be used for low-resolution data collection and 2) transmit information regarding aircraft health (e.g., battery level) and geographic position via a video overlay.

Available Sensors

There are a variety of sensors available for sUAS-based environmental remote sensing. The most popular are integral cameras in the visible spectrum. As mentioned above (see Table 1) these are digital cameras with pixel array sizes between 12 and 20 million. While the resolution of these cameras is partially a function of pixel array sizes, other important factors include camera optics quality, shutter speed, ISO, forward image motion, vibration, height above target, and noise inherent in the camera electronics. In practical terms,

Figure 1. DJI Phantom 4® equipped with A) a Sentera® Single NDVI camera®, and B) the RGB camera.

RGB camera resolution is maximized at low sUAS speeds and low flying heights. Faster shutter speeds and lower ISOs also contribute to better resolution.

Multispectral or specialized vegetation cameras can also be conveniently carried by a sUAS. Some are light enough to fly in tandem on sUAS with integrated camera systems (e.g., Figure 1). The typical spectral bands captured with these sensors are blue, green, red, and infrared. Other sensors capture only green, red, and infrared bands.

Some of these multispectral sensors are specially designed to capture data specific to vegetation indices such as NDVI, red edge, or normalized difference red edge. For example, the Sentera (Minneapolis, MN) Quad Sensor captures traditional red, green, and blue data, and has three specialized sensors to acquire data centered at 655, 725, and 800 nm respectively. The purpose of this sensor suite is to capture vegetation indexes such as NDVI, NDRE, and Green NDVI. Table 2 contains a sampling of multispectral sensors available for sUAS. The resolution of these sensors at a flying height of 100 m is about 10 cm

Like the multispectral systems mentioned, hyperspectral sensors for sUAS have also been used in several agriculture and forestry applications. Adão et al. (2017) reviews both the use of hyperspectral sensors on sUAS and lists commercial variants. The number of bands available in current hyperspectral sensors ranges from 40 to 660, with a spectral range between about 400 nm and 1000 nm typical. Short-wave infrared sensors with ranges between about 850 and 2000 nm are also available (Adão et al. 2017, 7).

A significant challenge to successfully using multispectral and hyperspectral data acquired from sUAS is the low spatial resolution of the imagery in comparison to the typical RGB camera. Although a few higher spatial resolution sensors can be found, most small pushbroom hyperspectral sensors have cross-track spatial resolutions between about 640 and 1000 pixels. The resolution of the multispectral cameras described in Table 2 is typically 1248 × 950. In contrast, a typical 12MP digital camera mentioned in Table 1 above has a CMOS array of 4000 × 3000 pixels.

The other popular class of sensors designed for sUAS is lidar. Lidar technology can be used in a variety of applications, including mining, construction planning, topographic mapping, and environmental management. A more recent remote sensing technology than multispectral cameras, lidar has increased in popularity since the payload weight, package size, and power requirements were all reduced sufficiently for sUAS hosting.

A sampling of lidar sensors designed for photogrammetry (rather than navigation) are included in Table 3. Except for the Riegl VUX-1UAV® lidar, the characteristics are similar. Unlike the passive sensors described above, battery weight is a significant component of the sensor package. Lidar mounted UAVs have found some use in forestry, archaeology, civil engineering applications, and infrastructure corridor monitoring. For

Table 2. Multispectral sensors suitable for hosting on sUAS.

Model	High Res RGB	Other Bands	Weight (grams)
Sentera Quad Sensor®	No	RGB + 655 nm, 725 nm, 800 nm at 1.2 MP	170
Parrot Sequoia®	16 MP	Green, red, red edge, near infrared at 1.2 MP	135
MicaSense RedEdge-M®	No	Blue, green, red, red edge, near infrared at 1.2 MP	173
Tetracam ADC Lite®	No	Red, green, near infrared at 3.2 MP	200
senseFly eBee MultiSPEC 4C®	No	Green, red, red edge, near infrared at 1.2MP	160

Table 3. Lidar sensors designed for photogrammetry.

Model	Range (m)	Accuracy (± cm)	PPS*	Weight (kg)	Power consumption (watts)
Riegl VUX-1UAV®	55–350**	1	50K – 550K**	3.7	60
RouteScene®	100	2	700K	2.5	11†
Velodyne HDL-32E®	100	2	695K – 1.4M	1.0	12
Velodyne Puck Hi-Res®	100	3	300K-600K	0.8	8
Velodyne Puck Lite®	100	3	300K-600K	0.6	8
YellowScan Mapper II®	150††	5	18.5K – 40K	2.1	10

* Points Per Second
** Airborne applications. Depends on selected laser pulse repetition rate. Lower altitudes permit higher rates. At 100m above ground level, maximum rate is approximately 550K PPS.
† Estimated.
†† Absolute. 75–100 meters typical

example, Wallace et al. (2012) found a UAV lidar system competent to measure tree location, height, and crown width in an experiment conducted at a university farm in Tasmania.

The long wave infrared part of the electromagnetic spectrum is found between about 8 and 15 nanometers. Advances in infrared thermography have included thermal sensors designed for hosting on sUAS platforms. Infrared sensors can be used in a variety of applications such as effluent monitoring, urban heat island studies, mammal inventory, security monitoring, sea ice mapping, fighting forest fires, infrastructure monitoring, and soil moisture assessment. In 2017, there were about a dozen thermal sensors suitable for sUAS. A sampling of these sensors are summarized in Table 4. As the table shows, although the thermal spectral range of the cameras is very similar, there is a wide variation in other specifications. The precision of collected data, measured in degrees Celsius, is not published for many sUAS thermal cameras, but a value of about 5 degrees C would be typical within the middle of the sensor temperature range. To obtain absolute temperatures from sUAS camera digital numbers, calibration and emissivity data are required. In our experience temperature measurements taken in streams and ponds concurrently with the overflights can be used for calibration.

Table 4. FLIR sensors available for use on sUAS.

Model	Pixel array	Weight (grams)	Spectral range (micrometers)	Temperature range (°C)
Workswell WIRIS 2nd gen. 640®	640 x 512	390	7.5 – 13.5	−25 – + 150*
Yuneec CGOET®	160 x 120	278	8.0 – 14.0	−10 – + 180
Thermoteknix MicroCAM 3®	384 x 288†	107	8.0 – 15.0 ††	−40 – + 70
FLIR Vue Pro®	336 x 256	106	7.5 – 13.5	−20 – + 50

* Resource management range cited. Other range options are available.
† Configurable resolution. 640 × 480 alternative.
†† Estimated

The paucity of available sensors has largely been mitigated by the amount of currently available sUAS and sUAS sensors. However additional sUAS airframe and sensor development will continue to inform sUAS environmental remote sensing research.

The challenge of payload weight

The sUAS research of Hardin and Jensen was always dogged by the need to minimize payload weight. Weight requirements constrained their sUAS battery, avionics, and sensor choices. When deploying sensors on an sUAS, the payload weight must still be considered.

Increasing weight involves tradeoffs. Increased weight can increase aircraft stability but will decrease flight time. Too much weight can also make an sUAS too dangerous to fly as surplus engine power, designed into the aircraft for obstacle avoidance or other emergencies, is required to lift the payload and not available for its intended purpose.

The maximum takeoff weight of the DJI Phantom 4® shown in Figure 1, is 3.3 kilograms. This is somewhat light for a sUAS craft which is designed for carrying cameras. Other small rotary wing sUAS in the "hobby" category can lift between 4 and 8 kilograms. Heavy-lift multicopters suitable for research and available for commercial purchase can carry over 22 kilograms. This provides a significant payload capacity for a research agenda requiring it and a research budget that can afford it. To be sure, heavier payloads can be carried in modern multicopters than anything flown by Hardin and Jensen before 2011. In summary, the challenge of payload capacity perseveres, but there is hope with advanced and robust airframe and propulstion technology.

The challenge of data analysis

Large quantities of digital data can be acquired on a sUAS sortie. For example, just a few minutes of 4K video data collection can create a video file greater than a gigabyte. Collecting still imagery of reasonable scale and overlap over areas images over an area of 20 acres can result in hundreds of individual images that need to be processed. As noted in Hardin and Jensen (2011), processing this amount of data can be a challenge. The problem is not one of computer storage. Large capacity hard drives, large capacity micro-drives (e.g., microSD cards), and on demand cloud storage (e.g., Box, Dropbox, etc.) make data storage a non-issue. This remains true even when multiple sorties and cameras are employed. The problems of preprocessing are mostly auxiliary in nature. These issues primarily originate in the complexity of managing the large number of data files typically produced in sUAS flights.

Much of the problem cited by Hardin and Jensen (2011) was in preprocessing the image – creating a georeferenced image with uniform map-like geometric characteristics that could be analyzed thereafter. When wind and turbulence increased, aircraft pitch and roll introduced tilt displacement into their imagery. In moderate crosswind conditions, significant noticeable yaw was required to keep the aircraft moving along the desired flight track. As a result, determining the geographic coordinates of the image center, rectification, and image mosaicking procedures required time consuming manual manipulation of each photograph. Even so, results were frequently unsatisfactory, and a large percentage of imagery was discarded as unusable. Like a high-wing propeller aircraft (compared to low wing), the center of mass of a sUAS carrying a camera under its belly makes the craft inherently stable – in the absence of other forces, the primary axis of the sUAS would return to vertical from gravity alone. Although crosswinds will move an sUAS horizontally off flightpath, the natural stability and automated motion-stabilizing pilot aids of some sUAS (described above) decrease much of the turbulence problem. In addition, modern sUAS flight recorders

collect positional data for each image and video acquired. This geotag information can be used to help accurately georeferenced the aerial images and video.

As a quadcopter moves downtrack, it tilts. In fact, the physics of quadcopter flight *require* it to tilt for downtrack progress to be made. Many sUAS cameras are gimbal mounted, obviating the problems of tilt. If not, there will always be a measure of tilt displacement in resulting imagery. However, our quadcopter image acquisition flights are usually done at slow speeds to reduce forward image motion blur in the imagery. The quadcopter tilt is very small in such cases. In our own research, we have not had enough obvious tilt displacement to require correction. In the absence of evidence, we offer a conjecture. Under windless conditions where quadcopter speed is constant, the aircraft tilt would be consistent in direction and magnitude from photo to photo. This consistency would make automated processing of the imagery straightforward once the angle of tilt is determined. We recognize that 1) calculating the magnitude of the tilt is difficult, 2) any quadcopter rotation complicates the matter, and 3) image preprocessing is seldom straightforward.

To facilitate data processing and analysis, several processing software packages and applications have been developed by vendors and included as an accessory to the UAV (e.g., Pix4D®, DroneDeploy®, Drone2Map®). Dronedeploy® allows users to upload imagery – including GNSS receiver and flight recorder data – to their servers where the data are processed to create orthophotos, digital terrain models, point clouds, and many other datasets. Pix4D® has some cloud-based services. However, Pix4D® and Drone2Map® typically process aerial images on the user's machines. Open source toolkits/packages such as OpenDroneMap (http://opendronemap.org/) are slowly springing up which provide an alternative to vendor provided postprocessing software.

In our experience, despite the large volume of still imagery and video acquired during sUAS missions, contemporary quadcopter sUAS data handling and analysis is less complicated and ad-hoc than when Hardin and Jensen (2011) was written. The software listed above enables researchers to create georeferenced and preprocessed data with less manual interaction. Additionally, researchers have started taking interest in automating, and minimizing error with, the process of georeferencing and mosaicking images (Zheng et al. 2017). Also, cloud computing offerings by federal agencies for example NASA's NEX supercomputing cluster and other industry providers such as Amazon Web Services (AWS), Microsoft Azure, and Google Cloud Platform not only provide ample computing resources that might be needed it also obviates the need for moving the data back and forth between servers and clients. NEX and AWS provide viable alternatives for researchers interested in applying artificial intelligence and machine learning methods to earth science data (Ganguly et al. 2017). While the cloud service providers obviate the need to think about hardware and software, especially image processing related, still remains a bottleneck. Most image processing tasks, especially novel algorithms being developed for image processing and computer vision, are being developed as software libraries (Bradski 2000; Christophe, Inglada, and Giros 2008; Inglada and Christophe 2009; van der Walt et al. 2014) which are easy to program in but not at all user friendly. The problem of data analysis has largely been resolved for most sUAS research, and we anticipate that even more applications and software packages will be available in the future.

The challenge of regulation

In the United States, sUAS flight is regulated by the Federal Aviation Administration (FAA). Until recently, nearly all environmental research utilizing sUAS within the National Airspace System was conducted within the bounds set by a Certificate of

Authorization (COA). COAs were generally difficult to obtain and COA approval consisted of fulfilling many requirements as described in Hardin and Jensen (2011). However, the FAA recently implemented rules and regulations specifically for recreational as well as commercial sUAS users. The purpose of this section is not to directly quote FAA flight rules and regulations. However, the section describes many of the FAA's policies that may be useful to researchers using sUAS in the United States.

The FAA defines sUAS as: "An unmanned aircraft system is an unmanned aircraft and the equipment necessary for the safe and efficient operation of that aircraft. An unmanned aircraft is a component of a UAS. It is defined by statute as an aircraft that is operated without the possibility of direct human intervention from within or on the aircraft" (FAA 2017; https://www.faa.gov/uas/faqs/). Recreational sUAS use is defined by the FAA as "Recreational or hobby UAS use is flying for enjoyment and not for work, business purposes, or for compensation or hire. . . . UAS use for hobby is a "pursuit outside one's regular occupation engaged in especially for relaxation." UAS use for recreation is "refreshment of strength and spirits after work; a means of refreshment or diversion" (FAA 2017; https://www.faa.gov/uas/faqs/). Commercial users of sUAS are defined as those users who do not fit the definition of a recreational user.

Recreational sUAS users do not need to have a remote pilot license to fly their sUAS. However, they must adhere to the basic safety guidelines (FAA 2017; https://www.faa.gov/uas/getting_started/fly_for_fun/). All other non-recreational (or commercial) sUAS pilots must follow the guidelines in the Small UAS, Part 107 rule with the following pilot requirments (FAA 2017; https://www.faa.gov/uas/getting_started/fly_for_work_business/):

(1) Must be at least 16 years old
(2) Must pass an initial aeronautical knowledge test at an FAA-approved knowledge testing center
(3) Must be vetted by the Transportation Safety Administration (TSA)

After obtaining a remote pilot license, a non-recreational pilot can pilot a sUAS that weighs less less than 55 pounds and is registered with the FAA. An sUAS may be registered at the FAA's sUAS website (https://registermyuas.faa.gov/) at a cost of $5 for two years. Further, non-recreational remote pilots are bound by eight operating rules (FAA 2017; https://www.faa.gov/uas/getting_started/fly_for_work_business/):

(1) May only fly in Class G airspace. Class G airspace is uncontrolled airspace that extends from the Earth's surface to the base of Class E airspace (FAA 2017)
(2) Must keep the aircraft in sight at all times (visual line-of-sight)
(3) Must fly under 400 feet
(4) Must fly during the day
(5) Must fly at or below 100 mph
(6) Must yield right of way to manned aircraft
(7) Must NOT fly over people
(8) Must NOT fly from a moving vehicle

Some of these rules may impact environmental remote sensing. For example, if a researcher wishes to study urban heat using a FLIR sensor mounted on an sUAS, the researcher can not fly over people while collecting data. This may make data collection very difficult. However, each of the rules above are subject to FAA waiver. So, permission may be granted to fly over people in urban and other areas provided that the appropriate

waiver has been granted. Remote pilots may obtain waivers via the FAA's Request a Waiver website. (https://www.faa.gov/uas/request_waiver/).

Prospective pilots can study for the test with materials provided by the FAA and through online or in-person "ground schools" offered in many locations. After passing the Aeronautical knowledge test, the prospective pilot must still complete FAA Form 8710–13 for a remote pilot certificate (FAA Airman Certificate and/or Rating Application).

Like any FAA certified pilot, certified sUAS pilots must keep accurate and up-to-date flight logs detailing pre-flight, in-flight, and post-flight checklists. Further, any scheduled maintenance and/or repairs to the aircraft should be noted in the log. Remote pilots are required to hand over their flight logs and/or checklists anytime a representative from the FAA asks for them. There are many good sources available to determine what should be noted in the log including several recommendations for each flight phase (Air Vid 2017; Drone Wisdom, http://dronewisdom.com/drone-checklist/#1482115659838-c4125a60-31be; see Appendix).

The FAA has made the rules and regulations governing sUAS flight much easier to understand. Further, the remote pilot license process is very clear and the license itself provides a very succinct credential for remote pilots who fly sUAS for commercial purposes. It is imperative that those pilots doing commercial work obtain their remote pilot certificate and follow the rules and regulations set by the FAA. While a license does not remove pilot liability in case of an accident, an unlicensed pilot involved in an accident may increases both civil and criminal liability. The FAA regulations described above represent significant progress toward standardizing sUAS hobby and commercial flights in the United States. However, laws and policies are subject to change, and researchers should often check to make sure they are in compliance with current standards.

Flight regulations and rules in other countries

Each country has their own sUAS laws and policies. Several websites have been created to aid sUAS pilots in understanding these laws and policies, such as, 'Global Drone Regulations Database, (GDRD 2018) and 'Master List of Drone Laws (UAV Coach 2018). sUAS pilots can find flight information for individual countries by searching through these websites. Usually, the website will list general flight requirements and provide a link to the country's official flight documentation policies. We recommend that anyone wishing to fly sUAS directly check the host country's policies to make sure they are fully in compliance with all flight rules and regulations.

Conclusion

All aircraft regardless of their size or purpose face the challenges cited in Hardin and Jensen (2011). For example, all aircraft have weight limits and are impacted by turbulence. Even so, the challenges they identified with using sUAS limited its practical utility as a widely applicable research tool. Based on our recent experience, we provide a conjecture. If the photographic flights upon which we based our observations were flown nowadays under identical environmental conditions, the six challenges we listed would be much less daunting and the final image products more valuable. However, challenges remain. Of the six challenges discussed herein, we consider short flight-times to be the most serious technological issue remaining. The difficulty of piloting on windy days remains the greatest environmental difficulty to sUAS employment.

This improvement between 2011 and the present came from technological advances. In the past, like most improvements in remote sensing, increased capabilities in sUAS were

driven by military needs to create weapons platforms, gather intelligence, and acquire imagery for strategic and tactical use (Hardin and Jensen 2011). Now, commercial hardware and software companies have made sophisticated sUAS aircraft and software available to the general public. While the sUAS commercial technology continues to evolve and progress (including both hardware and software) we recommend that environmental remote sensing researchers consider (or reconsider) using sUAS in a large variety of research projects.

We look forward to future advances and developments in sUAS remote sensing including: advances in aircraft; greater availability of multispectral, thermal-infrared, and LiDAR sensor systems; and longer-life intelligent battery technology. Of course, more user-friendly and sophisticated flight planning, data preprocessing, and data reporting software would be welcome. Furthermore, evolution in sUAS regulation is possible – all potential sUAS users should stay up-to-date with those changing rules.

Disclosure statement

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References

Adão, T., J. Hruška, L. Pádua 2, J. Bessa, E. Peres, R. Morais, and J. J. Sousa. 2017. "Hyperspectral Imaging: A Review on UAV-Based Sensors, Data Processing and Applications for Agriculture and Forestry." *Remote Sensing* 9: 1–30. doi:10.3390/rs9111110.

Anderson, K., and K. J. Gaston. 2013. "Lightweight Unmanned Aerial Vehicles Will Revolutionize Spatial Ecology." *Frontiers in Ecology and the Environment* 11 (3): 138–146. doi:10.1890/120150.

Bhardwaj, A., L. Sam, F. J. Akanksha, Martin-Torres, and R. Kumar. 2016. "UAVs as Remote Sensing Platform in Glaciology: Present Applications and Future Prospects." *Remote Sensing of Environment* 175: 196–204. doi:10.1016/j.rse.2015.12.029.

Bradski, G. 2000. "The OpenCV Library." *Dr. Dobb's Journal of Software Tools*. http://www.drdobbs.com/open-source/the-opencv-library/184404319

Christophe, E., J. Inglada, and A. Giros. 2008. "Orfeo Toolbox: A Complete Solution for Mapping from High Resolution Satellite Images." *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 37 (PART B4): 1263–1268.

Coach, U. A. V.. 2018. "Master List of Drone Laws (Organized by Country)." https://uavcoach.com/drone-laws/.

Colomina, I., and P. Molina. 2014. "Unmanned Aerial Systems for Photogrammetry and Remote Sensing: A Review." *ISPRS Journal of Photogrammetry and Remote Sensing* 92: 79–97. doi:10.1016/j.isprsjprs.2014.02.013.

DJI. 2017. https://www.dji.com/phantom-4/info#specs.

Everaerts, J. 2008. "The Use of Unmanned Aerial Vehicles (Uavs) for Remote Sensing and Mapping." *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 37 (2008): 1187–1192.

FAA. 2017. "Airspace." https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/17_phak_ch15.pdf.

FAA. 2018. "Unmanned Aircraft Systems." https://www.faa.gov/uas/media/faa-uas-part107-flyer.pdf.

Flynn, K. F., and S. C. Chapra. 2014. "Remote Sensing of Submerged Aquatic Vegetation in a Shallow Non-Turbid River Using an Unmanned Aerial Vehicle." *Remote Sensing* 6 (112): 12815–12836. doi:10.3390/rs61212815.

Ganguly, S., S. Basu, R. Nemani, S. Mukhopadhyay, A. Michaelis, P. Votava, … U. Kumar. 2017. "Deep Learning for Very High-Resolution Imagery Classification." In: *Large-Scale Machine Learning in the Earth Sciences*. CRC press. Retrieved from https://www.crcpress.com/Large-Scale-Machine-Learning-in-the-Earth-Sciences/Srivastava-Nemani-Steinhaeuser/p/book/9781498703871

GDRD. 2018. "Global Drone Regulations Database." https://droneregulations.info/index.html.

Green, D. R., and J. J. Hagon. 2017. "Coastal Data Collection – Applying Geospatial Technologies to Coastal Studies." In: *Marine and Coastal Resource Management Principles and Practice*, edited by D.R. Green and J.L. Payne. *Chapter 7:* 102-120.

Hardin, P. J., and R. R. Jensen. 2011. "Small-Scale Unmanned Aerial Vehicles in Environmental Remote Sensing: Challenges and Opportunities." *GIScience & Remote Sensing* 48 (1): 99–111. doi:10.2747/1548-1603.48.1.99.

Hardin, P.J., and T.J. Hardin. 2010. "Small-scale Remotely Piloted Vehicles in Environmental Research." *Geography Compass* 4 (9): 1297–1311. doi: 10.1111/j.1749-8198.2010.00381.x.

Inglada, J., and E. Christophe. 2009. "The Orfeo Toolbox Remote Sensing Image Processing Software." In: *2009 IEEE International* Geoscience and Remote Sensing Symposium, Cape Town, South Africa, 12-17 July 2009. doi: 10.1109/IGARSS.2009.5417481

Jensen, J. R. 2017. "Drone Aerial Photography and Videography: Data Collection and Image Interpretation." *Apple iBook*. https://itunes.apple.com/us/book/drone-aerial-photography-and-videography/id1283582147?mt=11.

Klemas, V. V. 2015. "Coastal and Environmental Remote Sensing from Unmanned Aerial Vehicles: An Overview." *Journal of Coastal Research* 31 (5): 1260–1267. doi:10.2112/JCOASTRES-D-15-00005.1.

Laliberte, A. S., A. Rango, and J. Herrick. 2007. "Unmanned Aerial Vehicles for Rangeland Mapping and Monitoring: A Comparison of Systems." Paper presented at The American Society for Photogrammetry and Remote Sensing Annual Conference, Tampa, FL, May 7–11.

Matese, A., P. Toscano, S. F. Di Gennaro, L. Genesio, F. P. Vaccari, J. Primicerio, C. Belli, A. Zaldei, R. Bianconi, and B. Gioli. 2015. "Intercomparision of UAV, Aircraft and Satellite Remote Sensing Platforms for Precision Viticulture." *Remote Sensing* 7 (3): 2971–2990. doi:10.3390/rs70302971.

Pajares, G. 2015. "Overview and Current Status of Remote Sensing Applications Based on Unmanned Aerial Vehicles (Uavs)." *Photogrammetric Engineering & Remote Sensing* 81 (4): 281–329. doi:10.14358/PERS.81.4.281.

Paneque-Galvez, J., M. K. McCall, B. M. Napoletano, S. A. Wich, and L. P. Koh. 2014. "Small Drones for Community-Based Forest Monitoring: An Assessment of Their Feasibility and Potential in Tropical Areas." *Forests* 5 (6): 1481–1507. doi:10.3390/f5061481.

Salamí, E., C. Barrado, and E. Pastor. 2014. "UAV Flight Experiments Applied to the Remote Sensing of Vegetated Areas." *Remote Sensing* 6 (11): 11051–11081. doi:10.3390/rs61111051.

Tomlins, G. F. 1983. "Some Considerations in the Design of Low-Cost Remotely- Piloted Aircraft for Civil Remote Sensing Applications." *The Canadian Surveyor* 37: 157–167.

van der Walt, S., J. L. Schönberger, J. Nunez-Iglesias, F. Boulogne, J. D. Warner, N. Yager, . . . T. A. Yu. 2014. "Scikit-Image: Image Processing in Python." *PeerJ* 2: e453. doi:10.7717/peerj.453.

Vid, A. 2017. "UAV Safety Checklist." https://air-vid.com/uav-safety-checklist/.

Von Bueren, S., A. Burkart, A. Hueni, U. Rascher, M. Tuohy, and I. Yule. 2015. "Deploying Four Optical UAV-based Sensors over Grassland: Challenges and Limitations." *Biogeosciences* 12 (1): 163. doi:10.5194/bg-12-163-2015.

Wallace, L., A. Lucieer, C. Watson, and D. Turner. 2012. "Development of a UAV-LiDAR System with Application to Forest Inventory." *Remote Sensing* 4: 1519–1543. doi:10.3390/rs4061519.

Watts, A. C., V. G. Ambrosia, and E. A. Hinkley. 2102. "Unmanned Aircraft Systems in Remote Sensing and Scientific Research: Classifications and Considerations of Use." *Remote Sensing* 4 (6): 1671–1692. doi:10.3390/rs4061671.

Wisdom, D. 2017. "Drone Checklist." http://dronewisdom.com/drone-checklist/#1482115659838-c4125a60-31be.

Zheng, M., S. Zhou, X. Xiong, and J. Zhu. 2017. "A Novel Orthoimage Msaic Method Using the Weighted A* Algorithm for UAV Imagery." *Computers & Geosciences* 109 (SupplementC): 238–246. doi:10.1016/j.cageo.2017.08.004.

Appendix

Sample sUAS checklist (Derived from Vid 2017; https://air-vid.com/uav-safety-checklist/, and Wisdom 2017; http://dronewisdom.com/drone-checklist/#1482115659838-c4125a60-31be)

Pre-flight

Airspace – Make sure you are authorized to fly in your area of interest. Note: the FAA has created a smartphone app called B4UFLY that relies on the smartphone's GNSS-derived location to let pilots know if they are in restricted airspace or if they need to communicate with an airport or other authority before they fly.

- Crew – Make sure your crew (if applicable; spotters, controllers, etc.) understands the mission and their role in making it successful.
- Obstacles/hazards – Note any obstacles (towers, power lines, buildings) that may interfere with the flight. Also, check for people and animals in the area.
- Weather – Check weather conditions to make sure they are suitable for flight.
- Propellors – Check props for defects (nicks, gouges, etc.).
- Airframe – Check airframe for any defects (loose or damaged motor, missing connections, etc.).
- Controller battery – Check to make sure the battery is sufficiently charged.
- Aircraft battery – Check to make sure the battery or batteries are sufficiently charged.
- Tablet/smartphone battery – Cake sure the tablet/smartphone is sufficiently charged (if applicable).
- Memory card – Make sure that adequate space is available for the mission.
- Power on – Turn on the controller, aircraft, and tablet/smartphone (if applicable).
- Tablet/smartphone application – Make sure the application is up to date.
- Firmware – Make sure both the controller and aircraft have the latest firmware.
- Compass – Make sure the compass is calibrated.
- Take-off location – Make sure the takeoff location is relatively flat and clear for ≥ 25 feet.
- Other landing sites – Identify other landing sites for the aircraft in case of an emergency landing or if the takeoff site becomes obstructed.
- Flight limits – Make sure that maximum altitude and "return to home" altitude are set.
- Camera – Make sure camera settings are appropriate for the mission.

Start of flight and flight

- sUAS motors – Make sure each motor starts and runs with no abnormal noise.
- Hover – While the sUAS hovers between 3 and 5 feet AGL, ensure all flight and gimbal controls are working properly.
- Home point – Make sure the sUAS records home point.
- Follow all FAA rules and regulations while in flight.
- Landing – Land the aircraft away from obstacles, people, and animals.

Post-Flight

- Shutdown – Turn off the power to the sUAS, controller, and tablet/smartphone.
- Inspect – Check the aircraft and propellers for signs of damage and/or excess wear.
- SD Card – Remove the card from the aircraft and check to make sure that images and/or videos were saved during the mission.
- Log flight – Log this flight in the logbook.

The items above do not necessarily represent an exhaustive checklist. Remote pilots could add or delete items based on individual circumstances.