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Unoccupied Aircraft Systems in Marine Science and Conservation

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Abstract

The use of unoccupied aircraft systems (UASs, also known as drones) in science is growing rapidly. Recent advances in microelectronics and battery technology have resulted in the rapid development of low-cost UASs that are transforming many industries. Drones are poised to revolutionize marine science and conservation, as they provide essentially on-demand remote sensing capabilities at low cost and with reduced human risk. A variety of multirotor, fixed-wing, and transitional UAS platforms are capable of carrying various optical and physical sampling payloads and are being employed in almost every subdiscipline of marine science and conservation. This article provides an overview of the UAS platforms and sensors used in marine science and conservation missions along with example physical, biological, and natural resource management applications and typical analytical workflows. It concludes with details on potential effects of UASs on marine wildlife and a look to the future of UASs in marine science and conservation.

INTRODUCTION

Over the past two decades, advances in microelectronics, battery technology, and wireless communications have driven the development of small consumer- and professional-grade robotic platforms for both entertainment and work purposes. Small service robots that clean floors and mow lawns are now available for purchase in many countries, and a variety of robots have been developed for purposes ranging from education and companionship [e.g., Sony's AIBO (Artificial Intelligence Robot) dog and Wonder Workshop's Dash] to exploration of the near-surface waters of the ocean (e.g., the OpenROV Trident) (Engelhardt 1989, Kopacek 2000, Shiomi et al. 2006).

Unoccupied aircraft systems (UASs, also known as drones) are a perfect example of this phenomenon. Small, portable, and affordable, aerial drones are now used recreationally in many countries and are revolutionizing a variety of work tasks, from journalism (Holton et al. 2014) to precision agriculture (Zhang & Kovacs 2012). Drones are also increasingly used by scientists to rapidly collect high-resolution data in many ecosystems (Koh & Wich 2012) and are poised to revolutionize spatial ecology (Anderson & Gaston 2013). While occupied aircraft can collect relatively high-resolution data, they can be cost prohibitive for smaller-scale projects (Arona et al. 2018), including those that need high temporal resolution. For larger-scale projects over broader areas, the economic benefits may not be realized (Angliss et al. 2018, Ferguson et al. 2018). Occupied aircraft also present significant risks for scientists (Sasse 2003), especially in marine applications, and are sensitive to weather conditions such as clouds and humidity. Satellite-based methods are becoming cost effective over larger areas where the timing of data collection is not critical, but they cannot collect data at the temporal and spatial scales required by some forms of marine and coastal research, and many satellite-based sensor systems remain sensitive to image-degrading atmospheric effects and weather.

Figure 1 provides a graphical overview of where drones fit into the spectrum of sampling capabilities for marine science and conservation. At ground level, marine scientists and resource managers can collect high-resolution data but struggle to efficiently sample across larger spaces. Until relatively recently, collecting data quickly over larger scales required the use of occupied aircraft (flying at altitudes of 150 m or greater) or satellites in orbit. It would be shortsighted to think that drones can completely replace these methods; however, they can augment them and fill a gap in sampling capabilities that marine scientists have long struggled with.

Drones are poised to revolutionize many aspects of marine science and conservation (Colefax et al. 2018), affordably filling the gap between in situ sampling and established remote sensing approaches (Lomax et al. 2005). Data can be collected directly by individual researchers under a greater array of weather conditions and with centimeter-scale spatial resolution (Laliberte & Rango 2009, Seymour et al. 2017b). The timing of surveys and spatial coverage are user defined, allowing for efficient, essentially on-demand sampling at tidal and finer sampling scales. This freedom and flexibility allows researchers to surpass approaches focused on simple detection of change and execute studies that identify causal processes. The use of UASs in marine science applications is on the rise in physical and biological oceanography, with applications focused on coastal ocean processes, habitats, and species. UASs have now been used to assess wave run-up on shorelines (Casella et al. 2014), ocean temperatures (Inoue & Curry 2004), ocean aerosols (Corrigan et al. 2008), algae biomass ((Xu et al. 2018), and coastal geomorphology (Mancini et al. 2013), and new sensors have been developed for high-resolution mapping of parameters such as sea surface salinity (McIntyre & Gasiewski 2007). UASs are also now used to assess the health of coral reefs (Clenet et al. 2015) and seagrass beds (Merrill et al. 2013), to conduct shoreline habitat mapping and coastal erosion studies (Mancini et al. 2013), and to assess the abundance and health status of marine vertebrates (Durban et al. 2015, Hodgson et al. 2013). Drones also present great

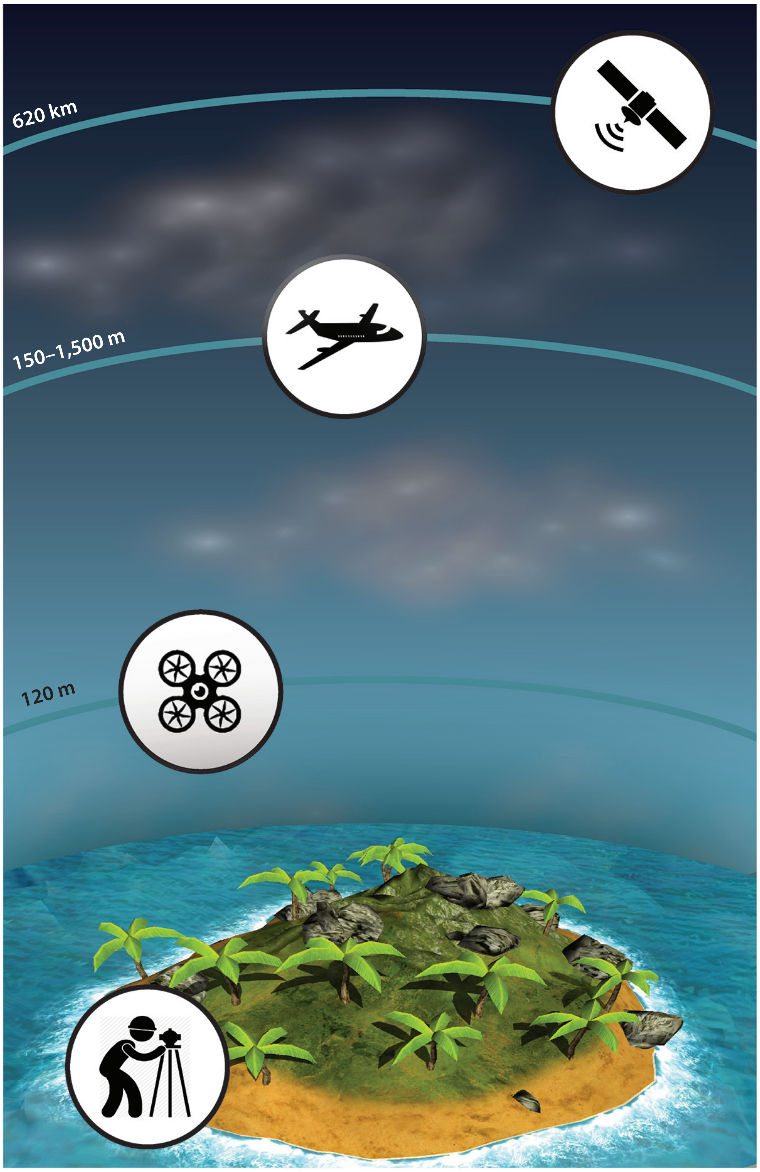

Figure 1

An overview of how unoccupied aircraft systems fit into the sampling spectrum. Marine scientists and resource managers can collect high-resolution data at ground level but cannot efficiently sample larger spaces. Previously, collecting data quickly over larger scales required the use of occupied aircraft or satellites in orbit, both of which are constrained by atmospheric effects and present logistical challenges.

opportunities for enhancing conservation and management tasks, including assessing both legal fishing and illegal, unreported, and unregulated fishing (Toonen & Bush 2018) and monitoring marine and protected areas (Maxwell et al. 2014).

This article provides a broad overview of UAS technologies presently being applied in marine science and conservation projects along with examples of UAS studies across a range of marine science and conservation applications, and briefly addresses the primary analytical workflows employed. Examples of studies focused on testing for disturbance of marine wildlife are also presented. The review concludes with thoughts on future directions in the use of UASs in marine science and conservation missions.

UNOCCUPIED AIRCRAFT SYSTEM, REMOTELY PILOTED AIRCRAFT SYSTEM, OR DRONE? A NOTE ON TERMINOLOGY

Several terms are used to describe small robotic aircraft used in marine science and conservation. In the United States, the terms unmanned aircraft system and unmanned aerial vehicle are used predominantly in both the scientific literature and the commercial market, and some have expressed concerns that this may deter female participation in the field (Smith 2004). The gender-neutral term unoccupied (or, occasionally, uncrewed) is increasingly substituted for unmanned, and may stem from comparisons with the term human-occupied vehicle used in marine science [e.g., the submarine Human Occupied Vehicle (HOV) *Alvin*]. Using gender-neutral language provides an opportunity to help reduce gender biases in human societies, which is important when one considers that in the United States, only 24% of the science, technology, engineering, and mathematics workforce (Noonan 2017) and fewer than 4% of licensed drone pilots (Beacon Sky Surv. 2017) are female. Outside of the United States, the term remotely piloted aircraft system (RPAS) is commonly used. This review uses the term unoccupied aircraft system (UAS) interchangeably with the word drone, which is the most accessible and widely used term to describe small robotic aircraft used in marine science and conservation. Initially, the term drone carried negative connotations, likely due to pervasive use of the term when describing the use of these platforms in military operations. However, as small UASs become increasingly available to the general public and used for a variety of entertainment purposes, these negative connotations appear to be waning.

OVERVIEW OF UNOCCUPIED AIRCRAFT SYSTEM PLATFORMS

A variety of UAS platforms are used in marine science and conservation missions. These platforms can be categorized into three main types of aircraft—multirotor, fixed wing, and transitional—according to their airframe configuration, propulsion method, and flight characteristics. These categories are described briefly below and are presented in plan views along with representative wingspans in **Figure 2**.

Multirotor UASs (**Figure 2*a*–*d***) use multiple engines and/or propellers to provide lift and propulsion and to maneuver while flying (e.g., controlling pitch, roll, and yaw). In some cases, these aircraft have one large rotor that provides lift and propulsion in all directions (pitch and roll) and a smaller tail rotor to address engine torque and point the aircraft in a certain direction (yaw). The majority of multirotor UASs (often referred to as multicopters) employ four (quadcopter; **Figure 2*b***), six (hexacopter; **Figure 2*c***), or eight (octocopter; **Figure 2*d***) motors and propellers that provide lift and control pitch, roll, and yaw by synoptically increasing or decreasing the output of individual motors. The larger six- and eight-rotor UASs can suffer from the loss of a motor and still fly, providing some redundancy. However, this redundancy is usually accompanied by a reduction in efficiency. Multirotor UASs are often made of lightweight materials such as plastic, aluminum, or carbon fiber to increase efficiency and tend to have wingspans ranging from 35 to 150 cm. They are ideal for marine science and conservation missions because they can be launched and recovered from small areas, like the deck of a small boat. In many cases, launch and recovery from such a boat is best accomplished by hand, with a flight crew member holding the drone above their head when launching and then recovering the aircraft in a similar manner. There are

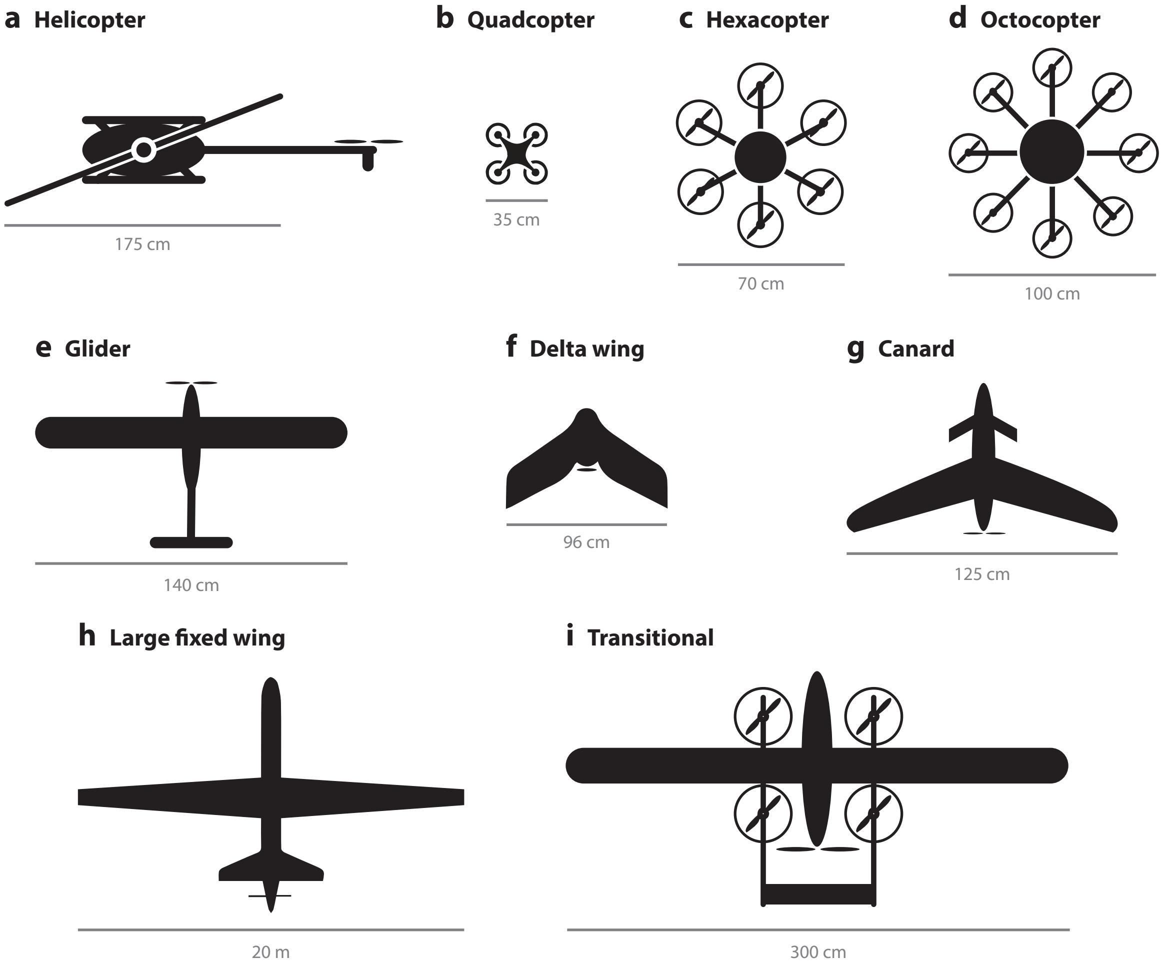

Figure 2

Plan views of typical (*a*–*d*) multirotor, (*e*–*h*) fixed-wing, and (*i*) transitional unoccupied aircraft systems used in marine science and conservation, along with representative wingspans.

some specific complications associated with launch and recovery from a moving platform, such as a boat or ship. Most multicopters calibrate their inertial sensors at startup, and some require a motionless platform to complete the process. In these cases, the aircraft will not operate properly, and in many situations simply will not fly, if it is booted on a moving boat. To alleviate these issues, many multicopter platforms have motion-boot or boat-mode calibration sequences that use calibration parameters collected during a previous startup on land.

Fixed-wing UASs (**Figure 2*e*–*h***) have one or more large wings that provide lift and maneuverability; they are usually driven by one or two motors and propellers in a push or pull configuration. Several wing configurations of fixed-wing UASs are available. Many use a typical glider airframe (**Figure 2*e***), with a large forward wing and a smaller tail wing driven by pull propulsion. Delta-wing UAS airframes (**Figure 2*f***) are also common, with one large midbody wing accompanied by vertical wing tips and push propulsion. Canard-style fixed wings have also been used in marine science missions. In this case, a small forward wing is accompanied by a larger wing at the rear of the aircraft (**Figure 2*g***). Fixed-wing UASs are manufactured from lightweight but strong materials, including various forms of expanded foam (e.g., polypropylene, polyolefin, or polystyrene) and carbon fiber. Fixed-wing UASs tend to have much better flight efficiency than multirotors because they use fewer motors and gain lift with large airfoil surfaces (Floreano & Wood 2015). Fixed-wing UASs used in marine science and conservation missions tend to have wingspans ranging from 90 to 350 cm, although some larger platforms (with wingspans greater than 20 m) have been used for extended missions (**Figure 2*h***). Small fixed-wing UASs are usually launched by hand and recovered through a circular or linear landing on their bellies. This represents a significant challenge for using small fixed-wing UASs for pelagic missions, as they are extremely difficult to land on small boats. Larger fixed-wing UASs are often launched with the aid of a catapult to help the aircraft overcome stall speed during takeoff. These larger aircraft are then recovered by ship-based wire traps or nets in maritime environments.

A growing number of aircraft combine aspects of multirotor and fixed-wing UASs to provide greater flexibility in their use. These transitional aircraft (**Figure 2*i***) take off and land vertically like a multirotor but then transition to and from horizontal flight supported by a large wing. Vertical flight is typically driven through three or four motors facing upward, and horizontal flight is driven by a motor and propeller in a push configuration. In some cases, the engines themselves rotate to provide both vertical and horizontal thrust. Transitional platforms are usually constructed from composite and carbon fiber materials and have wingspans of 200–400 cm. Transitional aircraft can be flown from tight locations because of their ability to take off and land vertically (e.g., on the deck of a ship) and exhibit the efficient flight characteristics of standard fixed-wing aircraft, making them ideal for marine science and conservation missions.

The majority of UASs used in marine science and conservation are battery powered. In most cases they are powered with lithium polymer batteries, which provide significant energy density and can discharge electrical current rapidly to support variable and rapid engine and payload electrical current requirements. Some smaller systems use lithium ion batteries, which tend to have a higher energy density but slower discharge rate. A growing number of systems are hybrids, employing battery-powered electric motors along with combustion engines. Petroleum-based fuels like gasoline provide the highest levels of energy density at affordable prices. A small number of UASs can now use hydrogen fuel cells as power sources.

Interestingly, the vast majority of UAS platforms used in marine science and conservation are not waterproof, and only a few platforms are environmentally sealed sufficiently to fly in rain or snow (e.g., the FreeFly ALTA 6 and 8). While this may seem to be a shortcoming for operating in corrosive and conductive marine environments, the trade-off appears to be with weight, and in some cases barometer performance. Waterproofing UAS platforms seals their electronics and ultimately increases their weight, which results in shorter flight times and further constrains the weight of sensor payloads. Waterproof UASs therefore tend to have limited options in payloads and short flight times (∼10–12 minutes) in real-world conditions.

Most UAS platforms employ an autopilot for flight control. These units provide positional information via GPS and inertial measurement units and coordinate engine output and control surfaces to maintain stable flight, often in the absence of pilot input. There are two main approaches to controlling UAS platforms during scientific and management missions. In some cases, drones are flown manually with a handheld controller, enabling data collection on moving animals or video capture from specific perspectives. Many marine UAS missions are conducted with considerable autonomy. In these cases, ground control stations (generally laptops or tablet computers) run specific software that allows pilots to rapidly program complex survey patterns to achieve optimal sampling. In these cases, the UAS follows predetermined flight paths and sampling behaviors (e.g., acquiring images) without direct input from the pilot. The pilot remains in control of the

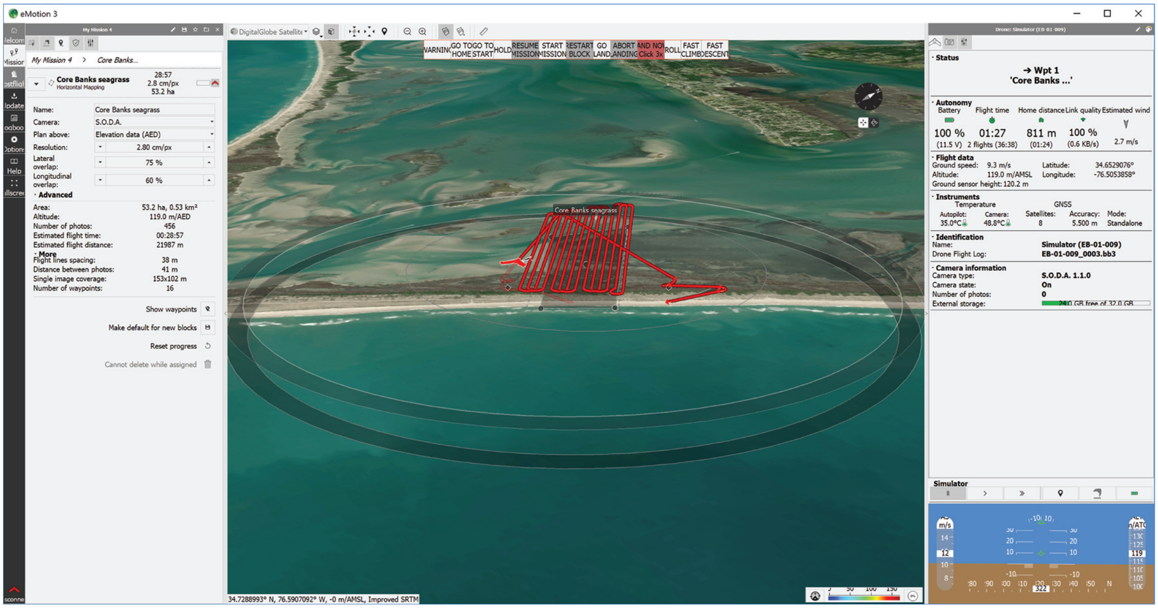

Figure 3

A typical flight plan for an unoccupied aircraft system mapping seagrass in a coastal ecosystem (Cape Lookout National Seashore). The flight path is shown in red, depicting the trajectory of the drone and the takeoff and landing sites. The translucent cylinder represents a geofence that constrains the movement of the drone vertically and horizontally. The left panel provides details on the mapping mission itself, including the predicted flight time, expected ground-sampling distance, and area to be mapped. The right panel provides details on the status of the aircraft, including its location, altitude, current flight time, and attitude (pitch, roll, and yaw), along with information on the wind speed experienced during the flight.

aircraft, but the nuances of flight (maintaining appropriate altitude, following the track line in a crosswind, and even landing) are addressed by the drone's autopilot. **Figure 3** provides an example of a three-dimensional flight plan for a 29-minute fixed-wing UAS survey of seagrass habitat at Cape Lookout National Seashore. The illustrated mission is typical for mapping seagrass with a high-resolution RGB sensor and would produce a map of 53.2 hectares of habitat at a ground resolution of 2.8 cm per pixel.

One of the most important components of autopilots used for marine science and conservation is the GPS unit. The quality and performance of the GPS unit in a drone will dictate, to a large extent, how consistently the aircraft flies and how accurate the resulting geospatial data products will be. Most consumer-grade UAS platforms employ affordable GPS units referred to as mapping-grade GPS units. These units provide positional information (latitude, longitude, and altitude) to the drone's autopilot with errors on the order of 2–5 m. Some UAS platforms use high-performance GPS units for navigation purposes, which can provide accuracy at 3–5 cm through several features, including the abilities to connect to the L2 satellite frequency and to actively stream correctional data from a nearby reference station (often referred to as real-time kinematic correction).

UNOCCUPIED AIRCRAFT SYSTEM SENSORS

The vast majority of sensors used in marine science and conservation UAS missions are essentially digital cameras, often referred to as electro-optical sensors. These sensors convert detected light across a specific range of the electromagnetic spectrum (generally 400–10,000 nm) into electrons that can be interpreted as images through either a charge-coupled device or a complementary metal-oxide semiconductor device.

A broad array of electro-optical UAS sensors are available, ranging from a variety of standard RGB cameras to multispectral (red edge and near infrared), thermal infrared, and hyperspectral systems that are sensitive to wavelengths not detectable by human eyes. Initially, many RGB sensors used in marine UAS missions were essentially modified point-and-shoot cameras (often based on low-weight, high-resolution consumer products by Canon and Sony). Action cameras such as GoPro HERO modules are often employed for RGB imaging, especially for video capture. Many multirotor systems used in marine science and conservation work come with integrated camera systems that provide high-quality still and video imagery (e.g., the DJI Phantom Pro 4 has a low-distortion, 20-megapixel complementary metal-oxide semiconductor camera). Many UASs employ light, high-resolution mirrorless cameras produced by Sony, Olympus, and other manufacturers. These systems provide excellent image quality in a relatively small and light package along with flexibility in imaging through their interchangeable lenses. Finally, some RGB sensors are created specifically for UAS operations. For example, senseFly produces a sensor optimized for drone applications, the S.O.D.A. (Sensor Optimized for Drone Applications) camera, which has a large (1.6 cm) 20-megapixel sensor optimized for UAS-based photogrammetric surveys.

Several commercially available multispectral optical sensors (e.g., MicaSense RedEdge and Parrot Sequoia cameras) are now used in marine science workflows, mostly for mapping marshes and other coastal resources. These sensors sample multiple bands of the electromagnetic spectrum—green (~560 nm), red (~670 nm), red edge (720 nm), and near infrared (840 nm)—and have incoming radiation sensors to help with radiometric calibration of reflected light. These wavelength combinations are useful for assessing the health of plants in coastal systems. While multispectral sensors generally detect radiation in a small number of bands with relative large bandwidth (20–40 nm), hyperspectral sensors can sample a broad range of the electromagnetic spectrum with a much larger number of bands—hundreds of them—with narrower bandwidths (2–5 nm each). Adão et al. (2017) reviewed a range of hyperspectral sensors used with UASs.

Thermal imaging is now used extensively in studies of marine and coastal organisms and their habitats (Gooday et al. 2018, Seymour et al. 2017a). These sensors generally detect long-wave infrared energy (8–15 μm) emitted by objects in the camera's field of view and can provide detailed images and maps of temperature in the absence of illumination. A variety of long-wave infrared sensors are designed specifically for fixed-wing (e.g., the senseFly ThermoMAP) or multicopter (e.g., the FLIR Duo and Vue series) UAS platforms. Short- and midwave infrared sensors are also available for UAS platforms. These sensors differ from long-wave infrared cameras because they detect reflected light in shorter infrared wavelengths. Lidar (light detection and ranging) is also now being used to sample and image natural environments from UAS platforms. These sensor packages use lasers to scan the environment to produce three-dimensional point clouds of the terrain and vegetation. A small number of turnkey UAS lidar systems are presently available, such as Routescene's LidarPod and Phoenix LiDAR Systems' Scout Ultra.

Some UAS platforms are built to collect physical samples in marine and aquatic environments, including water and sediment (e.g., Di Stefano et al. 2018), and UASs are now being used to collect marine aerosol samples over the ocean (Corrigan et al. 2008, Terada et al. 2018) as well as whale respiratory vapor (Pirotta et al. 2017). Other examples of UAS-deployable sensors that are potentially applicable to marine science and conservation missions include Geiger counters (Di Stefano et al. 2018), magnetometers (e.g., Macharet et al. 2016), and a variety of air-quality sensors (reviewed in Villa et al. 2016). In some cases, drones can be used to deploy radio-linked sensors into the environment (Di Stefano et al. 2018).

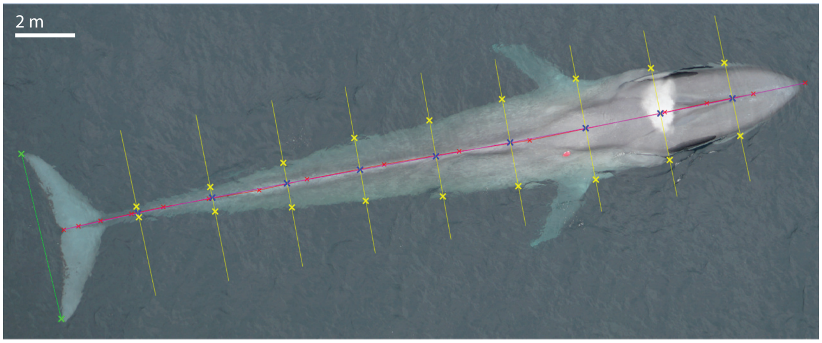

Figure 4

An aerial image of a blue whale generated from a photogrammetric survey using an unoccupied aircraft system. The whale has been proportioned into tenths, and measurements of its width are represented by yellow lines perpendicular to the long axis of the whale.

EXAMPLE APPLICATIONS OF UNOCCUPIED AIRCRAFT SYSTEMS IN MARINE SCIENCE AND CONSERVATION

This section provides a broad overview of present applications of UASs in marine science and conservation missions. Due to rapid advances in both sensor and platform technologies, these descriptions are not meant to be exhaustive reviews of how UASs are being applied in each category. In fact, some of the application areas discussed below could be the subjects of lengthy individual review articles on their own. Instead, representative studies are presented to provide an overall picture of how UASs are being employed within that sector of marine science and conservation.

Animal Morphometrics and Individual Health

It is remarkably difficult to accurately measure the size, mass, and morphology of large ocean animals. Their size often precludes capture, and because they live away from people and only spend small proportions of their lives on the surface, they are largely unavailable for scientific observations. Drones help overcome some of these challenges—they are easy to operate and can be launched rapidly, they collect high-resolution imagery that can be used in photogrammetric workflows, and they are amazingly affordable in comparison with approaches that rely on occupied aircraft. In this context, obtaining nadir imagery of whales from a known altitude allows individual pixels in imagery to be scaled to real-world values. This enables researchers to obtain high-resolution measurements of whole whales and their visible body parts (Durban et al. 2015). **Figure 4** provides an example of how a blue whale is proportioned and measured through this type of workflow.

Several research groups have made significant strides in this area, illustrating that UAS-based photogrammetry of marine animals is changing how we study these animals. Early aerial photogrammetric studies of terrestrial (Croze 1972) and marine animals (Perryman & Lynn 1993) were conducted via occupied aircraft and often relied on expensive cameras. For many of these animals, the on-demand nature of UASs provides greater opportunity to collect data, with higher resolution and often lower costs. The vast majority of UAS-based photogrammetric work has been conducted on cetaceans, including published studies of killer whales (Durban et al. 2015), humpback whales (Christiansen et al. 2016a), right whales (Christiansen et al. 2018), and blue whales (Durban et al. 2016). Obtaining repeated measurements of animals over time provides opportunities to study how their bodies change in response to energetic activities such as breeding (Christiansen et al. 2016a, 2018). Furthermore, UAS-based imaging of whales in a photogrammetric context allows researchers to measure their control surfaces (e.g., flukes and flippers). This capability opens up a whole slew of challenging research avenues focused on animal performance and kinematics in relation to body size and configuration (see Goldbogen et al. 2017). Drone-based photogrammetry has also been applied to some pinniped species (Goebel et al. 2015, Krause et al. 2017) and has applications for studying the morphometrics of other large ocean creatures, such as sea turtles (Rees et al. 2018, Schofield et al. 2017), basking sharks, and whale sharks. Drones can also be used to collect biological samples from whales during their exhalation. This application, often referred to as exhalate, blow, respiratory vapor, or snot collection, can yield a variety of details about sampled animals, including information on their population identities, hormone levels, and respiratory microbiomes and viromes for use in health assessment models (Apprill et al. 2017, Geoghegan et al. 2018, Pirotta et al. 2017). This application is now generating innovation in the UAS platform space, as researchers are creating drones to carry specific snot-sampling devices to optimize sample collection and retention (Pirotta et al. 2017).

Animal Population Assessments

Perhaps the most frequent use of UASs in marine science and conservation is for assessing the abundance and density of marine organisms. UASs have been used to count seabirds (Hodgson et al. 2016), pinnipeds (Sweeney et al. 2016), dugongs (Hodgson et al. 2013), sea turtles (Sykora-Bodie et al. 2017), and sharks and rays (Kiszka et al. 2016). In some cases, these assessments are done using relatively large fixed-wing UASs with a flight endurance of more than 15 hours (Hodgson et al. 2013), whereas others focus on smaller regions and use small UASs (Sykora-Bodie et al. 2017). Multirotor UASs are also employed for these purposes (Kiszka et al. 2016), often for nearshore regions due to the limited flight times of most multirotor UASs.

Several studies have also focused on comparing traditional counting methods with new UAS-based approaches. For example, Johnston et al. (2017) compared colony counts and imagery of gray seals collected by small fixed-wing UASs with data collected through the use of an occupied Twin Otter aircraft. The comparison revealed that drone-based imagery was as good as, if not better than, that produced through the traditional method and, most importantly, that UAS counts of seals were reliable for population assessment purposes (for an example of seal surveys in eastern Canada, see **Supplemental Video 1**). Other studies have confirmed this conclusion and suggest that UAS-based counts can often provide better data. A recent controlled experiment using lifelike replicas of seabirds revealed that UAS-derived counts of seabirds were 43–96% more accurate than the traditional ground-based data collection methods (Hodgson et al. 2018). Gains in survey performance are not always realized when using UASs. For example, Ferguson et al. (2018) found that UASs were not as efficient at detecting cetaceans during aerial surveys in Alaska, likely because of the limited strip width sampled by the UASs compared with that of visual observers. Thermal sensors deployed on drones can also help refine population assessments for marine birds and some mammals. For example, a thermal survey of gray seals in eastern Canada was able to detect seals that had positioned themselves in a sparse coniferous coastal forest, whereas surveys with a high-resolution RGB camera could not resolve them. **Figure 5** illustrates the thermal detection of gray seals at a colony on Hay Island, Canada, during the breeding season. Drones can also be incorporated into multimodal population assessment workflows (Marvin et al. 2016). For example, Borowicz et al. (2018) used ground-based counts, UAS-based counts, and multispectral satellite imagery to estimate the abundance of previously unassessed Adélie penguin colonies in the Danger Islands, Antarctica.

Supplemental Material >

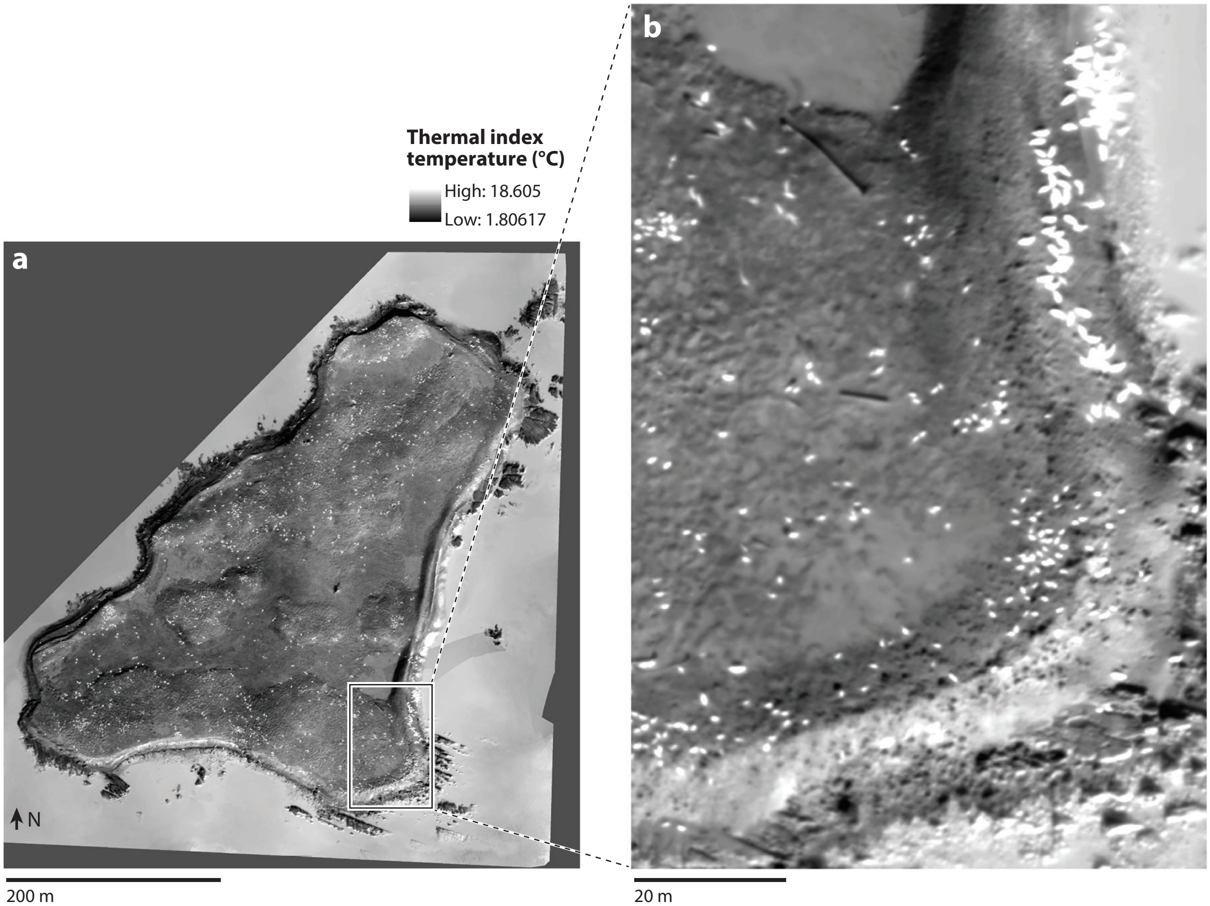

Figure 5

Thermal images of gray seals at a colony on Hay Island in eastern Canada, showing (*a*) a view of the entire colony and (*b*) a detailed view of individual seals. **Supplemental Video 1** provides an example of how drones are used to survey these colonies.

Supplemental Material >

Behavioral Ecology

Both video and still imagery collected from drones can be applied to studies focused on marine animal behavior. Recent reviews of how UASs (and other technologies) can be applied to marine animal studies identified this area as a key benefit of the technology (Fiori et al. 2017, Nowacek et al. 2016, Rees et al. 2018). That being said, very few studies actually employ UASs to study the behavior of marine animals. One recently published example provides behavioral details of how both saltwater crocodiles and tiger sharks consumed a humpback whale carcass off Western Australia (Gallagher et al. 2018). In this case, details on how the animals approached the carcass and fed on it were collected, including information on interactions among the scavengers. Drones have also been used to study the shoaling behavior of sharks in tropical reef systems, providing baseline data on the alignment of animals within groups in different microhabitats (Rieucau et al. 2018). My laboratory is currently using drone video and still imagery to assess the bubble-net feeding behavior of humpback whales in the western Antarctic Peninsula region (**Figure 6**). During the austral summer, humpback whales congregate in the coastal waters off this peninsula to feed on

Figure 6

Two humpback whales imaged by an unoccupied aircraft system during a bubble-net feeding event in the Bellingshausen Sea, Antarctica. The whale in the center is floating vertically and pointed directly at the drone. The spiral of white bubbles is the bubble net itself, which the whales use to corral and consume krill. **Supplemental Video 2** shows four humpback whales feeding in this way.

Supplemental Material >

krill. During feeding events, some humpbacks release a stream of bubbles while circling krill swarms. These rising bubbles form a cylindrical net that limits the escape avenues for krill as the whales lunge into them (Goldbogen et al. 2017). In some cases, multiple humpbacks work in a coordinated fashion in this manner (for details on humpback whale bubble-net feeding, see **Supplemental Video 2**). Another notable example of using UASs for behavioral ecology is the study of the in-water courtship and mating behavior of sea turtles (Bevan et al. 2016, Schofield et al. 2017).

Habitat Assessments and Coastal Geomorphology

UASs can greatly facilitate assessments of coastal and marine habitats. Because the technology provides essentially on-demand data collection at extremely high resolution, researchers and managers can efficiently study habitat components as they respond to acute and long-term perturbations. UASs are being applied to the mapping and three-dimensional modeling of coral reefs through fluid lensing techniques (where ocean waves are used to compute a magnified image of the ocean floor and reduce the effects of refraction; see Chirayath & Earle 2016) as well as for assessing coral health and bleaching events (Levy et al. 2018). Similarly, UASs are being used to assess the extent of seagrass beds (Merrill et al. 2013), and the data collected by UAS are so detailed that it is possible to assess how seagrasses respond to disturbances such as propeller scars (**Figure 7**, left inset) or stingray foraging (**Figure 7**, right inset).

Some researchers are using drones to study the changing morphology of estuarine mud flats (Jaud et al. 2016), and researchers are increasingly turning to UASs to study the geomorphology of beaches (Mancini et al. 2013, Seymour et al. 2017b). In these applications, high-resolution digital elevation models derived from repeated UAS surveys and structure-from-motion (SfM) techniques are used to track changes in elevation. Through accurate ground control and the use of platforms with survey-grade GPS units, these studies resolve changes in geomorphology at centimeter scales (Seymour et al. 2017b). Drones are also being applied to the study of salt marshes, oyster reefs, and other tidal habitats (Kalacska et al. 2017, Ridge et al. 2017). Drones can also be fitted with portable lidar systems to assess geomorphology (Lin et al. 2011), although few studies of coastal systems exist. Notably, UAS-derived imagery of marine habitats is incredibly useful for ground-truthing measurements made from satellites, and efforts to train classification systems with UAS imagery to classify habitats imaged by orbital sensors are under way (P. Gray, J.T. Ridge, S.K. Poulin, A. Seymour, A.M. Schwantes, et al., manuscript in review).

Management

The use of UASs in management is rapidly being explored in the terrestrial context. Drones have been used to disperse seeds for replanting areas (Elliott 2016), to ignite and monitor controlled burns (Twidwell et al. 2016), and in some places in attempts to monitor areas for illegal practices, such as poaching (Mulero-Pázmány et al. 2014), which can include the use of computer vision to track and identify poachers (Olivares-Mendez et al. 2015). However, natural resource management in marine systems is lagging behind in the application of drones for management purposes. Most examples provided in this review focus on experimental, proof-of-concept, or calibration exercises, and very few programs are operationally using UASs for natural resource management in marine systems. For example, Brooke et al. (2015) tested the utility of both small and large fixed-wing UASs for monitoring natural resources at the Papahānaumokuākea Marine National Monument in the Northwestern Hawaiian Islands, but those systems are not being used operationally to monitor the marine monument. A small number of studies have illustrated that UASs can be used to detect and identify fishing vessels (Miller et al. 2013), monitor fishing activities, and relay that information to law enforcement (Kopaska 2014). However, few operations are consistently using drones to monitor and manage fisheries or monitor other marine resources.

Maritime Archaeology and Infrastructure

Drones have been applied extensively in terrestrial archaeology (Campana 2017) and are revolutionizing building inspections (Irazarry et al. 2012). Indeed, several researchers are now using UASs to study coastal infrastructure and historic structures in coastal systems, both modern and ancient. For example, King et al. (2017) demonstrated how UASs can be used to assess the condition of seawalls and hardened shorelines, as well as to image recent shipwrecks to develop insight into their condition and fate. The oil and gas industry uses UASs to inspect offshore equipment and coastal infrastructure (Shukla & Karki 2016). My research group has partnered with local national park officials to image lighthouse infrastructure in order to help scope the extent of renovations required for an upcoming refurbishment of the building. We have also conducted mapping missions of the Ghost Fleet of Mallows Bay in support of a nomination for it to be listed as a US National Marine Sanctuary. Mallows Bay is a small bay on the Potomac River near Washington,

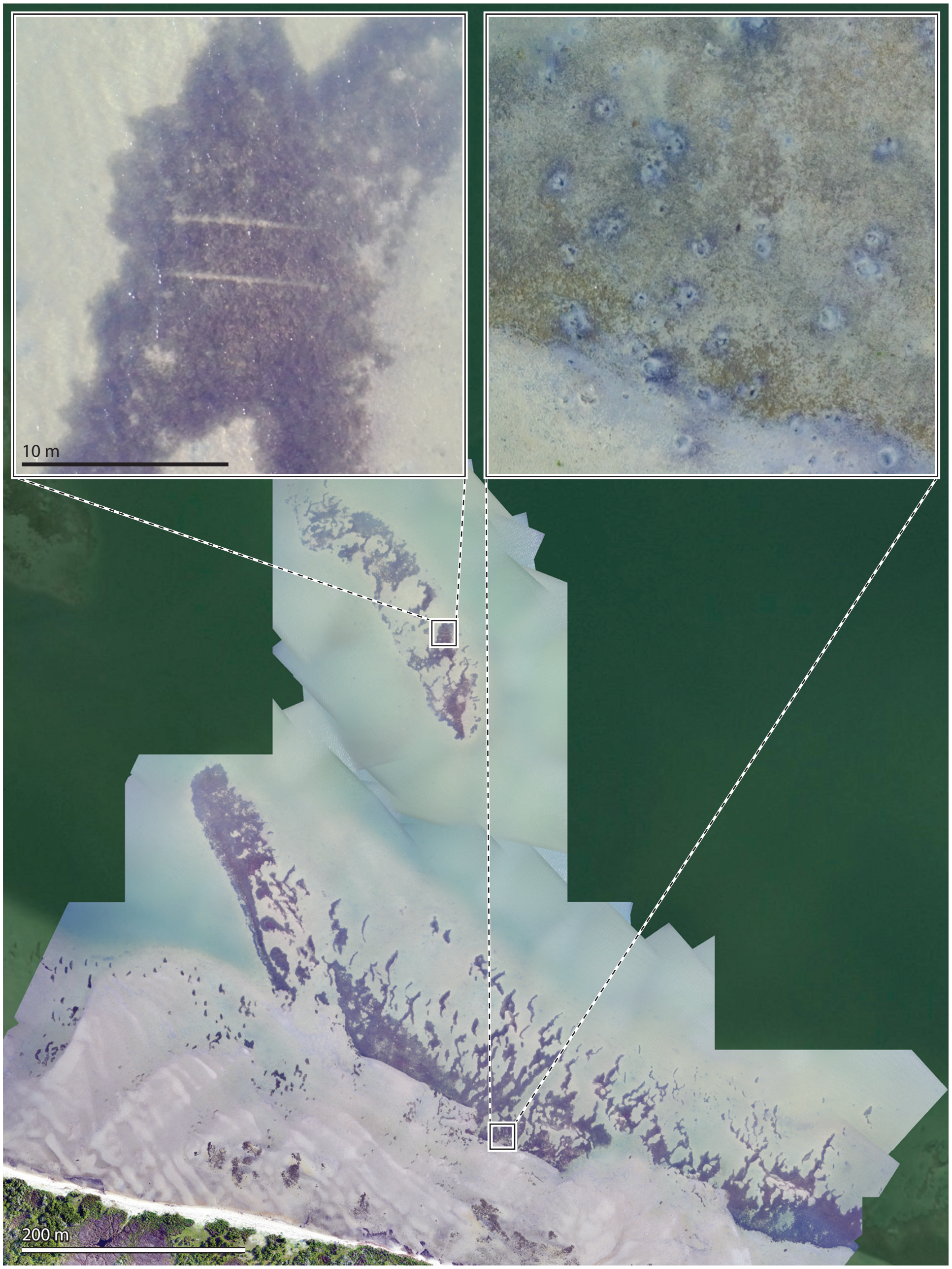

Figure 7

Map of seagrass habitats at Cape Lookout National Seashore collected via a fixed-wing unoccupied aircraft system. The inset on the left illustrates the presence of propeller scars in the seagrass; the inset on the right provides an overview of stingray foraging pits in the meadow.

DC, that is the final resting place of hundreds of shipwrecks. The majority of these wrecks are the remains of World War I liberty ships that average approximately 85 m in length. UAS surveys of the bay provide an amazing overview of the wrecks plus detailed mapping products that contain accurate geolocation information for each identified ship (**Figure 8**). Drones are also being applied to study ancient clam garden aquaculture systems on the west coasts of Canada and the United States. In this case, inter- and subtidal stone structures were constructed by indigenous people to provide greater and more predictable access to shellfish (Jackley et al. 2016), and drones are ideal tools to map and measure their topography and geographic context (Laidlaw 2017).

Pollutants

Several researchers are using UASs to study marine pollution because their flexibility and favorable spatial and temporal resolution provide significant opportunities to study fine-scale and unpredictable events. The combination of thermal imaging and UAS platforms is particularly useful for tracking terrestrial inputs into coastal systems. These sources tend to be vectors for a variety of pollutants into these systems. For example, Lee et al. (2016) employed a drone with a thermal sensor to define groundwater discharge into the coastal zone of Korea, and Lega et al. (2012) employed UAS-based thermography to detect illegal and unauthorized sewer and storm-drain environmental policy violations for both river and ocean environments. Drones have also been employed to track rhodamine dye tracers in aquatic systems (Powers et al. 2018), including within the surf zone (Brouwer et al. 2015). Some researchers are employing UASs to assess marine debris pollution on coastlines and at sea. For example, Hengstmann et al. (2017) used a small quadcopter to assess the extent of macrolitter on beaches of the Isle of Rügen, Germany. At-sea surveys for marine debris using UASs are possible with a variety of sensors (Veenstra & Churnside 2012) but so far have yielded only limited success.

Physical and Biological Oceanography

A variety of UAS applications for physical oceanography have emerged over the past decade. Researchers are now able to map and measure sea surface temperature from drones (Lee et al. 2016), and new sensors can measure sea surface salinity from UAS platforms (McIntyre & Gasiewski 2007). It is also possible to use drones to collect water samples for these types of measurements; Terada et al. (2018) were able to deploy a bottle sampling system from a drone and collect water from approximately 1-m depth. More advanced systems allow for the collection of multiple samples in a single UAS flight (Ore et al. 2015). Researchers have used drones to assess wave run-up energy on beaches (Casella et al. 2014) and assess concentrations of aerosols over the ocean (Corrigan et al. 2008). UAS platforms can be used to determine water velocity in some instances (Detert & Weitbrecht 2015), and drones are now being used to determine bathymetry in shallow-water regions through spectral (Shintani & Fonstad 2017), photogrammetric (Casella et al. 2016), and speed-of-wave-crest (Matsuba & Sato 2018) techniques. Drones are increasingly being used in biological oceanography as well. For example, researchers have used drones to assess chlorophyll and macroalgae concentrations in the water (Su 2017, Xu et al. 2018) and optical sensors to monitor the progress of harmful algal plumes (Lyu et al. 2017).

ANALYTICAL APPROACHES

The various applications described above can quickly create large amounts of data, and efficient workflows are essential to avoid backlogs and bottlenecks. In most cases, the data collected from

Figure 8

The shipwrecks of the Ghost Fleet of Mallows Bay mapped through unoccupied aircraft systems. The inset provides details on several wrecks that have become islands that support a variety of plants and animals.

drone sampling regimes are assessed manually. For example, most of the population assessment studies cited above required human analysts to count individual organisms before density or abundance estimates could be calculated. This generally requires many hours of scanning photos and identifying organisms, and images are assessed by multiple analysts to avoid observer biases in counts. To address this analytical bottleneck, researchers are turning to computer vision and machine learning techniques to speed up analysis of imagery (Weinstein 2017). For example, Seymour et al. (2017a) used object recognition and geoprocessing techniques to identify and enumerate adult and young-of-the-year gray seals in thermal imagery collected from a small UAS. Because adult seals are larger and slightly warmer than younger seals, it is possible to have the computer use these factors to identify and then count the animals. My laboratory is currently applying this technique to estimating Adélie penguin numbers at colonies in the western Antarctic Peninsula and estimating the body sizes of cetaceans. Machine learning techniques can also be used with drone imagery to assess populations; for example, Borowicz et al. (2018) applied a neural network system to UAS imagery from the Danger Islands, Antarctica, to automatically count Adélie penguins.

Machine learning and computer vision techniques are also being applied to the classification of wetland habitats, including the use of drone imagery to train systems that can classify coastal habitats in satellite remote sensing products (P. Gray, J.T. Ridge, S.K. Poulin, A. Seymour, A.M. Schwantes, et al., manuscript in review). Many researchers use UAS data to develop three-dimensional models of what they are surveying through SfM techniques, which estimate three-dimensional structures from two-dimensional image sequences. Briefly, the computational workflow treats each photo in a UAS mapping mission as a separate camera and performs stereophotogrammetry on key points in these photos to generate elevation data and create a three-dimensional model of the structures mapped. **Figure 9** shows an SfM model of Torgersen Island, a well-studied Adélie penguin colony in the western Antarctic Peninsula, illustrating both the

Supplemental Material >

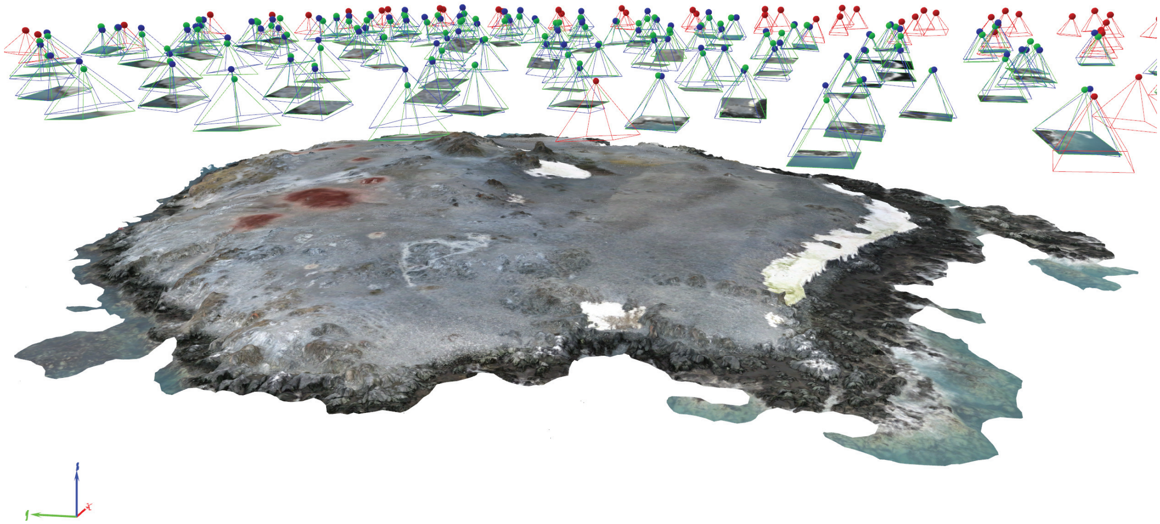

Figure 9

A three-dimensional rendering of Torgersen Island and its Adélie penguin colonies created from a structure-from-motion workflow. The upper part of the figure shows the positions and altitudes of the unoccupied aircraft system when it captured the images used to create the model. **Supplemental Video 3** shows a fly-through of this model.

Supplemental Material >

reconstructed terrain and the locations of UAS cameras used in the creation of the model (for a fly-through of this model, see **Supplemental Video 3**). This technique is at the core of most UAS applications that measure elevation and variation in topography. Several software packages to undertake SfM processing are commercially available (e.g., Pix4DMapper and Agisoft PhotoScan), and open source libraries are also available [OpenDroneMap (**http://opendronemap.org**)].

DISTURBANCE OF MARINE WILDLIFE

The rapid growth of UAS applications and the availability of platforms has outpaced many regulatory frameworks. As such, obtaining authorizations and permits to fly UASs for scientific applications can be frustrating and has likely reduced adoption by some researchers. Many countries now have legal frameworks to fly UASs for commercial purposes, although the rules vary considerable from country to country. These regulations usually focus primarily on deconflicting UASs and occupied aircraft traffic and to a lesser extent on issues of privacy and security. Agency permitting processes, by contrast, tend to focus on whether or not UAS surveys disturb wildlife or disrupt their normal activities. A growing number of studies have addressed the potential disturbance of wildlife by UASs, although much work is needed to completely understand their effects on most taxonomic groups (e.g., Smith et al. 2016). Several studies have assessed the disturbance effects of UASs on seabirds, and the results indicate that flying at higher altitudes tends to reduce disruptive effects (McEvoy et al. 2016, Rümmler et al. 2015). These studies have also pointed out that particular UAS configurations, such as delta-wing UASs, can elicit stronger reactions, possibly because the aircraft resemble diving predatory birds (McEvoy et al. 2016). Canard- and glider-style UASs tend to elicit smaller effects. By contrast, studies of the effects of delta-wing UASs on pinnipeds have revealed little to no disturbance (Arona et al. 2018). In some cases, seals can be disturbed by low-flying multirotor aircraft, and the magnitude of their reactions appears to be modulated by life history status and altitude of flight, with animals at breeding colonies most affected by low-flying UASs (Pomeroy et al. 2015).

Some studies have attempted to define disturbance thresholds for marine wildlife exposed to UASs (Bevan et al. 2018). However, small sample sizes and a limited understanding of what stimulus animals are responding to (e.g., noise, shadows, or aircraft silhouette) make it difficult to draw strong conclusions. Large whales do not appear to be disturbed by close approaches by UASs (Domínguez-Sánchez et al. 2018), and the acoustic disturbance of submerged marine animals appears to be unlikely because UAS sounds are not transmitted efficiently from the air to the water (Christiansen et al. 2016b).

FUTURE DIRECTIONS

The use of UASs in marine science and conservation is increasing. There remains considerable need to explore how these systems can be used to addresses challenging questions, and there is growing opportunity to use UASs and workflows operationally to increase efficiency and reduce risk in a variety of tasks. The use of transitional UASs that combine the flexibility of multirotors and the endurance of fixed wings will likely become standard procedure for marine operations, especially when staging operations from boats or ships. It is also likely that multimodal or cross-domain systems will be used more frequently for marine science and conservation missions. For example, Weisler et al. (2017) have developed a cross-domain fixed-wing UAS that can fly over ocean areas for visual surveys, then land in the water and dive below the surface to conduct submerged observations; **Figure 10** provides an overview of this system's operation. Cross-domain platforms such as this have great potential to detect and identify near-surface animals or

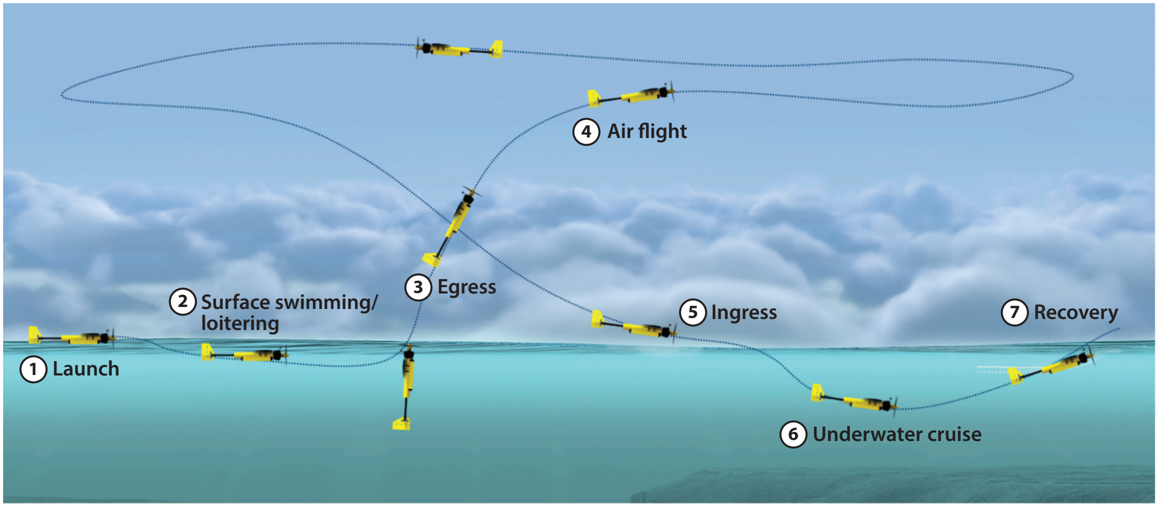

Figure 10

An overview of the operation of a cross-domain unoccupied aircraft system that can conduct aerial operations, land on the water for surface operations, and then submerge for underwater operations. Image courtesy of M. Andersen, Teledyne Scientific.

oceanographic phenomena and then sample those systems more directly with a suite of in situ sensors focused on oceanographic parameters (e.g., salinity and temperature) and passive and active ocean acoustics. Along these lines, there is likely to be growth in the coordinated use of aerial, surface, and submerged robotic platforms for marine missions. For example, Shkurti et al. (2012) demonstrated how aerial, surface, and underwater drones could be used together to monitor environmental conditions in a coral reef ecosystem. Sensor technology is evolving rapidly for UAS platforms, and in the near term it is likely that affordable aquatic lidar and hyperspectral cameras will become available to researchers and managers. Other novel uses of UASs are emerging, including using platforms to radio track animals (Tremblay et al. 2017) or act as data mules—an application in which drones collect data from distributed sensors and transport them to a central location for analysis (Lukaczyk et al. 2016).

The majority of studies introduced above focus on using UASs to collect information on inanimate components of marine systems, vegetation, or nonhuman animals. However, simply studying inanimate and nonhuman organisms is rarely enough to solve pressing marine conservation problems. Considering the capabilities of UASs to collect high-resolution information, they hold incredible potential for studying how humans interact with marine and coastal systems, and they can be used for both pure and applied scientific purposes in this context. In terrestrial systems, drones are being applied to human wildlife conflicts such as poaching (Mulero-Pázmány et al. 2014), although with variable results. In marine systems, some studies have indicated that drones can be used to facilitate management of fisheries and patrol protected areas, but few if any published studies focus on how researchers can use drones to quantify human behavior.

There are many challenges associated with using UASs to study humans in marine systems. Some are obvious regulatory limitations associated with safety concerns, such as the baseline restriction on commercial operators in the United State against overflying people, or the associated requirement that UASs remain within the pilot's visual line of sight during flight. Some challenges are more technological, such as platform flight endurance or sensor capabilities needed to collect the right type of information. The challenges that are perhaps most difficult to resolve are ethical and legal, where researchers must apply best practices and conduct their work in a manner that does not invade the privacy or erode the security and well-being of people being studied. Some authors have pointed out that using drones for science brings significant concerns in these areas (e.g., Sandbrook 2015); however, no comprehensive set of best practices exists to guide researchers in their efforts to explore the use of drones in the study of human behavior in marine systems.

The availability of small, low-cost, easy-to-fly consumer drones will transform how natural resource managers work on a day-to-day basis. It is easy to imagine a marine resource scientist or manager heading out for a day's work (along a coastline or on a small boat) with a small drone in their backpack. Flown with their smartphone and streaming data to the operator and, when needed, to a central monitoring facility, this UAS would extend their in situ monitoring reach while providing real-time information to support staff or supervisors. This enhanced capability would allow for rapid identification and documentation of coastal hazards (e.g., oil spills, rapid coastal erosion, or marine animal stranding events), document important human activities, and speed up robust decision-making in emergencies.

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