



Unmanned Aerial Vehicle (UAV) applications in coastal zone management—a review

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Abstract Climate change and intense anthropogenic activities have heightened the vulnerability of coastal areas globally. The intensification in the dynamism and uncertainty of coastal processes and change in the past few decades have led researchers and coastal managers to explore new tools with the capability of undertaking a rapid assessment of coastal resources at a relatively lower cost compared with the conventional in situ data collection. The latest advances in unmanned aerial vehicle (UAV) platforms and sensor technologies have made them useful environmental remote sensing tools due to the high temporal and spatial resolution and relatively inexpensive operating

costs. This study reviews literature that explored UAV applications in five different areas of the coastal zone comprising the intertidal, coastal organisms and habitats, marine litter, coastal zone disaster management, and coastal zone land use and land cover mapping. The review provides evidence of the potentials and effectiveness of UAVs for coastal zone management (CZM). However, factors such as difficulty in imaging water, setting out ground control points (GCPs) for geolocation of images, and processing large volumes of data can pose a challenge to coastal managers. Extensive review shows the capabilities of current UAV technologies for monitoring and tracking changes in the coastal environment at high spatial and temporal resolution.

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Introduction

Over 10% of the world's population lives in areas just under 10 m above sea-level and 40% lives within 100 km of the coast (United Nations, 2017). Coastal regions are densely populated and experience increasing rates of population growth and urbanization, making them more vulnerable to threats posed by climate change and land use and land cover change (Neumann et al., 2015). Coastal flooding, shoreline erosion, and

degradation of coastal resources are gradually affecting people, properties, and ecosystems around the world (Appeaning Addo et al., 2018; Crossland et al., 2005; Lovelock et al., 2017; Wong et al., 2014). The rapid population growth in the coastal areas has led to the widespread transformation of natural coastal landscapes into agricultural, industrial, and residential areas. Coastal areas have become the hotspot for commercial activities and the most economically productive areas worldwide (Crossland et al., 2005). As the population continues to grow and the commercial and development activities intensify in the coastal areas, the demand for land keeps rising, resulting in the encroachment of green spaces. There is, therefore, the need for effective management of coastal resources to ensure sustainable development in the region. Coastal zone management (CZM) has emerged as a formal framework for balancing development needs and protecting natural resources in the coastal areas. CZM is vital for generating and applying the information to design, monitor, and manage conservation sites, fisheries resources, disaster risk reduction, and other investments to increase resilience (Clark, 1997; Thia-Eng, 1993). The increase in the uncertainties in recent years caused by increased anthropogenic activities and climate change have led coastal researchers to use and develop new tools to monitor and manage the coastal zone.

Remote sensing methods have been shown to be accurate and reliable for coastal zone observation compared with conventional field studies, which are expensive and laborious (Mumby et al., 1999). Several studies have used Landsat and Sentinel satellite imagery to detect changes in the coastal areas (Díaz-Delgado et al., 2018; Schulz-Stellenfleth & Staneva, 2019; Vanhellemont et al., 2014; Yang et al., 2019); however, very high-resolution satellite images that can detect smaller changes are expensive and must be pre-ordered and programmed for acquisition, which is similar to airborne photogrammetry (Díaz-Delgado et al., 2018). Unmanned aerial vehicles (UAVs), which are aircraft operated remotely or autonomously with preprogrammed flight planning, are increasingly becoming auspicious tools in coastal zone management, thanks to the advancement of reliable, low-cost, and lightweight UAVs and the fast development of computer applications. UAV-based surveying is being widely used to produce high spatial resolution image products for studying coastal processes and change

(Chabot et al., 2018; Chen et al., 2018; Collin et al., 2018; Jaud et al., 2019). The UAV has the advantages of being maneuverable, versatile, and able to collect data in various coastal zone areas compared with other remote sensing tools. UAV applications in the coastal zone employed recently include marine organisms and habitat studies (Cao et al., 2018; Casella et al., 2016a; Chabot et al., 2018; Díaz-Delgado et al., 2018), intertidal studies (Barlow et al., 2017; Chen et al., 2018; Jaud et al., 2019), coastal disaster management (Appeaning Addo et al., 2018; Duo et al., 2018), and coastal land use planning (Darwin et al., 2014).

The paper is organized into six sections. The “Unmanned aerial vehicle applications in coastal zone management” section discusses the opportunities and benefits of UAV that are available for coastal zone management. The platforms are discussed in the “UAV platforms” section. In the “UAV sensors” section, sensors used in various areas of the coastal zone studies are explored. A review of the most common software used is summarized in the “Software packages for data capture, processing, and analysis” section. The “Validation techniques” section discusses the various techniques adopted to complement the UAV imagery. Finally, the “Challenges in UAV applications in CZM” section explores some accompanying inherent challenges in the use of UAVs for coastal studies. This study will better inform coastal managers and researchers on the appropriate UAV type, accessories, and methods suitable for monitoring and predicting aspects of coastal processes and change at different spatial and temporal scales.

Methods

The research addressed papers published in peer-reviewed journals in relevant online repositories, including Google Scholar and Elsevier. The search terms used were “unmanned aerial vehicles coastal zone,” “UAV application to coastal zone management,” “coastal zone management drones,” “low altitude aerial photogrammetry of coastal zone,” “coastal area UAVs photogrammetry,” “UAV coastal habitats,” and “unmanned aerial vehicles land use and land cover mapping.” The search was limited to articles written in English, and no time period was set. Studies that pertained to the application of submerged aquatic vehicles were not included. The

study also excluded thesis describing the use of UAVs in the coastal zone. The search found 124 published documents on the application of UAV technology for coastal zone management. The papers that met the inclusion criteria and were considered in the study were 97. The papers were grouped into general intertidal UAV studies ($n = 57$), marine litter studies ($n = 6$), studies on coastal organism and habitats ($n = 24$), use of UAVs in coastal disaster management ($n = 3$), and the use of UAVs for coastal land use and land cover mapping ($n = 3$). For further analysis, 17 papers that largely focused on the use of UAVs for coastal zone assessment and included information on the hardware, software, camera, product generated, field validation methods, and challenges encountered were selected (Fig. 1).

Results and discussion

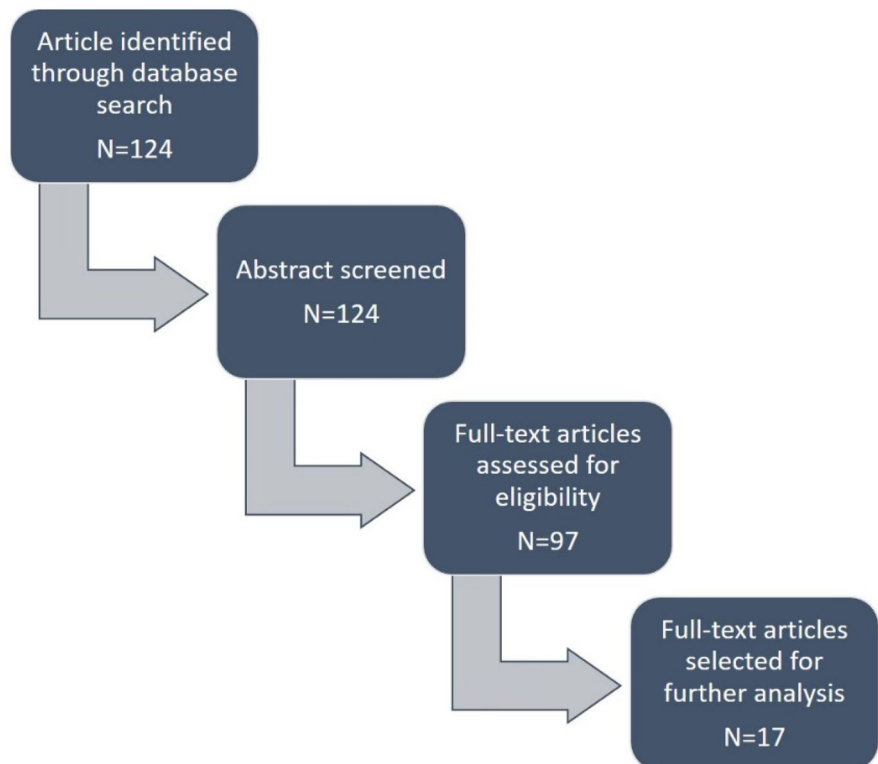
Unmanned aerial vehicle applications in coastal zone management

The advancement of autonomous technologies has increased the use of UAVs in recent years. Commercial

UAVs have been upgraded in different parts such as platforms, photographic and video sensors, navigation systems, and software (Klemas, 2015). There are different types of UAV platforms available, and they can be mounted with less expensive cameras such as GoPro and relatively more expensive sensors such as thermal cameras and hyperspectral sensors. Several studies have reported on the increasing use of UAV technology, its affordability compared with traditional field cost, and simplicity of use for different environmental assessments. The affordability of UAV surveys and its efficiency over airplane or satellite imagery acquisition in terms of time and cost have been reported (Apeaning Addo et al., 2018; Barlow et al., 2017; Casella et al., 2016a; Chen et al., 2018; Duo et al., 2018; Jaud et al., 2019). Besides, coastal UAV survey has been considered in the literature for its low cost of data collection and large-scale mapping (Casella et al., 2016a; Chabot et al., 2018; Chen et al., 2018; Sturdivant et al., 2017). A summary of the studies reviewed is presented in Table 1.

Examples of UAV applications in coastal zone management include monitoring coastal/marine organisms (e.g., sharks and rays) and habitats (e.g.,

Fig. 1 Literature search workflow for the study



coral reefs, wetlands, and mangroves). Kiszka et al. (2016), for instance, used DJI Phantom 2 to investigate shark and ray densities in the coastal lagoon of Moorea (French Polynesia). The study revealed that UAVs could be used at low cost to quantify marine fauna densities in low coastal lagoons for a short period. In terms of coastal flora, Cao et al. (2018) used UAV hyperspectral images to classify mangrove species using object-oriented image processing techniques. The study indicated the usefulness of UAV hyperspectral images for classifying mangrove vegetation which might usually be hard to come by using the conventional remote sensing approaches. Díaz-Delgado et al. (2018) also assessed how UAV multispectral images could be used to study long-term changes in the ecology of wetlands. The study mapped the distribution of aquatic plants, the turbidity of the water, and flood levels. The results confirmed the immense potential of multispectral UAV images in wetland ecological studies. Chabot et al. (2018) employed an object-based image processing method to map aquatic vegetation in shallow coastal waters using multispectral UAV imagery. It was observed that the spatial, temporal, and spectral resolution offered by UAVs could be used to assess changes in coastal wetland vegetation, which is laborious and challenging for field surveys. Also, Doughty and Cavanaugh (2019) combined seasonal field observations and multispectral UAV images obtained using two separate sensors to establish a simple mapping workflow for estimating salt marsh biomass. Casella et al. (2016a) used a DJI Phantom 2 UAV to map the coral reef in the Tiahura lagoon in France. The findings showed that it is possible to use low-cost drones as a rapid survey technique to map the spectral and height characteristics of coral reefs in shallow coastal waters in prevailing environmental conditions such as calm waters, low winds and less sun glint.

In the area of intertidal studies, Barlow et al. (2017) used point cloud and spectral data to measure the changes in chalk sea cliffs. The results obtained suggested that UAV imagery could provide a valuable basis for the study of slope stability along the stretches of the coast. Besides the potential of UAVs in mapping sea cliffs, Chen et al. (2018) also showed UAVs' capability to map significant geomorphic changes at the beach. The study used a quad-rotor UAV fitted with a non-metric sensor to complement existing

tools to detect topographic and geomorphic changes at the beach. Regarding long-term beach morphological changes, Jaud et al. (2019) performed a 12-year coastal monitoring operation with seven different types of UAV platforms and sensors. The study concluded that UAV photogrammetry is suitable for coastal morphodynamics surveys because of its rapid acquisition of high spatial resolution 3D topographic data. The study was able to detect cross-shore movements and features such as beach cusps. Shaw et al. (2019) compared two sensors (RGB camera and a UAV LiDAR system) to evaluate their capabilities of monitoring beach evolution for 6 months. The results showed that both photogrammetry and LiDAR observed a similar rate of change in terms of erosion and deposition volume estimates, indicating that both sensors are highly suitable for assessing changes in the beach.

For intertidal sediment studies, Ko and Lee (2019) used a DJI Phantom 2 UAV to detect geological structures in the west coast area of southwestern Korea. The study showed the potential of UAV application in structural geology in coastal areas. Fairley et al. (2018) also proposed a straight-forward UAV-based workflow for mapping intertidal sediments. Fixed-wing UAVs onboard with a thermal and multispectral camera were flown across three research sites comprising of sandy and muddy areas. The study established that using the thermal camera for sediment mapping did not perform well due to varied environmental factors such as temperature variation over the intertidal rather than sediment type. Relationships between both color and multispectral reflectance against surface moisture were identified. The study concluded that UAVs are a suitable tool for remote sensing of intertidal sediment.

UAVs have also been used to assess the quantity, type, distribution, and accumulation rate of marine litter in coastal areas (Deidun et al., 2018; Fallati et al., 2019; Martin et al., 2018; Merlino et al., 2020). Deidun et al. (2018) developed a protocol with the Marine Strategy Framework Directive to detect and monitor marine litter using a consumer-grade UAV. The protocol presented proved to be very relevant for management as a large sampling area can be covered with the UAV in a short time. Merlino et al. (2020) also used a DJI Phantom 4 UAV to conduct a long-term study of beach litter dynamics in the Marine Protected Area of Migliarino, Massacciuccoli and

Table 1 An overview of the selected UAV applications in coastal zone management

Category	Location	UAV Platform	Sensor	Phenomena/Object of interest	Validation	Challenges	Example Reference
Coastal organism and habitat	Moorea, French Polynesia	DJI Phantom 2	GoPro HERO 3+	Shark and Ray density estimation	Observer counts and GPS survey	Flight restriction and species disturbance	Kiszka et al. (2016)
	Qi'ao Island mangrove nature reserve, China	Multi-rotor UAV platform	UHD 185 hyper-spectral	Mangrove species	Location of mangrove species sample with GPS	Reflection of water and turbidity	Cao et al. (2018)
	Braila Island, Romania	Sensefly eBee	Sequoia	Wetland ecology	In situ measurement of water turbidity, depth, aquatic plant species abundance and dominance	In situ measurement of vegetation could not be done using handheld spectroradiometers	Díaz-Delgado et al. (2018)
Inter-tidal studies	Trent-Severn Waterway, Ontario, Canada.	Sensefly eBee	Sequoia	Aquatic Vegetation	In situ vegetation sampling using transects.	Data processing and analyzing all the images was a challenge.	Chabot et al. (2018)
	Carpinteria Salt Marsh Reserve, Santa Barbara County, CA, USA	DJI Matrice 100	Micasense Rededge	Wetland Biomass	In situ vegetation sampling using transects and ASD Handheld 2 Spectrometer	Sky conditions caused radiometric variability	Doughty and Cavanaugh (2019)
	Tiahura lagoon Moorea, French Polynesia	DJI Phantom 2	GoPro HERO 4	Coral reefs	Collection of GCP with a handheld GPS	Reflection of water and turbidity	Casella et al. (2016b)
	Jukmak Beach, southwestern Korean Peninsula	DJI Phantom Pro 4	1-inch 20-megapixel CMOS sensor	Coastal geological structure detection	Field Observation and measurement	Large volume of data resulting from low altitude flights. Weather conditions	Ko and Lee (2019)
	Telcombe cliff, East Sussex, UK	DJI S1000 octocopter	Nikon D810 FX DSLR 36	Seacliff stability	Collection of GCP	Not specified	Barlow et al. (2017)
	Wujiao Bay, Dongshan Island, China	MD4-1000 quad-rotor UAV	Pentax Option A40	Beach topography	Collection of GCP	Not specified	Chen et al. (2018)

Table 1 (continued)

Category	Location	UAV Platform	Sensor	Phenomena/Object of interest	Validation	Challenges	Example Reference
Marine litter studies	Porsmilin Beach, France	Pixy DRELIO 5 DRELIO 6 DRELIO 7 DRELIO DRELIO 10 DJI Phantom 4	Fuji S2 Pro Nikon D200 Nikon D200 Nikon D700 Nikon D700 Nikon D800 FC6310	Long-term beach Morphology	GCPs were fixed	Removable targets made from different materials were tested as GCPs because of the permanent changes in the beach.	Jaud et al. (2019)
	Warmbro Sound, Western, Australia	DJI Phantom Pro 4 DJI Matrice 200 DJI Matrice 600	1 inch, 20 megapixel CMOS Zenmuse XT camera Riegl Mini-VUX	Beach Monitoring	GCP's positioned at the centre and corners of the study area	Not specified	Shaw et al. (2019)
Marine litter studies	Neath Estuary Appledore and Llansteffan	Sensefly eBee Sensefly eBee Plus	ThermoMAP Sequoia	Temperature Moisture content	In situ measurement of sediment temperature and moisture content	Technical and regulatory factors	Fairley et al. (2018)
	North-East Marine Protected Area of the Maltese Islands	DJI Phantom Pro 4	1-inch 20-megapixel CMOS sensor	Marine litter identification	Field measurement	Drone flight restrictions Weather conditions (Wind speed)	Deidun et al. (2018)
Coastal disaster management	Marine Protected Area of Migliarino, Massaciuccoli, and San Rossore (SRPRK) park, Italy	DJI Phantom Pro 4	1-inch 20-megapixel CMOS	Beached marine litter dynamics	Field measurement	Weather condition (Heavy rain, lighting condition)	Merlino et al. (2020)
	Fuvemeh community, Ghana	DJI Phantom 3	1/2.3" CMOS	Coastal flooding and erosion	Collection of GCP	Not specified	Appeaning Addo et al. (2018)
Coastal land cover mapping	Emilia-Romagna, Italy	DJI Phantom Vision 2+	FC200 Camera	Coastal flooding	Collection of GCPs for the target area	Not specified	Duo et al. (2018)
	Black Beach, Buzzards Bay, MA, U	DJI Phantom 3	1/2.3" CMOS	Land cover mapping	Collection of GCP with a handheld GPS	Not specified	Sturdivant et al. (2017)
	River Breeze Park in Oak Hill, FL, USA	Parrot Bluegrass quadcopter	Sequoia	Land cover mapping and NDVI	Collection of GCP with a handheld GPS	Not specified	Yang et al. (2019)

San Rossore (SRPRK) Park, Italy. The study showed a good agreement between the results from the UAV and field manual counting which was done based on SeaCleaner protocol and OSPAR guidelines.

UAVs have not only given ease to marine litter studies but also able to assess the rate of coastal erosion and flooding and their associated impacts. Appeaning-Addo et al. (2018) used a quadcopter drone to acquire orthophotos of Fuvemeh community in 2016 and 2017. The study showed how the adverse impacts of sea-level rise had threatened rural livelihoods and properties. It also emerged that within a period of 12 years (2005–2017), coastal erosion and flooding have destroyed more than 77, rendering over 300 inhabitants homeless. Similarly, Duo et al. (2018) also used DJI Phantom Vision 2+ to perform damage assessment immediately after an extreme storm that struck the Emilia–Romagna coast in February 2015. The study demonstrated the potential and advantages of an integrated approach that integrates Real-Time kinematic (RTK) UAV survey with local experiences for coastal damage assessments.

Coastal resource inventory and mapping are performed to acquire baseline information on resource distribution and abundance for which priorities area can be determined for management. UAV technology has proven to be very efficient in coastal land cover mapping. Sturdivant et al. (2017) demonstrated how UAV imagery could be used to map land use and land cover of a coastal area using a supervised classification algorithm. The study indicated that in the supervised classification routine for land use and land cover mapping, the combination of elevation and slope data significantly enhances the reliability of classification results. In comparison, improvement in spatial resolution has little effect on accuracy. Yang et al. (2019), on the other hand, demonstrated how the multispectral UAV mapping technique could be improved for coastal land use and land cover mapping. Normalized difference vegetation index (NDVI) and classified maps generated from both UAV and Sentinel satellite images were compared. The results showed how UAV multispectral mapping methods could be used to complement other satellite data in areas where there is insufficient information.

UAV platforms

The two primary UAV platforms used in the reviewed studies were fixed-wing and rotorcraft UAVs. Although,

Jaud et al. (2019) reported a paramotor and three remote-controlled helicopters that used a combustion engine. This review study observed that rotorcraft were mostly used in coastal studies compared with the fixed-wing UAVs. A summary of the platforms used in the reviewed studies is presented in Table 1. Most of the rotorcraft platforms were products from DJI™ platforms, while the common of the fixed-wing platforms were products from eBee™. Fixed-wing platforms are alternatives for rotorcraft platforms. However, these platforms have their inherent pros and cons. For example, fixed-wing UAVs can carry heavy and large payloads. The structure of fixed-wing UAVs makes its aerodynamics more efficient, which gives them the benefit of longer flight durations and can reach more extensive areas under autonomous flight. The disadvantage of fixed-wing UAVs is that it requires an open area for launching and landing. Compared with fixed-wing UAVs, modern rotary-wing UAVs have very complex in-built mechanisms that enable them to operate at low speeds and to be well suited for applications requiring evasive maneuvers in narrow spaces. Rotary-wing UAVs are advantageous for closer data capture, such as 3D coastal mapping, because of their ability for vertical takeoff and landing (Papakonstantinou et al., 2016). Rotary-wing UAVs have been largely used in wetlands and marshes studies as it is often challenging to locate a dry place to safely launch and land a fixed-winged aircraft in these areas (Cao et al., 2018; Doughty & Cavanaugh, 2019; Jaud et al., 2016a, b).

UAV sensors

Rapid improvements in photographic and video sensor technologies have resulted in a variety of less expensive, small, lightweight digital cameras and sensors that are suitable for UAVs (Green et al., 2019). These include panchromatic, RGB cameras, multispectral, hyperspectral, thermal, and LiDAR sensors. Detailed descriptions of these sensors are described in Colomina and Molina (2014) and Yao et al. (2019). Unmanned aerial vehicle sensors are constrained by the lifting capacity of the platform. Growing varieties of UAV sensors have been used in various areas of the coastal zone studies. In this study, different sensors ($n = 16$) were identified in the papers reviewed (Table 1). Details of some selected sensors are provided in Table 2. Most of the reviewed studies were conducted with RGB cameras (Appeaning Addo et al., 2018; Barlow

Table 2 Details of selected UAV sensors used in CZM

Sensor	Example	Resolution	Weight	Spectral Range	Example reference
RGB Camera	GoPro HERO4	12 megapixels	87 g	~400–700 nm	Casella et al. (2016b) and Collin et al. (2018)
	Nikon D800	36 megapixels	996.20 g	~400–700 nm	Jaud et al. (2019)
	1/2.3" CMOS	12.76 megapixels	-	~400–700 nm	Appeaning Addo et al. (2018)
	Pentax Optio A40	12 megapixels	150 g	~400–700 nm	Chen et al. (2018)
Multispectral	Sequoia	1280 × 960 pixels		530–810 nm	Chabot et al. (2018), Díaz-Delgado et al. (2018) and Yang et al. (2019)
	Micasense Rededge	1280 × 960		400–900 nm	Doughty and Cavanaugh (2019)
Hyperspectral	UHD 185 hyperspectral	1000 × 1000	490 g	450–950 nm	Cao et al. (2018)
Thermal	ThermoMap	0.1°C	134 g	7.5–13.5 μm	Fairley et al. (2018)
UAV LiDAR	Riegl Mini-VUX	Up to 100,000 measurements per second	1542.21 g	-	Shaw et al. (2019)

et al., 2017; Casella et al., 2016b; Chen et al., 2018; Duo et al., 2018; Jaud et al., 2019; Sturdivant et al., 2017) and five of the studies employed multispectral cameras (Chabot et al., 2018; Díaz-Delgado et al., 2018; Doughty & Cavanaugh, 2019; Fairley et al., 2018; Yang et al., 2019). For hyperspectral, thermal, and LiDAR sensors, only one study was found for each of the sensors (Cao et al., 2018; Collin et al., 2018; Fairley et al., 2018). The patronage of RGB sensors for coastal research can be attributed to their low cost, lightweight and high resolution. The studies involving the mapping of coastal organisms and habitats utilized multispectral and hyperspectral sensors because they are very important in mapping coastal vegetation and water quality. Though hyperspectral sensors have a wide range of light spectrum bandwidths, they are often less available due to their high cost and UAV-compatibility sensor constraints. Developers of hyperspectral sensors are now making small and compact sensors enough to fit on comparatively lightweight UAVs (Yao et al. 2019).

Software packages for data capture, processing, and analysis

The application of UAVs in coastal zone management has been aided by the proliferation of inexpensive and user-friendly softwares to process and analyze the data. There are softwares available for UAV flight mission planning, image capture, image processing,

orthomosaicking of images, and visualization, as shown in Table 3. There is no single software that encompasses the entire workflow and a combination of software packages has always been used. In the review of software packages, the most commonly used software was Agisoft PhotoScan developed by Agisoft LLC (St. Petersburg, Russia). According to Jaud et al. (2016b), Agisoft PhotoScan is more straight-forward and has a relevant distortion model that limits deviations in the Digital Surface Model (DSM). Other software packages used included eMotion for flight planning, Pix4D Mapper, Adam 3DM, ArcGIS, ENVI, and MATLAB for image processing and analysis.

Validation techniques

Field observation data (ground-truthing) is an important part of remote sensing research. Remote sensing requires measurements and observations of the form, scale, condition, and other physical or chemical properties of the phenomenon or object being studied. Remote sensing analysis requires field validation to assess the reliability of the final outputs. This, according to Foody (1992), ensures data quality and user confidence. Almost all the studies reviewed validated their remotely sensed images (Table 1). The validation techniques employed included a sampling of aquatic vegetation (Cao et al., 2018; Chabot et al., 2018; Díaz-Delgado et al., 2018; Doughty & Cavanaugh, 2019), in situ measurements of water turbidity and depth (Díaz-Delgado et al., 2018), field measurements of sediment temperature and moisture

Table 3 Software packages for data capture, processing, and analysis

Workflow	Software	Usage	References
Mission and flight planning	eMotion	Flight Planning	Díaz-Delgado et al. (2018)
	DJI		Sturdivant et al. (2017)
	Cubert Pilot		Cao et al. (2018)
	OpenDrone Mapper		Deidun et al. (2018)
	DRONEHarmony		Merlino et al. (2020)
Image processing	Agisoft Photoscan	Mosaicking, orthorectification and georeferencing to generate digital surface models, orthomosaics	Appeaning Addo et al. (2018), Cao et al. (2018), Casella et al. (2016a), Chen et al. (2018), Jaud et al. (2019), and Sturdivant et al. (2017)
	Pix4D Mapper		Chabot et al. (2018), Díaz-Delgado et al. (2018), and Duo et al. (2018)
	ADAM 3DM		Barlow et al. (2017)
	MicMac	Jaud et al. (2019)	
	MATLAB	Image processing	Jaud et al. (2019) and Sturdivant et al. (2017)
	ArcGIS		Appeaning Addo et al. (2018), Chen et al. (2018), Díaz-Delgado et al. (2018), and Sturdivant et al. (2017)
	QGIS		Chabot et al. (2018)
	ENVI	Image segmentation	Chabot et al. (2018)
	GRASS		Chabot et al. (2018) and Sturdivant et al. (2017)
		Cloud Compare	Point cloud analysis and extraction
Spatial analysis	QGIS	Spatial analysis	Chabot et al. (2018)
	DSAS	Shoreline calculation	Appeaning Addo et al. (2018)
Visualization	ArcGIS		Chen et al. (2018) and Díaz-Delgado et al. (2018)
	QGIS		Chabot et al. (2018)

content and collection of GCPs with either handheld or Real-Time Kinetic GPS (Appeaning Addo et al., 2018; Barlow et al., 2017; Casella et al., 2016a; Chen et al., 2018; Duo et al., 2018; Jaud et al., 2019; Sturdivant et al., 2017; Yang et al., 2019).

Challenges in UAV applications in coastal zone management

Although the studies reviewed show that coastal managers could successfully apply UAVs in monitoring changes in the coastal zone, there are some challenges associated with the use of UAVs for coastal studies (Table 1). In this study, it was observed that environmental conditions such as temperature variation and the sun glint are problems that need to be addressed to enhance

the use of UAVs for coastal zone research (Jaud et al., 2019). It was observed that the use of fixed GCPs in long-term beach studies was a challenge since the beach was permanently changing (Jaud et al., 2019; Shaw et al., 2019). Instead, different removable targets should be used as GCPs to ensure accuracy in images collected (Jaud et al., 2019). The reflection and turbidity of water were the setbacks in the coral reefs and mangrove studies (Cao et al., 2018; Casella et al., 2016a). Flight restrictions imposed by aviation authorities were also reported to cause some challenges in the use of UAV in coastal zone management (Deidun et al., 2018; Fairley et al., 2018; Kiszka et al., 2016). Other challenges identified included technical issues relating to the processing and analysis of large volumes of images (Chabot et al., 2018; Fairley et al., 2018). One main problem that was reported

in most of the papers reviewed was the difficulty in setting out evenly distributed GCPs for image capture due to the inaccessibility of some coastal areas.

Conclusion

Unmanned aerial vehicles have proven to be valuable tools for capturing remotely sensed data for coastal zone management due to their high temporal and spatial resolution of images and relatively low operating cost. Unmanned aerial vehicles provide the vital information required to monitor and track coastal organisms, habitat change analysis, inter-tidal studies, marine litter studies, coastal land use, and land cover mapping and damage assessment. In recent times, there has been a significant rise in the use of UAVs for coastal zone management applications as the UAV platforms, sensors and processing tools become cheaper. The adoption of UAVs for studies in the coastal zones will continue to rise with the advancement in all the technologies involved and with the corresponding decrease in cost. The development of small and lightweight hyperspectral and LiDAR sensors for UAVs is expected to exponential increase in the use of UAVs coastal research. It was also found that the critical problems in the application of UAVs for coastal management are the weak spectral reflectance of water, flight restrictions, setting up of GCPs for the geolocation of images and processing of large volumes of data.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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