A Framework for Integrating Unoccupied Aircraft Systems Technology into Environmental Readiness at Naval Information Warfare Center Pacific

Jennie Shield

Advisor: David Johnston

Masters Project

Duke Nicholas School of the Environment

April 2021

Executive Summary

Unoccupied Aircraft Systems (UAS) (i.e., small drones and sensors) is a rapidly emerging technology with a growing number of applications across industries. Over the last decade, the availability of compact, low-cost, and user-friendly UASs has made them a practical and attractive tool for a variety of environmental monitoring and natural resources management applications. UAS-collected data (e.g., aerial imagery) can support tasks such as baseline mapping, habitat characterization, wildlife detection and identification, and physical and biological change analysis, among others. The versatility, repeatability, immediacy, and increased spatial extent of UAS-based surveys allows for efficient data collection, supplementing or replacing traditional in-situ sampling methods.

The Department of Defense (DoD) is mandated by law to protect and manage its natural resources in accordance with a suite of federal, state, and local regulations. As one of the largest land-owners in the United States, sustainable management of DoD lands and adjacent waters requires comprehensive planning, coordination, and implementation of practices designed toward specific and measurable objectives; thus, environmental monitoring is an important part of natural resources management because it provides data for informed decision-making.

At Naval Information Warfare Center Pacific (NIWC Pacific) the Environmental Readiness (ENVR) branch supports a variety of monitoring projects throughout Southern California on behalf of the Navy and Marine Corps. The ENVR team has identified an opportunity to enhance its data collection capabilities by applying commercially available UAS technology to its monitoring tasking. This would allow the ENVR team to generate higher-value deliverables (e.g., reports) with greater precision through increased spatial-temporal resolution.

This project provides a framework for integrating UAS technology into ENVR tasking by examining the following monitoring applications: 1) rocky intertidal 2) coastal seagrass 3) coastal sage scrub, and 4) wildlife detection. For each application, there is a project background summary, a description of current practices, and a UAS integration assessment. Lastly, there is a discussion of the observed challenges and limitations of this approach, as well as recommendations and next steps. This basic framework serves as a foundation for future exploration and implementation by the ENVR branch at NIWC Pacific.

Background

According to the Congressional Research Service (CRS) (2020), the Department of Defense (DoD) is the fifth largest federal land managing agency in the United States, with nearly nine million acres under its purview (and approximately 27 million globally). California, specifically, is home to over 30 military installations distributed across approximately two million acres (CRS, 2020; State of California, 2020). This well-developed defense infrastructure of military bases and training and testing ranges includes a unique and valuable combination of assets including weather, climate, and terrain (CRS, 2020; State of California, 2020).

The value and importance of federally owned natural resources is well documented. For example, research identifies more than 500 at-risk species either on or adjacent to military installations (Boice, 2006). Additionally, federal lands comprise a variety of ecosystems with diverse habitats and native wildlife (Stein et al., 2008). Much of these lands are undeveloped and biodiverse, and therefore, important for conservation (Stein et al., 2008). According to Stein et al. (2008), “federal lands provide habitat for a considerable number of rare and endangered species, and are likely to play an increasingly important role in sustaining the nation’s complement of plants and animals.” It is crucial to protect and effectively manage these lands and other resources as both natural and anthropogenic stressors continue to put pressure on native ecosystems (Stein et al., 2008).

In addition to their ecological value, these federal lands serve as important deployment analogs by providing realistic conditions and diversity of terrain in which to train and test (Galgano & Rose, 2021). These unique and challenging environments are a finite and valuable resource, and they are subject to degradation without proper management (Galgano & Rose, 2021). The benefit of sustaining overall ecological integrity is, therefore, two-fold: Effective management is a critical enabler of mission readiness (i.e., preparedness), and it safeguards native habitats and at-risk species.

Federal statutes such as the Sikes Act, the Endangered Species Act, the Clean Water and Air Acts, and the National Environmental Policy Act, among others, require compliance from federal agencies. Adherence to federal, state, and local environmental regulations allows the Navy to execute its mission in an uninterrupted and cost-effective manner by avoiding regulatory encroachment, which could severely limit training and testing capabilities, negatively impacting overall mission readiness (CNIC, 2021). As Commander, Navy Region Southwest states, “While the Navy’s mission is national defense, we are committed to operating our forces in a manner compatible with the environment (e.g., natural, historical, and cultural resources). National defense and environmental protection are not mutually exclusive goals" (CNIC, 2021).

The DoD demonstrates its commitment to environmental stewardship through explicit instruction, dedicated environmental support programs (e.g., conservation, pollution prevention, range sustainment), and robust basic and applied research programs such as the Navy's Living Marine Resources (LMR) and Marine Species Monitoring programs, Strategic Environmental Research and Development Program (SERDP), and Environmental Security Technology Certification Program (ESTCP). DoD Instruction 4715.03 (2011) states the following:

> The principal purpose of DoD lands, waters, airspace, and coastal resources is to support mission-related activities. All DoD natural resources conservation program activities shall work to guarantee DoD continued access to its land, air, and water resources for realistic military training and testing and to sustain the long-term ecological integrity of the resource base and the ecosystem services it provides.... DoD shall manage its natural resources to facilitate testing and training, mission readiness, and range sustainability in a long-term, comprehensive, coordinated, and cost-effective manner.

Introduction

Natural resources managers within federal agencies, such as the Navy, seek to balance the dual priorities of ecological protection and mission readiness. To do this, they rely on accurate and timely information in order to make sound decisions amongst competing demands. Thus, there are significant implications to adopting tools, techniques, and processes that offer potential improvements and efficiencies. For example, adopting new monitoring tools, such as those offered by UAS technology, could provide an efficient alternative or enhancement to traditional data collection methods.

Environmental monitoring, using traditional survey and sampling methods, can be tedious and resource-heavy; and, often, potentially important sampling locations or entire habitats are excluded because of limited accessibility or inherent safety risks (Nowak et al., 2018). For example, aerial survey methods, using small, occupied aircraft are costly and can pose undue risk to the pilot and passengers (Johnston et al., 2017; Linchant et al., 2015). Additionally, due to their expense, occupied survey flights are used infrequently; therefore, the data often lacks the granularity for robust analysis and timely decision-making (Johnston et al., 2017; Linchant et al., 2015). Furthermore, on-the-ground sampling methods can cause damage to sensitive habitats (Borrelle & Fletcher, 2017; Johnston et al., 2017; Linchant et al., 2015). Remote sensing, specifically UAS technology, can be integrated into traditional methods to improve consistency, reduce costs, mitigate risk to personnel, decrease degradation of sensitive species and habitats, and increase the spatial-temporal resolution of surveyed sites; thus, this technology is quickly becoming a popular mode of data collection in both terrestrial and marine environments (Cohen, 2019; Johnston et al., 2017; Linchant et al., 2015).

Unoccupied Aircraft Systems (UAS) technology continues to rapidly evolve, and has gained significant traction in the environmental monitoring field over the last decade (Johnston et al., 2017; Linchant et al., 2015). It is widely recognized that UAS technology has the potential to transform the field of environmental monitoring through inherent qualities such as affordability, efficiency, immediacy, quality, and safety (Cohen, 2019). In addition, the increasing versatility of commercially available platforms (e.g., fixed-wing, multirotor) and payloads (e.g., thermal, multispectral) offers a multitude of application opportunities (Johnston, 2019). Currently, common UAS applications in natural resources and environmental management within the terrestrial realm include habitat and wildlife surveys, fire and flood vulnerability assessments, hydrologic flow analysis, archeological and cultural resources mapping, and rapid post-event (e.g., wildfire, hurricane) disturbance or damage assessment, vegetation classification and characterization assessments (DOI, 2016; Manfreda et al., 2018; Nowak et al., 2018). Marine applications of UAS include habitat and wildlife surveys, shoreline change (e.g., coastal erosion, tidal inundation, etc.) analysis, oil spill, algal bloom, and marine debris assessments (Alliance for Coastal Technologies, 2018; Johnston, 2019). Although, coastal research using UAS technology is still in the early stages of development it is proving to be an exciting area of novel research.

Objectives

It is important for natural resources managers and practitioners within the DoD to regularly evaluate and improve upon their methods in accordance with best available science, and as applications of new technology become practicable. When evaluating the feasibility of incorporating a new technology or practice into tasking an assessment should be made based on criteria such as affordability, efficiency, safety, security, agility, and scalability.

For several years, the ENVR team at NIWC Pacific has been aware of UAS as an emerging technology with exciting environmental survey applications, and there is growing interest in integrating UAS technology to both improve and expand its capacity for environmental monitoring. Applying UAS technology to current tasking would allow for increased sampling, improved accuracy, and more timely deliverables to our sponsors. Additionally, it provides a future pathway to grow the ENVR monitoring portfolio by offering new products and services to project sponsors. Furthermore, integrating UAS offers opportunities for professional development (e.g., skill building). Hence, there is an urgent need for a basic framework as a necessary first step. Developing a framework for UAS integration would serve to align the ENVR strategy with best available science, and current federal rules and regulations (e.g., Federal Aviation Administration), as well as DoD and NIWC Pacific guidelines (e.g., acquisition, operation) regarding UAS.

For this master's project the primary objective is to provide a foundation and basic framework for UAS integration. To do this, I would need to develop an understanding of 1) UAS applications and methods for environmental monitoring, and 2) the current operational landscape of UAS on federal installations. Development of this framework for provides a strong foundation for future implementation by the ENVR team at NIWC Pacific.

Methods

Strategy Development

As a member of the ENVR branch at NIWC Pacific, I am embedded in the Navy's environmental management community. I support at-sea training and testing compliance initiatives, and I participate in a variety of monitoring projects throughout Southern California. Therefore, I understand, and I am directly connected to, the concept of environmental readiness. Being positioned within the Navy's environmental community affords access to important stakeholders, existing partnerships, data and information, study sites, equipment, and subject matter expertise. However, I began this project with a limited understanding of UAS technology; thus, I was initially guided by basic questions such as the following:

- *What technology is available? And how is it being applied?*
- *What UAS methods are being used successfully?*
- *What deliverables (e.g., final products) could be provided to project sponsors?*
- *What operating materials and supplies would be needed?*
- *What are the costs of required hardware and software?*
- *How would we acquire funding?*

- *What are the necessary skills for data collection and processing? And what training is available?*
- *What are the DoD and Navy guidelines regarding UAS acquisition and operation?*
- What are the data collection protocols for existing ENVR tasking? And are there data gaps and/or unanswered questions?

Stakeholder Engagement

To begin answering these questions I first conducted qualitative interviews, framed as "structured brainstorming" sessions, with two ENVR colleagues. Each colleague has the role of task manager and supports a variety of research projects. It was important to understand other perspectives on UAS technology integration to catalyze and inform a branch-wide strategy. For example, the interview process identified questions, concerns, and ideas for further investigation. Moreover, these interviews served as a starting point for more targeted outreach and communication with important stakeholders.

These stakeholder engagement efforts created opportunity to develop important relationships through communication and information exchange with the understanding that developing social capital would encourage continued engagement and support. For this effort to gain traction outside the confines ENVR branch, I needed to begin building a stakeholder network or "community of support." To continue building momentum, the next step would be to grow this community of support into a "community of interest", and eventually into a "community of practice;" the latter being the ultimate goal.

The semi-structured interviews, informal meetings, and frequent discussions, served as important touchpoints which helped to build relevance and trust with stakeholders. Also, as a result, what was learned informed other key aspects such as training requirements, labor costs, materials and supplies, and details on UAS acquisition and operations processes. This information was then used to develop an initial cost estimate which will be a critical component of any future funding proposal. Additionally, I was able to gain a deeper understanding of the ENVR monitoring portfolio, and project-specific aspects including objectives, methods, risks and challenges, budgets, and funding mechanisms. In addition, I tried to better understand the technical skills and training that would be required for UAS-based data collection and processing, so that my team could leverage adjacent opportunities (e.g., geospatial analysis) to develop or strengthen these skillsets. Developing a better understanding of project-specific information, available resources, challenges, and needs would allow me to make informed recommendations on potential UAS applications, and to provide overall guidance for this effort.

Literature Review

I performed a comprehensive literature review of both peer-reviewed and gray literature to increase my knowledge of UAS applications in environmental monitoring and natural resources management. This would allow me to make initial recommendations for existing monitoring projects in the ENVR portfolio that could benefit from UAS integration. In addition, this literature review led to the development of a living electronic database (e.g., EndNote library). This library will be made available to the ENVR team for future proposal, report, and publication development.

Science Application

Finally, building on the stakeholder engagement activities and the literature review allowed me to provide an initial UAS integration assessment for four project applications 1) rocky intertidal 2) coastal seagrass 3) coastal sage scrub, and 4) wildlife detection. For each project application below, I present a background summary, a description of current practices, and a UAS integration assessment. Lastly, I discuss the observed challenges and limitations of this approach, and I provide recommendations and next steps.

Monitoring Application Assessments

Rocky Intertidal

According to the Multi-Agency Rocky Intertidal Network (MARINe) (2020), the rocky intertidal zone is defined as “the interface between terrestrial and marine environments.” This unique coastal zone is both physically complex and rich in biological diversity (MARINe, 2020). The biological communities of intertidal habitats are often the first to exhibit impacts to environmental change; therefore, long-term monitoring and assessment of intertidal reefs is necessary to 1) discern natural change from human-induced change 2) determine the level of change, and 3) inform management decisions (Konar & Iken, 2018).

The Multi-Agency Rocky Intertidal Network (MARINe, 2020) is a consortium of more than twenty research groups lead by the University of California Santa Cruz (MARINe, 2020). Biodiversity and monitoring surveys of the rocky intertidal ecosystem are completed annually at sites along the Pacific Coast of North America, from Southeast Alaska into Mexico, using a fixed-plot approach to record species abundances and document changes in coverage (MARINe, 2020). Fixed-plot or quadrat sampling is a common and reliable method for quantifying organisms in the benthic environment, and is often used in conjunction with photographic image analysis (Konar & Iken, 2018). The main objective is to collect compatible data that can be recorded in a centralized database for long-term monitoring and research (MARINe, 2020). On behalf of MARINe, the Navy Marine Ecology Consortium (a collaborative partnership between NIWC Pacific and NAVFAC Southwest scientists and field technicians [NMEC]) survey sites on the Point Loma peninsula and on the Channel Islands on a bi-annual basis. Currently, NMEC performs intertidal monitoring using traditional visual survey methods such as quadrat plot or fixed-plot sampling and ground camera imagery collected by on the ground observers during seasonal low tide events.

Recent research demonstrates the utility of UAS technology in the intertidal environment (Fairley et al., 2018; Konar & Iken, 2018; Murfitt et al., 2017; Tait et al., 2019). Generally, UAS technology offers new opportunities to evaluate coastal ecosystems with the ability to capture centimeter resolution aerial imagery and topographic data (Murfitt et al., 2017). Conventional intertidal survey methods yield fine-scale (i.e., high taxonomic resolution) data; however, they offer a limited spatial extent for sampling in this environment (Konar & Iken, 2018; Murfitt et al., 2017). Konar and Iken (2018) used a quadcopter outfitted with a high-resolution camera (i.e., GoPro) to determine percent cover in both rocky intertidal and seagrass environments. The UAS-based survey data resulted in a lower taxonomic resolution when compared with ground observer data, but varied depending on the tidal stratum analyzed (Konar & Iken, 2018). Murfitt el al. (2017) used a multirotor unoccupied aerial vehicle (UAV) equipped with a high-resolution camera to collect photo imagery <1 cm resolution in an intertidal reef environment. Although this data was not able to provide sufficient observation of understory species when compared to the conventional fixed-plot approach, it was able to provide a full coverage survey and accurate documentation of the dominant canopy habitat (Murfitt et al., 2017). Fairley et al. (2018) used a fixed-wing UAV equipped with both thermal and multispectral cameras to survey intertidal sediment (e.g., sandy and muddy areas). Although, data from the thermal camera was not viable for this application, data from the multispectral camera was used successfully in sediment classification (Fairley et al., 2018). Tait et al. (2019) conducted UAV-based intertidal and subtidal macroalgal surveys to compare data collected with a common camera (e.g., red-green-blue [RGB] visible light) and a multispectral (e.g., enhanced) sensor. They found the most consistent classification resulted when the separate data sets were combined (Tait et al., 2019).

The Navy Marine Ecology Consortium (NMEC), in coordination with project sponsors, identified an emergent need to collect aerial imagery to support the creation of accurate aerial maps of MARINe monitoring sites at San Nicolas Island (SNI), San Clemente Island (SCI), and Point Loma. Although there is existing LiDAR data for a subset of these sites (e.g., SNI), collected via a occupied aircraft survey, not all sites were included, and the data is also of insufficient quality for this application. Additionally, chartering another occupied survey flight to collect new, and possibly better quality, data exceeds available budgets. A baseline site mapping task, would serve as an initial opportunity to integrate UAS technology into an existing ENVR project. For this task, UAS-based surveys could be accomplished using a small multirotor UAV equipped with either a high-resolution camera and/or a multispectral LiDAR sensor. The high-resolution photo imagery could be used to create georeferenced site maps that accurately identify the location and orientation of quadrat plots at each survey site. The multispectral LiDAR data could be used to create 3D topographic and bathymetric site maps that accurately document reef elevation at low tide. Additional UAS-based surveys could support tasks such as habitat characterization, and physical and biological change analyses.

It is recommended, that the first attempts to collect UAS-based data would take place at the Navy's rocky intertidal monitoring sites on the Point Loma peninsula, which are located within the NIWC Pacific UAS-approved Point Loma "Range"(PL-1 – PL-10) (see Figure 1). These survey sites are located in close proximity to the ENVR lab and office facilities, making it logistically more feasible. This location would allow for thorough pre-flight site survey(s) and mission planning, opportunities to develop and refine data collection methodologies, and also to practice field team roles and responsibilities. Once data collection methods have been tested and refined, this task could be transferred to the more remote Channel Islands locations of SCI and SNI.

Figure 1: UAS-Approved Airspace Over the Point Loma Peninsula (PL-1-PL-10) and Approximate Locations of the Navy Rocky Intertidal Monitoring Sites

Applying UAS to the intertidal zone within a DoD installation presents a number of challenges, both technical and logistic. Many of these survey sites occur in remote locations and with limited accessibility and resources; therefore, an ideal UAV for these applications would have the following characteristics: stability, endurance, ruggedness, maintainability, and versatility. Suitable components (e.g., the vehicle, sensors, ground control station, and software) must be sourced to build a highly portable and compact system with ample flight time, that could handle a variety of environmental conditions (e.g., salt spray, wind shear) all while collecting precision data over a surface with high relief. Logistic challenges include managing operation permissions, and coordinating with range officials and air traffic control entities at DoD installations. Finally, data collection at all rocky intertidal survey locations would need to take place during seasonal low tide events to ensure full exposure of the intertidal strata; therefore, timing and coordination would be important considerations.

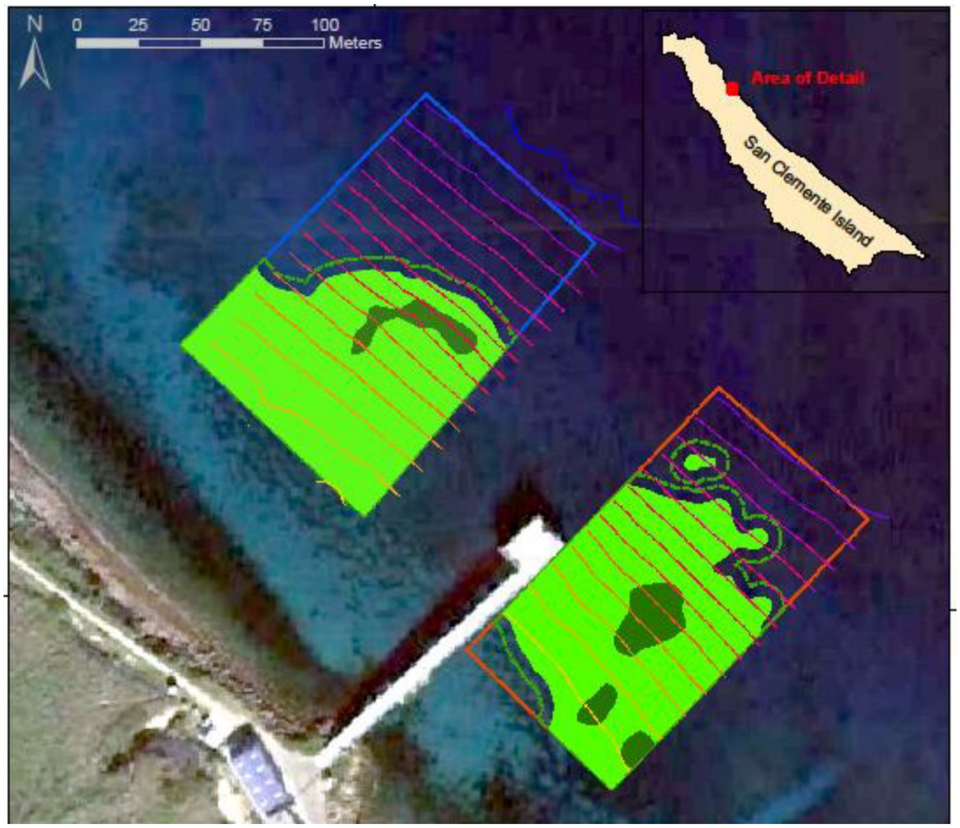
Coastal Seagrass

Marine seagrasses occur in shallow coastal environments worldwide (Duffy, 2006). Seagrass beds provide a variety of important ecosystem services in coastal regions throughout the world including the provision of nursery habitat, foraging grounds, and shelter for many marine species (e.g., fishes), sediment stabilization, improved water quality, and carbon sequestration (Collin et al., 2012; Duffy et al., 2018). Seagrass ecosystems are highly sensitive to environmental change, and are susceptible to anthropogenic impacts (e.g., pollution, physical habitat destruction, etc.) due to their occurrence in nearshore coastal waters (Duffy et al., 2018). Globally, seagrass beds have been in decline for several decades as a result of their sensitivity to both natural and anthropogenic stressors (Duffy, 2006).

Protection of temperate seagrass beds located in Southern California waters is mandated by state and federal regulations. Conservation mechanisms include essential fish habitat designations and California Eelgrass Mitigation Policy (CEMP). The Navy Marine Ecology Consortium (NMEC) conducts project-based eelgrass (*Zostera marina*) surveys in the San Diego Bay and adjacent to the Naval Ordnance Test Station (NOTS) pier at San Clemente Island (SCI). This monitoring is performed on behalf of the Navy in accordance with CEMP. The main objectives are to collect, process, and report data from these locations on bathymetry, environmental conditions (e.g., water temperature), biological conditions (e.g., species presence), and eelgrass density and distribution, contributing to the overall region-wide eelgrass monitoring program (Bernstein et al., 2011). This data is used to track and better understand changes over time due to both natural and anthropogenic factors.

Typical seagrass survey methods will differ depending on the size and depth of the survey area. Currently, NMEC uses a vessel-based line transect approach to collect hydroacoustic and video imagery data. Hydroacoustic data is collected along established transects using a single beam sonar system, and video imagery is collected using an underwater fixed camera-quadrat plot apparatus. Data is recorded in the field, and then processed using visual habitat software that interpolates between data points. Spatial distribution maps showing density and condition of eelgrass beds within the project site(s) (i.e., Area of Potential Effect [APE]) and reference site(s) are produced for final reporting (see Figure 2).

Figure 2: Spatial Distribution of Eelgrass Coverage at NOTS Pier, SCI (SSC Pacific, 2017)



Recent research demonstrates the utility of UAS technology for seagrass monitoring in the littoral zone (Collin et al., 2012; Duffy et al., 2018; Konar & Iken, 2018; Nahirnick et al., 2018). Collin et al. (2012) conducted a coastal habitat mapping study using LiDAR (light detection and ranging) in an urban coastal environment with a variety of cover types, including eelgrass meadow. They demonstrated the efficacy of a single multispectral LiDAR sensor in a complex, shallow-water coastal environment (Colling et al., 2012). They successfully classified 19 coastal habitat types; although, they found a higher level of inconsistency in habitat classification within the intertidal environment when compared with the subtidal environment (Collin et al., 2012). To reconcile mapping in this zone, they suggest integrating LiDAR altimetry and combining bathymetric LiDAR data with accurate topographic data (e.g., DEM) (Collin et al., 2012). Konar and Iken (2018) found no significant difference between UAV-based imagery and observer data when calculating seagrass percent cover; thus, they were able to evaluate variability in seagrass cover over a much larger spatial extent than a conventional survey. Additionally, UAV-based imagery was able to show small-scale variability within a seagrass bed (Konar & Iken, 2018). Duffy et al. (2018) used a multirotor UAV outfitted with a high-resolution camera and a metal-oxide semiconductor sensor to survey seagrass meadows. They processed the same data set using several classification techniques (e.g., optical texture, object-based image analysis) that resulted in varying levels of complexity and accuracy; however, they demonstrated the inherent utility of commercially available cameras for this, or similar, applications (Duffy et al., 2018). Nahirnick et al. (2018) examined the quality of UAS-derived imagery in seagrass habitats against varying environmental conditions (e.g., cloud cover, sun angle), and varying site characteristics (e.g., density). They found data reliability was most closely tied to environmental conditions, particularly sun angle, rather than site characteristics (Nahirnick et al., 2018).

Although there is not an urgent need for UAV-based seagrass mapping in ENVR tasking, there is value in exploring it as a tool for project improvement. Yang et al. (2020) provides training recommendations for UAV-based seagrass monitoring and mapping applications for both novice and advanced users. As a starting point, it is recommended the ENVR team become familiar with the basic training elements and workflow outlined in Yang et al. (2020). An initial boundary mapping task of Navy eelgrass monitoring sites in San Diego Bay could serve as a follow-on opportunity to rocky intertidal UAV-based data collection to further test available hardware and refine data collection methodologies for this application. If successful, there could be future opportunities to apply more advanced processing and analysis of UAS-collected data in support of seagrass monitoring and management.

Coastal Sage Scrub

Coastal sage scrub (CSS) is a biologically rich native coastal lowland ecosystem located throughout Southern California and Baja California (Bowler, 2000). This ecosystem provides important shelter, nesting, and foraging grounds, and serves as a biological corridor for many species including the endangered California gnatcatcher (*Polioptila californica*) (Bowler, 2000). Coastal sage scrub faces threats from habitat fragmentation and other natural and anthropogenic stressors (e.g., air pollution), and has been in decline for several decades (Bowler, 2000). According to Bowler (2000), more than 60 plant taxa and 30 animal taxa associated with CSS are considered at-risk.

The Environmental Readiness branch has provided long-term ecological monitoring program support at Marine Corps Base Camp Pendleton and the Navy’s Detachment Fallbrook. Currently, ENVR support at these installations is centered on terrestrial habitats (e.g., CSS) and focal species in support of the following protocols, projects, and programs:

- Invasive Flora Eradication Program (IFEP)
- Invasive invertebrate monitoring

- Effects analysis and data management: weather and trend monitoring, and data verification and management protocols
- Coastal sage scrub monitoring protocol
- Fuel moisture monitoring
- Fire studies and monitoring
- Remote Automatic Weather Station (RAWS) data accuracy and maintenance
- Endangered species mapping and conservation assessments

In general, these projects support compliance with a suite of federal regulations (e.g., Endangered Species Act) and DoD management plans (e.g., integrated pest management). Coastal sage scrub habitat monitoring supports at-risk species in San Diego County. Conventional monitoring includes evaluating the condition of CSS across multiple gradients (e.g., coast to mountains) through on-the-ground survey and sampling methods where the ratio of shrub cover versus non-native grasses is recorded along established line transects. Additionally, on a five-year cycle, installation natural resource managers fund occupied survey flights to support broad-scale vegetation mapping; however, the resulting data products provide only a course overview, and still require ground-truthing and verification on a finer scale.

Terrestrial-based UAV applications have a proven track record in the environmental monitoring and management fields (Dainelli et al., 2021; Laliberte et al., 2011; Lam et al., 2020; Manfreda et al., 2018; Nowak at al., 2018;). Dainelli et al. (2021) performed a review and analysis of UAV-based forestry research publications, and found that this data collection tool is optimized for precision forestry applications. In addition, practical forestry has benefitted from customized datasets, and improved spatial-temporal accuracy (Dainelli et al., 2021). Laliberte et al. (2011) demonstrated the efficacy of UAS-based multispectral imagery for rangeland vegetation classification collected with low-cost digital cameras, and developed a batch-processing workflow for more efficient data processing. Lam et al. (2020) collected vegetation data using small consumer grade UAVs equipped with RGB cameras flown at low altitudes. They used this imagery to test a deep learning workflow against an object-based image analysis approach for accurate weed mapping (Lam et al., 2020). Manfreda et al. (2018) conducted a robust literature review of UAS applications for environmental monitoring with an emphasis on the following: vegetation conditions, hydrological variables and flow, and soil properties and moisture content. Nowak at al. (2018) also performed a review and analysis of recent literature documenting the versatility of UAS applications in the field of environmental biology. They grouped studies into four general categories 1) vegetation monitoring (e.g., detection, assessment, threat prediction) 2) vegetation measurement (e.g., biophysical parameters) 3) quantification of habitat dynamics, and 4) animal population assessments and behavioral studies (Nowak et al., 2018).

UAS-based data collection and mapping is of great interest to ENVR project sponsors at Camp Pendleton and Detachment Fallbrook. Although, there are similarities between CSS monitoring and seagrass monitoring, there would likely be subtle, but potentially important differences regarding hardware choice and data collection methods due to inherent differences in marine and terrestrial environments. UAS-collected aerial imagery would support plant cover classification and mapping of CSS, as well as other habitats of interest (e.g., riparian forest). UAS-collected data could support the monitoring of CSS condition (e.g., moisture content, density of understory species) especially in relation to fire risk. This work would lead to a better understanding of the relationship of fire frequency to overall CSS stand health, and would allow installation managers to focus fire resources in areas of importance.

Wildlife Detection

Animal monitoring, through species detection and identification, is an important component of wildlife management and conservation (Hodgson et al., 2018). For example, species density and abundance information can help inform policy and management decisions by providing key insights such as species occurrence and population health (Hodgson et al., 2018). Wildlife monitoring activities that occur on or adjacent to federal installations is often a requirement of a federal, state, or local regulations or in support of basic science and research. For example, the Endangered Species Act affords protection for at-risk species, and marine mammals, specifically, are protected under the Marine Mammal Protection Act.

The Navy Marine Ecology Consortium performs marine mammal monitoring in the San Diego Bay and nearby coastal waters on behalf of the Navy. This data supports various marine mammal species density estimations for the Southern California region, which is a crucial input for Navy environmental modeling. Currently, NMEC conducts vessel-based line transect surveys, and records sighting data using Whale Identification and Logging Database (WILD) software. This biological and environmental data is then processed using Distance software to estimate species density and abundance.

Recent research demonstrates the utility of UAS technology for detection and identification of wildlife in both marine and terrestrial environments (Chabot et al., 2015; Burke et al., 2019; Hodgson et al., 2018; Johnston et al., 2017; Kellenberger et al., 2018; Landeo-Yauri et al., 2020; Linchant et al., 2015;

Mangewa et al., 2019; Schroeder et al., 2020). Chabot et al. (2015) conducted UAS-based surveys of a Common tern (*Sterna hirundo*) colony using a fixed-wing vehicle outfitted with a camera. The aerial imagery was processed and compared to ground survey data to determine the overall efficacy of a UAS-based survey approach (Chabot et al., 2015). Burke et al. (2019) tested the efficacy of a UAV-mounted thermal camera to survey riverine rabbits (*Bunolagus monticularis*). Although, they were successful in detecting these small mammals, they identified a need for further exploration and optimization of strategy and methods (Burke et al., 2019). Hodgson et al. (2018) used a small quadcopter to collect aerial imagery of a beach-based seabird colony. They compared count accuracy between the UAS-based data and ground collected data, and found improved accuracy and more precision in the UAS-derived data (Hodgson et al., 2018). Landeo-Yauri et al. (2020) used a small multirotor UAV to capture aerial imagery of Antillean manatees (*Trichechus manatus*) to support individual photo identification.

There are limitations to the current vessel-based survey methods employed by NMEC such as the large spatial extent of survey areas and the strain on resources (e.g., boat fuel, minimum of four personnel). Additionally, these surveys are highly dependent on weather and sea state which places seasonal constraints on data collection opportunities. Supplementing these conventional approaches with UAS technology for this specific activity is not recommended at this time due to the numerous logistic and technical challenges of conducting UAS operations at sea. Currently, ENVR does not support any terrestrial wildlife monitoring projects; however, there are several promising possibilities of future work in this area. If additional wildlife monitoring opportunities become available to the ENVR team, it is recommended that UAS applicability and feasibility be evaluated on a case by case basis.

Challenges

There are a number of barriers and uncertainties that exist between this framework and future implementation. First, As Yang et al (2020) asserts “geographical drone mapping and in situ fieldwork often come with a steep learning curve requiring a background in drone operations, Geographic Information Systems (GIS), remote sensing and related analytical techniques.” Although, the ENVR team is made up of experienced scientists and field technicians, these UAS-specific skillsets will require training and development. Second, natural resource budgets are typically conservative. The ENVR team will have to solicit financial support from project sponsors, as well as identify new funding mechanisms to avoid a fragmented approach and ensure a smooth transition. Third, a majority of the ENVR field work was cancelled during 2020 due to the global pandemic, COVID-19. Fortunately, it appears the ENVR team will be able to resume scheduled monitoring activities and associated field work in the near future. Fourth, a UAS operations cost center model was introduced at NIWC Pacific in September 2020, which could be prohibitive for projects with limited budgets. This cost center was designed to help off-set the general overhead and support costs associated with UAS operations at the Command. Thus, the ENVR team will need to closely monitor cost center developments, and account for any potential cost increases in projected budgets. Lastly, UAS is a rapidly emerging technology with important security implications for the DoD (e.g., information and operations security), and this results in a dynamic policy environment. These dynamics can create real challenges such as abrupt changes to hardware procurement and operational policies, which could unexpectedly interrupt or terminate UAS-based data collection efforts.

Recommendations

As presented, the goal of this project was to provide a basic framework, or clear next steps, to integrate UAS technology into ENVR tasking at NIWC Pacific. If sufficient funding can be coordinated for this effort, the ENVR team should leverage this framework for further development and refinement of ideas and methods. In the absence of immediate funding, the ENVR team should continue to engage stakeholders, and identify and align both short and long-term sponsors. Additionally, the ENVR team should continue to leverage adjacent opportunities at NIWC Pacific, and within the greater DoD environmental management and natural resources communities. For example, there is an ongoing workforce development initiative at NIWC Pacific that offers geospatial analysis training. This skillset will be required for basic and advanced processing of UAS-collected aerial imagery. Furthermore, the ENVR team should remain cognizant of relevant science, trends, and DoD policies related to UAS-based monitoring. Finally, the ENVR team should continue to evolve its UAS integration strategy over time, based on best available science, scope of work, subject matter expertise, and technical abilities.

Conclusion

The repeatability, immediacy, and increased spatial extent of UAS-based surveys allow for improved data collection and analysis, supplementing traditional *in-situ* environmental sampling methods. However, the applicability of UAS technology to monitoring is highly dependent on project objectives. Appropriate applications will require a detailed review of best available science to determine which methods and hardware are best-suited to the project-specific objectives since the overall utility of UAS-collected data can be highly variable. Whether or not UAS technology offers a more cost effective and logistically easier means of collecting environmental data will also be project dependent; however, there is ample opportunity for continued transformation in this field. According to Pereira et al. (2009) "Future generations of UAV systems will reflect the major current trends: increased levels of autonomy, lower cost, longer endurance, and networking capabilities." However, reimagining conventional approaches to environmental monitoring and management must remain a priority so this community can scale its efforts in the coming years. Thinking beyond UAS, what other strategic approaches and new tools should be considered? Deploying and embracing advancements in technology will create infinite opportunity for improvement in monitoring, management, and conservation efforts.

References

Bernstein, B., Merkel, K., Chesney, B., and Sutula, M. (2011). *Recommendations for a Southern California Regional Eelgrass Monitoring Program*. Southern California Coastal Water Research Project.

Boice, P. (2006). *Defense and conservation: Compatible missions*. Endangered Species Bulletin. 31(2), 4-7.

Borrelle, S. B., and A. T. Fletcher. (2017). Will drones reduce investigator disturbance to surface-nesting birds? *Marine Ornithology, 45*, 89-94.

Bowler, P. A. (2000). Ecological restoration of coastal sage scrub and its potential role in habitat conservation plans. *Environmental Management, 26*(S1), S85-S96.

Burke, C., M. Rashman, S. Wich, A. Symons, C. Theron, and S. Longmore. (2019). Optimizing observing strategies for monitoring animals using drone-mounted thermal infrared cameras. *International Journal of Remote Sensing, 40*(2), 439-467.

Chabot, D., S. R. Craik, and D. M. Bird. (2015). Population census of a large common tern colony with a small unmanned aircraft. *PLoS One, 10*(4), e0122588.

Cohen, S. (2019). Region-wide integration of UAS technology into DOD natural resource management through demonstration, coordination, training, and outfitting [Unpublished project proposal #RC19-D3-5218]. NAVFAC Engineering and Expeditionary Warfare Center. Port Hueneme, CA.

Collin, A., B. Long, and P. Archambault. (2012). Merging land-marine realms: Spatial patterns of seamless coastal habitats using a multispectral LiDAR. *Remote Sensing of Environment, 123*, 390-399.

Congressional Research Service (CRS). (2020). *Federal Land Ownership: Overview and Data*.

Commander, Navy Installations Command (CNIC). (2021). Environmental. Retrieved from https://www.cnic.navy.mil/om/base_support/environmental.html

Commander, Navy Installations Command (CNIC). (2021). Environmental Support. Retrieved from https://www.cnic.navy.mil/regions/cnrsw/om/environmental_support.html

Dainelli, R., P. Toscano, S. F. Di Gennaro, and A. Matese. (2021). Recent advances in unmanned aerial vehicle forest remote sensing—a systematic review. part I: a general framework. *Forests, 12*(3), 327.

Department of Defense. (2011). *Natural Resources Conservation Program*. (DODINST 4715.03).

Department of the Interior (DOI). (2016). *Demonstrated Unmanned Aircraft Systems (UAS) Mission Applications*.

Duffy, E. J. (2006). Biodiversity and the functioning of seagrass ecosystems. *Marine Ecology Progress Series, 311*, 233-250.

Duffy, J. P., Pratt, L., Anderson, K., Land, P. E., and Shutler, J. D. (2018). Spatial assessment of intertidal seagrass meadows using optical imaging systems and a lightweight drone. *Estuarine, Coastal and Shelf Science, 200*, 169-180.

Fairley, I., A. Mendzil, M. Togneri, and D. Reeve. (2018). The use of unmanned aerial systems to map intertidal sediment. *Remote Sensing, 10*(12), 1918.

Galgano, A., and Rose, E. P. F. (2021). Military geoscience. Encyclopedia of Geology (2nd Ed.), 648-659.

Hodgson, J. C., R. Mott, S. M. Baylis, T. T. Pham, S. Wotherspoon, A. D. Kilpatrick, R. Raja Segaran, I. Reid, A. Terauds, L. P. Koh, and N. Yoccoz. (2018). Drones count wildlife more accurately and precisely than humans. *Methods in Ecology and Evolution, 9*(5), 1160-1167.

Johnston, D. W., J. Dale, K. Murray, E. Josephson, E. Newton, and S. Wood. (2017). Comparing occupied and unoccupied aircraft surveys of wildlife populations: Assessing the gray seal (*Halichoerus grypus*) breeding colony on Muskeget Island, USA. *Journal of Unmanned Vehicle Systems, 5*, 178-191.

Kellenberger, B., D. Marcos, and D. Tuia. (2018). Detecting mammals in UAV images: Best practices to address a substantially imbalanced dataset with deep learning. *Remote Sensing of Environment, 216*, 139-153.

Konar, B., and Iken, K. (2018). The use of unmanned aerial vehicle imagery in intertidal monitoring. Deep Sea Research Part II: Topical Studies in Oceanography, 147, 79-86.

Laliberte, A. S., M. A. Goforth, C. M. Steele, and A. Rango. (2011). Multispectral remote sensing from unmanned aircraft: image processing workflows and applications for rangeland environments. *Remote Sensing, 3*(11), 2529-2551.

Lam, O. H. Y., M. Dogotari, M. Prüm, H. N. Vithlani, C. Roers, B. Melville, F. Zimmer, and R. Becker. (2020). An open source workflow for weed mapping in native grassland using unmanned aerial vehicle: using Rumex obtusifolius as a case study. *European Journal of Remote Sensing*, 1-18.

Landeo-Yauri, S. S., E. A. Ramos, D. N. Castelblanco-Martínez, C. A. N. Torres, and L. Searle. (2020). Using small drones to photo-identify Antillean manatees: a novel method for monitoring an endangered marine mammal in the Caribbean Sea. *Endangered Species Research, 41*, 79-90.

Linchant, J., Lisein, J., Semeki, J., Lejeune, P., and Vermeulen, C. (2015). Are unmanned aircraft systems (UASs) the future of wildlife monitoring? A review of accomplishments and challenges. *Mammal Review, 45*(4), 239-252.

Manfreda, S., M. McCabe, P. Miller, R. Lucas, P. M. V., G. Mallinis, E. Ben Dor, D. Helman, L. Estes, G. Ciraolo, J. Müllerová, F. Tauro, M. de Lima, J. de Lima, A. Maltese, F. Frances, K. Caylor, M. Kohv, M. Perks, G. Ruiz-Pérez, Z. Su, G. Vico, and B. Toth. (2018). On the use of unmanned aerial systems for environmental monitoring. *Remote Sensing, 10*(4), 641.

Mangewa, L. J., P. A. Ndakidemi, and L. K. Munishi. (2019). Integrating UAV technology in an ecological monitoring system for community wildlife management areas in tanzania. *Sustainability, 11*(21), 6116.

Multi-Agency Rocky Intertidal Network (MARINe). 2020. Overview. Retrieved from https://marine.ucsc.edu/overview/index.html

Murfitt, S. L., B. M. Allan, A. Bellgrove, A. Rattray, M. A. Young, and D. Ierodiaconou. (2017). Applications of unmanned aerial vehicles in intertidal reef monitoring. *Scientific Reports, 7*(1), 10259.

Nowak, M. M., Dzióbowski, K., & Bogawski, P. (2018). Unmanned Aerial Vehicles (UAVs) in environmental biology: a review. *European Journal of Ecology*, *4*(2), 56-74.

Pereira, E., R. Bencatel, J. Correia, L. Felix, G. Gonçalves, J. Morgado, and J. Sousa. (2009). Unmanned Air Vehicles for coastal and environmental research. *Journal of Coastal Research,* (SI 56).

Schroeder, N. M., A. Panebianco, R. Gonzalez Musso, and P. Carmanchahi. (2020). An experimental approach to evaluate the potential of drones in terrestrial mammal research: a gregarious ungulate as a study model. *Royal Society Open Science, 7*(1), 191482.

Space and Naval Warfare Systems Center Pacific (SSC Pacific). (2017). *Post-Construction Eelgrass (Zostera marina) Survey at Naval Ordinance Test Site (NOTS) Pier Maritime Test Bed (MTB) Cable Site, San Clemente Island, California*.

State of California. (2020). Governor’s Military Council. Retrieved from https://militarycouncil.ca.gov/

Stein et al_2008_Federal lands and endangered species

Stern, M. J. (2018). Social science theory for environmental sustainability: A practical guide. Oxford University Press.