Maritime Technology and Research
https://so04.tci-thaijo.org/index.php/MTR

Review Article

Using remote-controlled vehicles (ROV) as tools for sea cucumber conservation: A review

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Article information
Received: August 5, 2024
Revision: October 20, 2024
Accepted: November 25, 2024

Keywords
Remote controlled vehicles;
ROVs;
Sea cucumber;
Orthomosaics;
Mapping

Abstract
The use of Remotely Operated Vehicles (ROVs) in marine research and conservation has become increasingly popular due to their versatility and ability to operate in challenging environments. This technology shows great potential in the conservation of marine species such as sea cucumbers, which are vital for ecosystem balance but are threatened by overfishing and habitat degradation. This review explores the application of ROVs in sea cucumber population monitoring, highlighting their role in providing real-time data on population dynamics, habitat conditions, and human impacts. The integration of ROV data with aerial orthomosaics to improve the accuracy and reliability of habitat assessments is discussed. The versatility of ROVs extends beyond sea cucumber conservation, with applications in mapping coral reefs and monitoring fish nurseries, showcasing their broad utility in marine ecosystem protection. As these technologies continue to advance, ROVs offer immense potential for developing informed and effective conservation strategies. This review underscores the critical role of ROVs in marine conservation, emphasizing their capacity to enhance our understanding of sea cucumber ecology and to support sustainable management practices.

1. Introduction

The world's marine waters are rich in biological resources, hosting a wide variety of species including nekton, echinoderms, crustaceans, mollusks, and plankton. Sea cucumbers, or holothurians, are particularly widespread, inhabiting many marine ecosystems. These organisms thrive in shallow waters such as seagrass beds and coral reef environments, which span from intertidal zones down to depths of about 20 meters (Wisesa et al., 2018). Their distribution across various benthic zones highlights their ability to adapt to a range of environmental conditions, contributing to the health and stability of ecosystems worldwide (Slater & Chen, 2015).

Sea cucumbers, which are marine bottom-dwelling invertebrates, play a significant role in coral reef ecosystems. Their digestion of organic matter found in coral sand and rubble leads to the breakdown of acidic calcium carbonate particles, thereby increasing the local alkalinity in reef environments (Williamson et al., 2021). This digestive process is particularly important, as it may help mitigate the impacts of rising ocean acidification (Baker-Médard & Ohl, 2019). Additionally, sea cucumbers release ammonia (NH_3) as a by-product of digestion, which contributes to nutrient cycling and enhances productivity within coral systems (Munger et al., 2023). Moreover, through their bioturbation activities, sea cucumbers elevate oxygen levels in the sediment (Li et al., 2021).

Consequently, the presence of sea cucumbers can potentially enhance reef resilience and stability in the face of future human-induced stressors, with their removal potentially leading to reduced ecosystem functionality (Williamson et al., 2021).

Numerous tropical sea cucumber species hold significant commercial value, primarily harvested for beche-de-mer products consumed in Asian markets (Hamamoto et al., 2022). Their susceptibility to overfishing is heightened by factors such as easy collection, low recruitment, slow growth, and long lifespan (Xu et al., 2022). Consequently, driven by high global demand, approximately 70 % of tropical sea cucumber species are categorized as exploited, overexploited, or depleted, leading to local extirpation in many instances (Hamamoto et al., 2022). Effective management necessitates assessing spatio-temporal population dynamics, typically conducted through independent surveys by fisheries. Currently, underwater visual censuses (UVCs) dominate these surveys, providing density estimates via SCUBA diver or snorkeler transects (Li et al., 2021) Despite their importance, UVCs suffer from high costs, observer bias, limited spatial coverage, and impracticality in shallow sand flat habitats where sea cucumbers thrive (Xu et al., 2022). Given these limitations and the growing need for accurate sea cucumber abundance estimates, there is an urgent call to develop improved monitoring tools and techniques for these ecologically and economically vital populations, possibly integrating underwater drones into the survey methodology (Li et al., 2021).

Traditionally, surveys have revealed that sea cucumbers exhibit uneven distribution within reef systems and can cover distances ranging from 1 to 9 meters daily. These observations typically rely on conventional in situ survey methods, which involve tracking the movement patterns of a limited number of individuals over 24 hours, or counting sea cucumbers along designated transect lines or quadrats, using various methods such as walking, snorkeling, SCUBA diving, or manta tows (Gajdosechova et al., 2020).

Unmanned Aerial Vehicles (UAVs) could provide a bird's-eye view of sea cucumber distribution and movement across larger spatial scales and inaccessible or remote areas. By supplementing traditional survey methods with UAV technology, researchers could gain a more comprehensive understanding of sea cucumber populations and their ecological roles within marine ecosystems (Schofield et al., 2019). Integrating UAVs into such surveys could offer a more efficient and comprehensive approach, enabling broader coverage and more precise tracking of sea cucumber movements over time (Li et al., 2021). This technological advancement holds promise for enhancing our understanding of sea cucumber population dynamics and distribution patterns, thereby informing better management and conservation strategies for these important marine organisms (Félix et al., 2021).

2. Methodologies for using UAVs and ROVs in sea cucumber conservation

The integration of Unmanned Aerial Vehicles (UAVs) and Remotely Operated Vehicles (ROVs) into marine conservation offers advanced methods for monitoring sea cucumber populations and their habitats. UAVs and ROVs have distinct advantages in covering wide areas and providing high-resolution data, which are essential for understanding the spatial distribution and health of sea cucumber populations. The following section discusses the methodology for data collection and analysis using these tools, as well as the processes involved in evaluating and validating the data for conservation purposes.

2.1 UAV data collection and analysis for sea cucumber monitoring

The initial phase of any UAV-based sea cucumber monitoring effort involves careful platform and sensor selection. Commonly-used UAV models such as the DJI Phantom or Mavic series are favored for their portability, ease of use, and capability to capture high-resolution (4K) imagery. These UAVs can be equipped with either multispectral or RGB cameras, depending on the specific requirements of the study. Multispectral sensors are particularly advantageous in distinguishing benthic habitats based on their spectral signatures, which allows researchers to differentiate between various habitat types such as coral rubble, seagrass meadows, and sandflats (Crutsinger et al., 2016). Flight planning is another critical step, as it determines the altitude and flight path that the UAV will follow during data collection. Typical flight altitudes range between 5 and 50 meters above sea level, with lower altitudes being preferred for shallow-water environments where water clarity is essential for detecting benthic organisms, including sea cucumbers (Hodgson et al., 2018). Ensuring adequate image overlap- usually 60 - 80 %- is vital to create seamless mosaics of the study area. Environmental conditions also play a pivotal role in UAV data collection; for instance, flights are typically conducted under clear skies with minimal wind to reduce surface glare and distortions caused by the water column. The use of polarizing filters further improves image quality by minimizing surface reflections, particularly when surveys are conducted during low tide (Crutsinger et al., 2016).

2.2 UAV imagery segmentation and classification for habitat and species identification

After capturing imagery, the next step involves data processing using Object-Based Image Analysis (OBIA). This technique is crucial for segmenting the UAV imagery into distinct ecological units. Multi-resolution segmentation is one of the most widely-used methods for dividing imagery based on spatial, spectral, and textural properties, allowing researchers to classify different benthic environments (Blaschke et al., 2014). For instance, the method can be adjusted to distinguish large habitat types, such as sandflats or coral rubble, and then refined to detect specific features like individual sea cucumbers.

Spectral Object Pattern Recognition further enhances segmentation by analyzing the spectral reflectance properties of each object. Sea cucumbers, depending on their species, exhibit distinct spectral characteristics, which can be detected in high-resolution imagery. This method is particularly effective in scenarios where sea cucumbers camouflage themselves with sediment, making them difficult to distinguish from their surroundings (Laliberte & Rango, 2011).

Once segmentation is complete, classification algorithms are applied to assign ecological labels to the segmented objects. Two main types of classification methods are used: supervised and unsupervised classification. In supervised classification, labeled training data is used, and machine learning algorithms such as Random Forest (RF) or Support Vector Machines (SVM) classify the objects based on their spectral and spatial properties (Dujon & Schofield, 2019). RF is particularly effective in differentiating between sea cucumber species based on their morphology and reflectance.

Convolutional Neural Networks (CNNs), such as ResNet50, are also employed for automated species identification. CNNs can learn from training datasets to classify sea cucumbers based on size, shape, and texture (Ozbulk et al., 2016). However, the effectiveness of CNNs depends on the availability of large, annotated datasets, which can be a limitation for underrepresented species.

In cases where ground truth data is unavailable, unsupervised classification methods like K-means clustering and ISODATA are used to group objects based on their inherent spectral properties. Although these methods are effective in distinguishing between broad habitat types, they typically lack the accuracy needed for species-level distinctions and require further refinement (Laliberte & Rango, 2011).

2.3 Data collection methods with ROVs

ROVs complement UAV surveys by allowing for more precise, close-up monitoring in marine environments. Transect surveys conducted using ROVs involve navigating predetermined paths over the seafloor, capturing high-resolution video or images. These transects can be used to estimate the density of sea cucumber populations or to document habitat conditions (Durden et al., 2016). ROVs are particularly valuable in deep or turbid waters where UAV visibility is limited.

Additionally, ROVs equipped with environmental sensors can capture crucial habitat data, such as water temperature, salinity, and sediment characteristics. This data is essential for understanding the environmental variables that affect sea cucumber distribution.

2.4 Evaluation and validation of UAV and ROV data

The reliability of UAV-OBIA classifications is contingent on rigorous evaluation and validation processes. A widely-used validation method is the confusion matrix, which compares predicted classifications from UAV data to actual ground truth data. This matrix provides performance metrics such as overall accuracy, user accuracy, and producer accuracy, offering a robust measure of classification success. The Kappa coefficient, which accounts for the likelihood of chance agreement, is another key metric used to evaluate classification accuracy. A high Kappa value (close to 1) indicates strong agreement between predicted and actual classifications, while a low value suggests inaccuracies, especially in multi-class problems such as distinguishing between different sea cucumber species (Sloan & von Bodungen, 1980).

Ground truthing is another critical component of the validation process, ensuring that UAV-derived classifications accurately reflect real-world conditions. This involves conducting in situ field surveys, where researchers manually count and identify sea cucumber species and habitats. These field observations are then compared to the UAV-OBIA outputs to verify the accuracy of the classifications. Ground truthing is particularly important in heterogeneous and cryptic environments, where UAVs may have difficulty detecting organisms hidden within the substrate (Uthicke & Karez, 1999).

Finally, uncertainty and error assessment are vital in dynamic marine environments where spectral and visibility conditions fluctuate. Techniques such as Monte Carlo simulations are commonly used to model potential classification errors, providing a probabilistic framework for interpreting the results. By accounting for environmental variability, these simulations help ensure that abundance estimates and habitat classifications reflect realistic probability distributions (Dujon & Schofield, 2019).

3. Application of ROVs in sea cucumber population

Remotely Operated Vehicles (ROVs) have revolutionized the monitoring and conservation of sea cucumber populations, offering precise and detailed underwater imagery that enhances our understanding and protection efforts. These advancements in technology provide several advantages over traditional survey methods, significantly improving the accuracy, efficiency, and scope of marine research. One of the key benefits of ROVs is their ability to enhance the identification and measurement of sea cucumbers. Traditional methods, which often rely on manual work, can be time-consuming and prone to errors. However, ROVs equipped with advanced imaging technologies can automate these processes. For instance, Guo et al. (2019) demonstrated the use of deep residual networks for the automatic identification of sea cucumbers, achieving an accuracy of up to 89.53 % (Guo et al., 2019). Additionally, Zhu et al. (2023) introduced a method using YOLOv7 and GrabCut-RGBD for precise size measurement, with a recognition accuracy of 97 % (Zhu et al., 2023).

Furthermore, ROVs play a crucial role in survey design and habitat mapping. They allow researchers to assess the abundance and distribution of species in deep-sea habitats with greater precision. A research study by Li et al. in 2020 highlighted the importance of selecting appropriate sampling units and distributions for effective population studies, emphasizing the role of ROVs in such research (Tahara, 2020). Moreover, the integration of ROV data with aerial orthomosaics enhances habitat mapping by providing ground-truthing and close-up observations, thus increasing the accuracy and reliability of the data (**Figure 1**) (Mazza et al., 2023). Blue Carbon ecosystems, which have the potential to sequester significant amounts of carbon, are of particular interest due to their role in climate change mitigation. However, the global distribution of substantial carbon stores like seagrass remains largely uncharted. Drones have proven effective in mapping seagrass habitats using various data sources, including multispectral, hyperspectral, and RGB imagery. For example, Duffy et al. (2018) employed a 3D Robotics Solo multi-rotor drone equipped with a customized 3D-printed sensor mount to capture hyperspectral images of Zostera noltei in Wales. Their research explored the utility of such cameras, the accuracy of techniques for image classification, and their effectiveness in identifying various species and habitats. Notably, the study achieved high accuracy in classifying different species within heterogeneous meadows, offering opportunities to go beyond habitat delineation and to analyze within-patch variations. Drones have also been employed to monitor other vital Blue Carbon ecosystems, including mangrove forests in Malaysia (Ruwaimana et al., 2018), China (Wang et al., 2020), and Australia (Warfield & Leon, 2019), as well as salt marshes in Scotland (Green et al., 2020) among numerous other nations. By delineating the distribution of these habitats, it becomes possible to calculate estimates of the economic value associated with CO2 sequestration. Green et al. (2018) estimated that the value of Zostera marina in the UK ranges between £2.6 and 5.3 million.

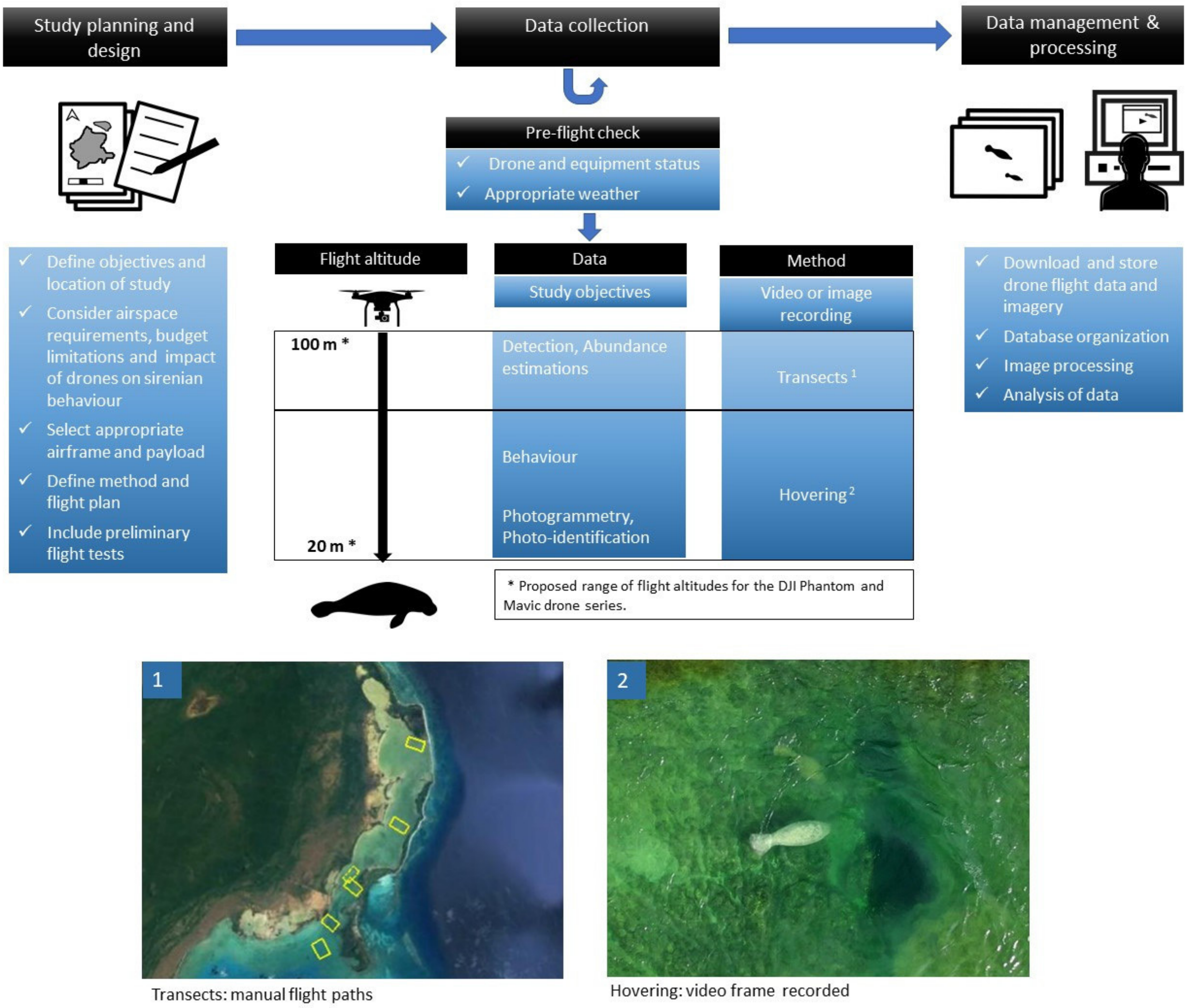

Figure 1 shows an example flowchart of operational protocol for drone-based sirenians research. Notably, flying parameters are defined by the species, airframe, payload, and study aims. The flight patterns utilized to look for sirenians are indicated by yellow squares. Adapted from Raoult et al. (2020).

The continuous and detailed monitoring capabilities of ROVs are essential for tracking changes in sea cucumber populations over time and evaluating the impacts of human activities (Mazza et al., 2023). This is critical for effective conservation strategies. Recent studies have discussed the global exploitation patterns of sea cucumbers and have underscored the need for better monitoring and management practices to ensure sustainable harvesting (Baker-Médard & Ohl, 2019).

Concurrently, advancements in technology have demonstrated the effectiveness of combining ROV data with traditional fishery methods. For example, drone imagery and deep learning algorithms have been successfully used to detect sea cucumbers, providing a scalable and efficient approach to population monitoring (Li et al., 2021). Additionally, studies have shown that population densities and habitat preferences can be accurately assessed through a combination of remote sensing and traditional in situ surveys (Hamamoto et al., 2022). These integrated methods enhance the precision of abundance and exploitation rate estimates, demonstrating the potential for improved management and conservation efforts (Scannella et al., 2022). Technological innovations continue to enhance the utility of ROVs in marine research. For example, Chimienti et al. (2018) illustrated the superiority of ROVs over trawling in studying benthic communities, providing more accurate data while minimizing environmental impact (Chimienti et al., 2018). Moreover, new sequencing technologies, as employed by Feidantsis et al. (2022), enhance our understanding of population genetics and support better management of marine resources (Feidantsis et al., 2022).

3.1 Aerial orthomosaics

Beyond their role in conservation, drones have played a crucial role in managing coastal areas and minimizing human-animal interactions. For instance, Butcher et al. (2020) investigated the use of drones to regulate conflicts between swimmers and sharks. Multirotor drones equipped with real-time detection capabilities were employed to identify shark analogues in the water across various climatic conditions in Australia, enabling real-time detection and alarms for swimmer protection. Additionally, drones have been instrumental in monitoring illegal fishing activities, enhancing sustainable fish stock management. Quadcopters equipped with live video streams have been employed in Belize to enhance coastal patrols for real-time detection and enforcement against illegal fishing activities (Howard, 2016). The collection of video evidence assists in effective prosecution, a practice that has also been adopted in other coastal regions like Jamaica and Costa Rica (Toonen & Bush, 2020). Larger drones, capable of traveling up to 500 kilometers in two days, have proven highly effective in the management of natural resources, particularly in enforcing environmental laws and regulations.

Furthermore, drones have been extensively utilized in terrestrial ecosystems to optimize agricultural operations, monitor crop growth, and assess environmental impacts resulting from events such as flooding (Puri et al., 2017). For example, in Ghana, UAVs have been used to monitor the consequences of flooding in the Volta Delta, quantifying land loss due to flooding and erosion, including farmland (Addo et al., 2018). Such information plays a pivotal role in managing coastal communities, informing resilient planning strategies, and facilitating compensation being paid to land managers. In the past decade, UAVs have experienced remarkable technological advancements, emerging as indispensable tools in ecological research, particularly for wildlife monitoring endeavors (Ivosevic et al., 2015). Their adoption has surged owing to a combination of factors, including their cost-effectiveness, user-friendly operation, capacity for wide spatial coverage, flexibility in flight path programming, and suitability for deployment in remote or challenging terrains, both terrestrial and aquatic (Colefax et al., 2018).

Primarily recognized for their utility in terrestrial ecosystems, UAVs have progressively extended their application domain into marine environments. In marine population monitoring, UAVs have garnered significant attention as replacements for traditional manned aerial surveys, especially for monitoring large marine vertebrates such as dugongs, cetaceans, sea turtles, and elasmobranchs (Álvarez-González et al., 2023). UAVs offer enhanced maneuverability, the ability to fly at lower altitudes, and reduced operational costs compared to manned aircraft, which has facilitated this transition (Barreto et al., 2021). Recent studies have expanded the applications of UAVs in marine ecology beyond population surveys, as presented in **Table 1**. UAVs have been used to investigate species behavior and assess changes in coral health dynamics, offering nuanced insights into ecosystem dynamics and species interactions (Ventura et al., 2018). For instance, UAVs have been utilized to create high-resolution maps of marine habitats and monitor ecological processes efficiently (Oosthuizen et al., 2020). Additionally, UAVs have proven effective in monitoring the behavior of marine megafauna, such as dolphins and whales, by providing detailed visual and acoustic data (Frouin-Mouy et al., 2020). These endeavors signify the expanding horizons of UAVs in marine ecological research, offering nuanced insights into ecosystem dynamics and species interactions.

Table 1 shows recent research on the application of ROVs in marine ecosystem monitoring and sea cucumber studies.

Title	Authors	Year	Summary
New technologies for monitoring and upscaling marine ecosystem restoration in deep-sea environments	Aguzzi et al.	2024	Discusses the use of ROVs in deep-sea ecosystem restoration, including the monitoring of sea cucumbers.
Deep-sea biology in undergraduate classrooms: open access data from remotely operated vehicles provide impactful research experiences	Gerringer et al.	2023	Utilizes ROV data to enhance understanding of marine biology, including sea cucumbers, in educational settings.
Marine robotics for deep-sea specimen collection: a taxonomy of underwater manipulative actions	Mazzeo et al.	2022	Examines the use of ROVs for collecting deep-sea specimens, including sea cucumbers, with an emphasis on robotic manipulation.
Eyes in the sea: unlocking the mysteries of the ocean using industrial, remotely operated vehicles (ROVs)	Macreadie et al.	2018	Highlights the application of industrial ROVs in scientific research, particularly in the study of sea cucumbers and other marine organisms.
Design and control of underwater robot system for sea cucumber fishing	Shi et al.	2022	Focuses on the development and control of ROVs specifically designed for sea cucumber fishing and related activities.

Table 1 provides an overview of recent studies highlighting the use of ROVs in various aspects of marine ecosystem monitoring and the study of sea cucumbers. These studies collectively demonstrate the diverse applications and significant contributions of ROV technology to marine biology and ecosystem management (Smith et al., 2020). One compelling prospect that remains underexplored within the realm of UAV application in marine ecology is their potential to furnish density estimates for shallow water invertebrate species (Jones & Lee, 2019). In habitats where conventional monitoring techniques such as remote underwater vehicles or diver transects encounter logistical or practical constraints, UAVs present an innovative alternative (Brown et al., 2021). By virtue of their aerial perspective, UAVs can efficiently survey shallow coastal regions, providing valuable data on the distribution and abundance of benthic invertebrates, which are pivotal components of marine ecosystems (Davis et al., 2018). Recent studies have demonstrated the efficacy

of UAVs in various marine monitoring tasks, including detecting marine debris and estimating population densities of marine species (Fallati et al., 2019), as well as mapping and monitoring ecological processes in coastal waters (Windle & Silsbe, 2021). The burgeoning utilization of UAVs in marine ecology underscores their transformative potential as versatile and efficient tools for ecological research and wildlife monitoring. The ongoing exploration of novel applications, including the assessment of shallow water invertebrate populations, promises to further enhance our understanding of marine ecosystems and contribute to informed conservation and management efforts in these critical environments (Hamel et al., 2021).

3.2 Bathymetric mapping

ROVs are instrumental in generating detailed three-dimensional maps of the seafloor through the use of sonar or laser technology. These maps are crucial for identifying and monitoring critical sea cucumber habitats, such as rocky reefs and coral gardens (Ludvigsen et al., 2016). The high-resolution imaging capabilities of ROVs allow for precise mapping of these habitats, which is essential for understanding the spatial distribution and ecological preferences of sea cucumbers (Chang et al., 2019). The creation of maps for underwater habitats, called benthic habitat maps, can be done in two main ways: either by scuba divers directly observing and mapping the seafloor, or by using expensive remote sensing methods involving remotely operated vehicles (ROVs) or sonar technology. Recently, the availability of affordable underwater drones has made benthic mapping more accessible and cost-effective (Micallef et al., 2020). While these drones still require on-site verification, they reduce the reliance on support boats. Previous studies explored the use of a high-resolution underwater camera attached to a PowerVision PowerRay to automate the creation of benthic maps (Johnson & Wang, 2021). They captured underwater images in an embayment off the coast of Malta in the Mediterranean Sea and used a Machine Learning technique called Self-Organizing Maps to classify the images (Micallef et al., 2020). The results were compared with a benthic habitat map generated through traditional methods in a previous study to evaluate their accuracy (Micallef et al., 2020).

Benthic habitat mapping has become a crucial tool in marine impact assessment and conservation efforts. It helps quantify human impacts on underwater habitats and aids in designing and managing Marine Protected Areas (MPAs) (Summers et al., 2022). The history of benthic mapping dates back to the thirteenth century when seafaring merchants created maps of the seafloor to assist navigation in the Mediterranean Sea (Dines, 2018). Since then, technological advancements have greatly improved this field, enabling the generation of more detailed seabed maps (Smith & Lee, 2020). High-resolution multispectral imaging sensors, for instance, provide detailed data on underwater habitats and water quality. Instruments like the Multibeam Echosounder can map extensive seabed areas, surpassing the capabilities of SCUBA diving. However, remote sensing techniques are generally expensive, and require expertise to operate and interpret the results (Hamamoto et al., 2022).

Due to the prevalence of reefs and algae in their habitats, harvesting sea cucumbers typically involves divers, yet prolonged underwater expeditions pose health risks to divers (Ma, 2019). To mitigate these risks, and enhance sea cucumber fishing efficiency, the utilization of underwater drones emerges as a pivotal advancement in sea cucumber aquaculture. A key challenge faced by underwater drones is the real-time detection of sea cucumbers, hindered by the scattering and light absorption properties of seawater, resulting in blurred underwater imagery (Ma, 2019). Thus, the significance of underwater drones lies in their potential to automate sea cucumber fishing, thereby reducing risks associated with manual harvesting, and overcoming the obstacles posed by underwater visibility limitations. In this context, Xia (2018) introduced a lightweight Single Shot Multibox Detector (SSD) model, tailored for sea cucumber detection. This approach uses specialized robots underwater to capture images of sea cucumbers, enhancing the images using techniques like Multi Scale Retinex. To improve efficiency without the need for advanced equipment, the model is modified to compress and optimize it for better performance. The images are taken at sea cucumber breeding bases, capturing various underwater conditions and terrains. Enhancements are particularly focused on improving imagery taken under less favorable conditions, such as cloudy days, to facilitate more effective detection of sea cucumbers (Guo et al., 2019).

In the context of bathymetric mapping, the integration of ROVs also offers a significant advantage as a validation tool for data collected through other remote sensing technologies, such as satellite and underwater acoustic methods. This multi-platform approach ensures more robust assessments of marine ecosystems, as ROVs can be used to validate and refine data collected over broader spatial scales, particularly in complex or poorly understood habitats. Piazzolla et al. (2024) demonstrated this multi-platform approach by combining ROV surveys with echo-sounding techniques, which provided accurate data on seagrass canopy height and seabed characteristics. These methods allowed for a detailed spatial mapping of habitats like those covered with the seagrass Posidonia oceanica, showcasing how the integration of ROV and acoustic data can strengthen bathymetric modeling and offer greater precision for habitat analysis. Thus, ROVs are integral for validating acoustic-based bathymetric measurements, improving the overall reliability of data in complex marine environments (Piazzolla et al., 2024).

4. Significant use of ROVs in sea cucumber conservation: Benefits and capabilities

The use of remotely operated vehicles (ROVs) in marine research has ushered in a new era of underwater conservation, particularly in the study and protection of sea cucumbers. These sophisticated technologies offer a plethora of benefits, including cost-effectiveness, enhanced survey capabilities, autonomous operations, and robust environmental monitoring. By harnessing the potential of modern ROVs, researchers can achieve comprehensive and efficient conservation efforts, ensuring the sustainability of sea cucumber populations (McLean et al., 2020).

One of the foremost advantages of ROVs in sea cucumber conservation is their cost-effectiveness and accessibility. Over the years, the cost of modern ROVs has significantly decreased, making them more accessible for scientific research and conservation initiatives (Lee et al., 2019). Smaller and more affordable ROVs can be deployed from small boats, enabling their use in various research activities, such as monitoring sea cucumber populations. This increased accessibility is pivotal for conducting extensive surveys and gathering critical data across diverse marine environments (Miller & Thompson, 2020). For instance, recent studies highlight how these cost-effective ROVs facilitate broader ecological surveys, allowing researchers to cover larger areas without incurring prohibitive costs (Aguzzi et al., 2020). Additionally, the development of low-cost ROVs has further expanded their application in ecological surveying and conservation planning, providing high-resolution data essential for marine ecosystem assessments (Buscher et al., 2020).

Furthermore, ROVs are equipped with advanced imaging and sensor technologies, significantly enhancing their survey capabilities (**Figure 2**). These technologies enable ROVs to conduct detailed habitat assessments and monitor sea cucumber populations, even in remote and challenging underwater environments (Brown & Kim, 2021). The ability to gather precise data on species distribution, habitat conditions, and environmental changes is invaluable for effective conservation planning and management (Garcia et al., 2018). Studies emphasize the importance of such capabilities, noting that ROVs allow researchers to collect comprehensive data that inform the development of targeted conservation strategies (Summers et al., 2022). By providing detailed insights into the ecology and behavior of sea cucumbers, ROVs help researchers understand the intricate dynamics of marine ecosystems and devise appropriate measures to protect them (Guo et al., 2019).

In recent years, advancements in autonomous ROV technology have further augmented their utility in marine research. Autonomous ROVs are equipped with sophisticated capture systems that utilize vision-based technology for target recognition and control. These systems enable the precise and efficient capture of marine organisms, such as sea cucumbers, with minimal human intervention

(Smith et al., 2022). This capability is particularly beneficial in harsh underwater conditions, where human-operated missions may be challenging or risky (Ji-yong et al., 2018). By reducing the need for human intervention, autonomous ROVs not only improve operational efficiency, but also ensure safer and more reliable data collection (Sørensen & Ludvigsen, 2016). Moreover, ROVs play a critical role in environmental monitoring and data collection, which are essential for understanding and preserving marine ecosystems. These vehicles can operate at various depths and are equipped with cameras, sensors, and sampling tools to monitor environmental parameters such as salinity, turbidity, and current velocity. The data collected by ROVs provide valuable insights into the habitats of sea cucumbers and other marine organisms (McLean et al., 2020). Continuous monitoring of environmental parameters enables researchers to identify trends and anomalies, facilitating the development of effective conservation and management strategies (Guo et al., 2019).

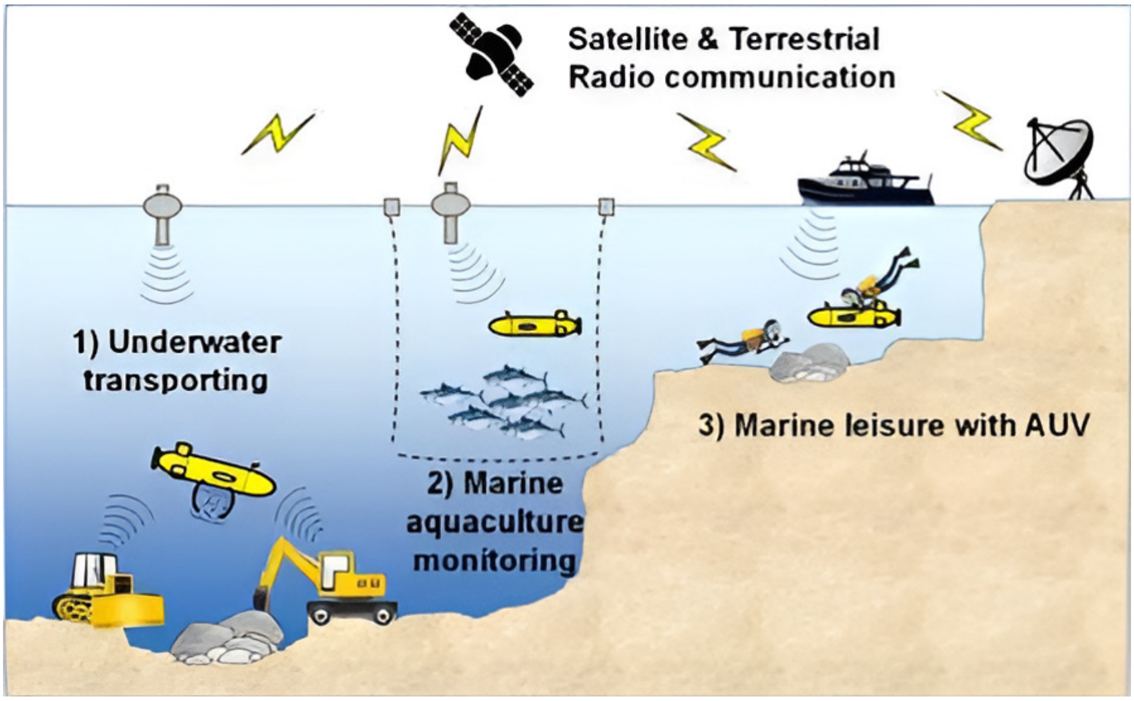

Figure 2 The applications of underwater drones.
Adapted from Muller et al. (2022).

5. Technological and environmental challenges of UAVs and ROVs in sea cucumber population surveys: Current limitations and future directions

5.1 Detection challenges and underestimation of abundance

Both UAVs and ROVs face significant challenges in accurately detecting sea cucumber populations, particularly in cryptic habitats. UAV surveys, for instance, have been shown to underestimate sea cucumber abundance, with UAV-derived counts at Heron Reef being 41 % lower than snorkeler-based transects (Hodgson et al., 2018). This underestimation is primarily due to the UAV's inability to detect sea cucumbers hidden under coral overhangs or buried within sediment. Similarly, ROVs face detection limitations in complex reef environments, where they struggle to access areas that divers can reach, leading to underreporting of sea cucumber populations (Durden et al., 2016).

High-density sea cucumber populations, where over 90 individuals can be found per 40 m², further complicate detection for both UAVs and ROVs. In such crowded conditions, both tools may produce a "hyperstable" index of abundance, masking fluctuations in population dynamics due to reduced sensitivity in highly populated areas (Hilborn & Walters, 1992). This limitation highlights the need for more sensitive detection techniques, particularly in heterogeneous and high-density environments.

5.2 Environmental and technical constraints

Environmental factors such as water clarity, depth, and surface reflections significantly affect the quality of data captured by both UAVs and ROVs. For UAVs, water column distortion, caused by light refraction and surface ripples, obscures sea cucumbers in aerial footage. Techniques such as flying at lower altitudes, using polarizing filters, and scheduling surveys during calm weather conditions have been applied to mitigate these issues (Crutsinger et al., 2016). However, such adjustments are not universally effective across all marine environments, limiting the versatility of UAVs in diverse conditions. ROVs, while equipped with lighting systems to navigate turbid waters, face similar challenges, particularly in deep or murky environments where light penetration is limited, reducing the clarity of the captured footage (Purser et al., 2013).

The technical specifications of both UAVs and ROVs also influence the quality of the data collected. For instance, UAVs equipped with high-resolution cameras, such as the DJI Mavic Air, must be flown at precise altitudes to maintain consistent image quality and avoid distortion caused by variable environmental conditions (Kilfoil et al., 2017). Similarly, ROVs rely heavily on their maneuverability and stability in water, especially in complex reef structures. In strong currents, or areas with uneven terrain, ROVs may struggle to maintain position, resulting in incomplete or inconsistent data collection (Durden et al., 2016).

5.3 Manual data processing and automation limitations

Processing the large datasets generated by UAVs and ROVs remains a time-intensive and laborious task, particularly when manual identification of sea cucumbers is required. For example, studies using high-resolution 4k video captured by UAVs have shown that manual identification and counting of sea cucumbers can require multiple observers and extend the time needed for data analysis (Joyce et al., 2019). Similarly, ROV footage, which captures hours of underwater video, often requires time-consuming manual data extraction (Durden et al., 2016). To alleviate this bottleneck, Convolutional Neural Networks (CNNs), such as ResNet50, have been employed to automate the classification and counting of sea cucumbers from both UAV and ROV imagery (Dujon & Schofield, 2019). However, these models are often constrained by the size and diversity of training datasets, leading to inaccuracies in more complex environments. This issue is particularly pronounced in high-density or cryptic habitats, where manual correction is still required. As machine learning models are highly dependent on environmental complexity, larger and more representative datasets are needed to improve the efficacy of these tools (Ozbulk et al., 2016).

5.4 Detection uncertainty and model limitations

Uncertainty in detection is a key limitation for both UAV and ROV surveys, particularly in cryptic environments. Sea cucumbers often burrow into sediment or hide under coral overhangs, making them difficult to detect using aerial or underwater imagery. Advanced statistical models, such as the Monte Carlo-Markov-Chain framework, have been used to incorporate detection probabilities and adjust abundance estimates in such scenarios (Dujon & Schofield, 2019). However, while these models help mitigate detection errors, they cannot fully account for the environmental variability and cryptic behaviors that complicate accurate population assessments.

In addition, environmental factors such as sediment type, water temperature, and depth significantly influence sea cucumber distribution, leading to highly patchy populations that may be missed by both UAVs and ROVs. UAVs, for example, struggle to detect fine-scale patterns in sea cucumber distribution, which are critical for accurate population assessments (Sloan & von Bodungen, 1980; Uthicke & Karez, 1999). ROVs, while offering a closer view of benthic environments, are similarly limited by their range and ability to access certain habitats, particularly in complex reef environments.

5.5 Platform limitations: UAV and ROV systems

Multi-copter UAV platforms, such as the DJI Matrice and Phantom series, dominate UAV-based ecological surveys, accounting for 77 % of studies on water resource mapping (Brito et al., 2019). These platforms are favored for their Vertical Take-Off and Landing (VTOL) capabilities, which allow them to operate in difficult terrains like coastal and reef environments. However, battery capacity remains a significant limitation, restricting the flight duration and area coverage of UAVs (Lyons et al., 2019). Frequent battery replacements or recharges disrupt data collection and reduce overall survey efficiency, particularly in large coastal or reef areas. Similarly, ROV systems, while offering greater depth range and precision, are constrained by tether length, battery life, and payload capacity. ROVs are typically tethered to a surface vessel, limiting their range of movement, particularly in areas with strong currents or rugged seafloor topography (Durden et al., 2016). Additionally, the limited payload capacity of most ROVs restricts the number of sensors and tools that can be equipped, posing challenges for comprehensive habitat and species monitoring.

5.6 Future research directions and technological improvements

To address the limitations of both UAV and ROV platforms, future research should focus on several technological and methodological advancements. Improved camera resolution and flight endurance will enhance the ability of UAVs to capture detailed imagery over larger areas, addressing some of the current challenges related to detection accuracy and environmental variability (Crutsinger et al., 2016). Similarly, advancements in ROV maneuverability and sensor integration will enable more accurate and efficient data collection in complex marine environments (Lyons et al., 2019).

Developing more sophisticated machine learning algorithms will be crucial for automating the identification and counting processes in both UAV and ROV imagery, reducing the time required for manual data processing. However, the success of these algorithms will depend on the creation of larger, more diverse training datasets that capture the variability of marine environments and species behavior (Ozbulk et al., 2016). Finally, future research should explore ways to optimize both UAV and ROV deployment strategies for deeper waters and more complex reef systems, where detection challenges are most pronounced.

6. Case studies

The integration of advanced technologies such as drone imagery, deep learning, and object-based image analysis (OBIA) has revolutionized marine habitat monitoring and conservation efforts. Various studies have showcased the effectiveness of these methods in detecting and mapping marine organisms, including sea cucumbers, and their habitats. **Figure 3** shows a graph on the number of research studies on using ROVs to map marine creature habitats from 2014 to 2023, illustrating a steady increase in the number of research studies, peaking in 2021, before experiencing a slight decline and stabilization in 2023. This trend reflects the growing adoption and technological advancements of ROVs in marine research. For instance, McLean et al. (2020) highlighted the role of ROVs in enhancing scientific research and conservation efforts (McLean et al., 2020). Similarly, Summers et al. (2022) explored the use of advanced imaging techniques with ROVs for mapping Arctic habitats, underscoring their importance in modern marine ecology (Summers et al., 2022).

6.1 Drone imagery and deep learning

One notable study by Li et al. (2021) utilized drone imagery and deep learning, specifically the You Only Look Once version 3 (YOLOv3) algorithm, to detect sea cucumbers on coral reef flats. The study achieved a high detection rate, successfully identifying 11,462 out of 12,956 individuals over a 2.7-hectare area. This impressive result demonstrates the potential for automated detection and large-scale monitoring of marine species using drone technology and deep learning. The ability to accurately detect and monitor sea cucumbers on such a large scale is a significant advancement in marine conservation, providing a valuable tool for researchers and conservationists (Li et al., 2021).

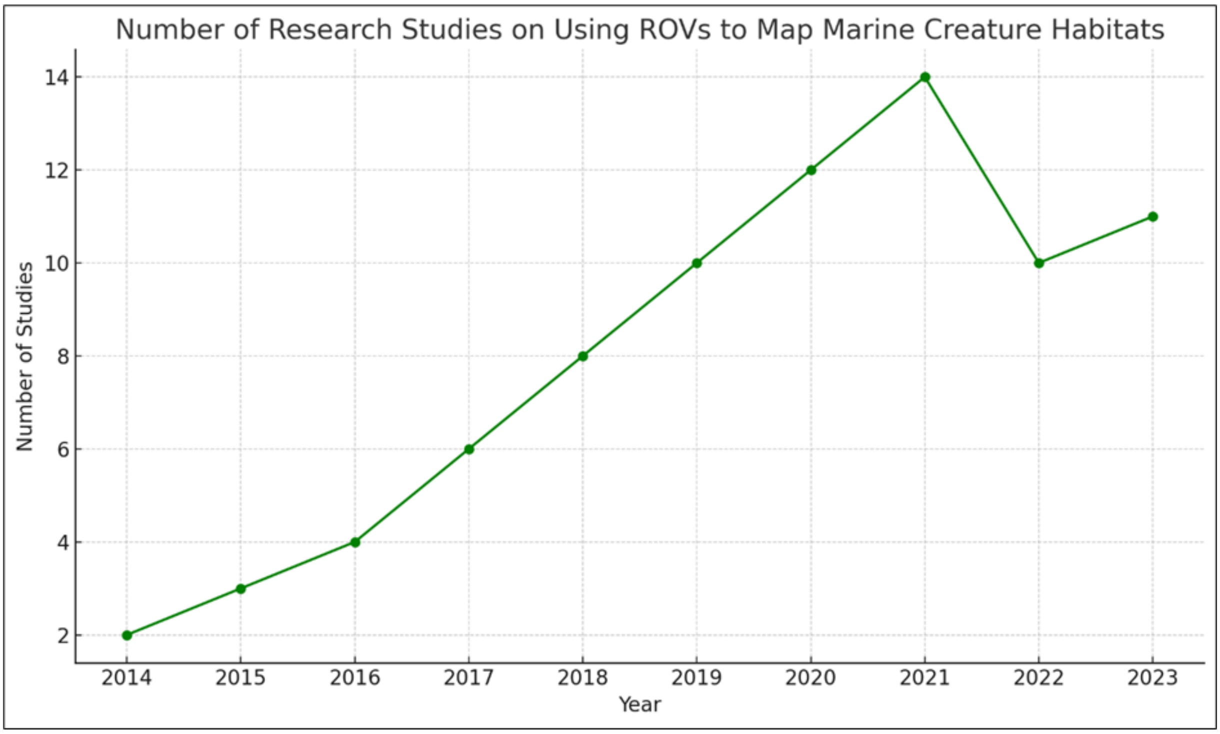

Figure 3 The number of research studies on using ROVs to map marine creature habitats.

6.2 Object-based image analysis (OBIA)

In another study, Nababan et al. (2021) employed drones in conjunction with object-based image analysis (OBIA) to map shallow-water benthic habitats. The study achieved high accuracy in habitat mapping, proving the effectiveness of this method in detailed habitat characterization, particularly in complex coral reef ecosystems. OBIA, which segments images into meaningful objects based on spectral and spatial information, allows for more precise mapping compared to traditional pixel-based methods. This approach is particularly useful in diverse and intricate habitats, where accurate mapping is crucial for effective conservation planning (Nababan et al., 2021).

6.3 Cost-effective mapping

The application of innovative technologies for marine habitat mapping has been successfully demonstrated in various case studies, highlighting their cost-effectiveness and efficiency. For instance, Piazzolla et al. (2024) illustrated the use of integrated platforms, including ROVs and USVs, for mapping Posidonia oceanica meadows, essential habitats for sea cucumbers. Their findings suggest that such methodologies can enhance conservation efforts by providing detailed spatial data on habitat distribution and health. Similarly, Gonzalez et al. (2021) showcased how employing low-cost remote sensing technologies can effectively monitor the impacts of human activities on critical marine ecosystems, underscoring the importance of these tools in informing management practices for sea cucumber habitats.

Furthermore, the feasibility of using low-cost drones for marine habitat mapping was demonstrated by Ventura et al. (2016). Their study focused on mapping coastal fish nursery grounds, showcasing the potential for affordable and efficient mapping solutions. By using low-cost drones, the study highlighted the accessibility of advanced mapping technologies to a wider range of researchers and conservationists, making it possible to conduct extensive surveys without substantial financial investment. This approach is especially beneficial for small-scale projects and organizations with limited resources, enabling them to contribute to marine conservation efforts (Ventura et al., 2016).

6.4 Integrating multiple methods

Some studies have explored the integration of multiple methods to create comprehensive maps of marine habitats. For instance, Hamad et al. (2022) and Gauci et al. (2020) combined aerial and underwater drones with various image processing techniques. This multi-method approach enhances the accuracy and detail of habitat characterization, providing a more holistic view of marine ecosystems. By integrating data from different sources, these studies were able to capture a wider range of habitat features and improve the overall quality of the maps. This approach underscores the importance of utilizing diverse technologies and methodologies to achieve more comprehensive and accurate results in marine conservation (Hamad et al., 2022; Gauci et al., 2020). These case studies demonstrate the significant advancements in marine habitat monitoring and conservation through the use of drone imagery, deep learning, OBIA, and multi-method approaches. The high detection rates, accurate mapping capabilities, and cost-effectiveness of these technologies provide valuable tools for researchers and conservationists. By leveraging these advanced methods, it is possible to conduct large-scale and detailed monitoring of marine habitats and species, contributing to more effective conservation strategies and efforts. These case studies highlight the potential and importance of integrating modern technologies in marine research, paving the way for more innovative and efficient conservation practices.

7. Ways forward: Using ROVs for sea cucumber conservation

7.1 Improved imaging and sensor capabilities

The use of drone remote sensing (RS) equipped with advanced object detection algorithms like YOLOv3 has shown great potential in quantifying sea cucumber densities in shallow reef environments. Drones can survey large areas, up to 2.7 hectares in less than 30 minutes, compared to traditional methods that cover only a few hundred square meters in a day. This efficiency reduces the time and resources needed for data collection, allowing for broader spatial coverage and more comprehensive datasets (Clark et al., 2019). Additionally, integrating open-source deep learning models for object detection can streamline the process of counting and labeling sea cucumbers, enhancing reproducibility and enabling data review by different experts. As UAV technology advances, especially with improved AI, the detection of marine organisms is expected to become more automated, further reducing the time needed for image review and making UAVs an increasingly valuable tool for conservation and management (Kelaher et al., 2020).

7.2 Autonomous operation

Autonomous Underwater Vehicles (AUVs) have been effectively used to track marine animals, such as sharks, by collecting behavioral and environmental data without direct human input. These vehicles can operate independently in various environments, accurately tracking and observing marine life under different conditions (Clark et al., 2019; Packard et al., 2013). The development of autonomous capabilities in ROVs has similarly enhanced their ability to perform complex tasks such as navigation and data collection without direct human control, greatly increasing the efficiency of marine surveys and reducing operational costs (Schjølberg & Utne, 2015).

7.3 Dexterous manipulation

Advancements in robotic manipulators have equipped ROVs with the ability to handle delicate marine organisms gently and accurately. These manipulators, often enhanced with tactile feedback and advanced control systems, are crucial for tasks such as the relocation of sea cucumbers for restocking or research purposes. This technology reduces the physical impact on marine ecosystems while improving the efficiency and precision of underwater operations (Kampmann et al., 2018).

7.4 Cost-effective solutions

The advancement of technology has made ROVs more affordable and accessible, broadening their use beyond well-funded institutions. The development of low-cost ROV models that retain essential capabilities for deep-sea exploration and monitoring has allowed more researchers and conservation organizations to participate in marine studies. This democratization of technology enables comprehensive and widespread data collection efforts, which are crucial for advancing marine research (Teague et al., 2018).

8. Conclusions

The use of Remotely Operated Vehicles (ROVs) as a tool for sea cucumber conservation signifies a transformative advancement in marine research and conservation methodologies. ROVs offer a cost-effective, accessible, and sophisticated means of conducting underwater research, capable of operating in diverse and challenging environments. Their integration with advanced technologies, such as autonomous operations and advanced image analysis techniques like deep learning and Object-Based Image Analysis (OBIA), enhances the accuracy, reliability, and efficiency of habitat mapping and ecological monitoring. This integration is crucial for effective conservation efforts and resource management. As ROV technology continues to evolve, it promises to further enhance the ability to monitor and protect sea cucumber populations and their habitats, ensuring the sustainability of these vital marine organisms and their ecosystems. Continued research and development in ROV capabilities, along with their integration with other technologies, are essential for advancing marine conservation efforts. The ongoing evolution and broader adoption of ROV technology are poised to play a pivotal role in the future of marine biodiversity conservation, equipping researchers and conservationists with the tools necessary to address the complex challenges facing our oceans.

Acknowledgment

The author would like to thank the Faculty of Applied Sciences and Technology, University Tun Hussein Onn Malaysia, Pagoh Campus, for providing facilities for this research. This study was supported by the Postgraduate Research Grant (GPPS) from the Universiti Tun Hussein Onn Malaysia (UTHM) (Code No. Q575). It is part of a thesis that will be submitted as partial fulfillment to meet the requirements for the Degree of Doctor of Philosophy at UTHM.

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