Improving Necropsy Methods of Stranded Marine Mammals Using Remote Sensing Techniques

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June 2024

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Science in Geography

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Abstract

Marine mammals serve as indicators of ocean health, reflecting the complex dynamics of marine ecosystems. This thesis explores the integration of 3D reconstruction technology in marine mammal stranding research, with a focus on its application in necropsies to enhance morphometric measurements and improve documentation. Utilizing accessible remote sensing tools, including mobile phones equipped with LiDAR sensors, this study evaluates the effectiveness of 3D reconstructions across ten marine mammal species under diverse environmental conditions including remote necropsies of large whales and more controlled laboratory necropsies of small marine mammals. Key findings demonstrate that 3D scanning not only augments traditional necropsy procedures by providing precise, non-invasive anatomical data but also reveals critical insights into the health and pathology of stranded marine mammals, thereby enhancing our scientific understanding of their responses to environmental and anthropogenic stressors. The implementation of this technology facilitates rapid, accessible assessments crucial for immediate conservation actions in remote areas, promoting broader community engagement and fostering collaborative research and effective conservation strategies. This research highlights the transformative potential of accessible technology in marine conservation, suggesting pathways for future advancements in marine mammal research and management.

Les mammifères marins servent d'indicateurs de la santé des océans, reflétant la dynamique complexe des écosystèmes marins. Cette thèse explore l'intégration de la technologie de numérisation 3D dans la recherche sur les échouages de mammifères marins, en se concentrant sur son application lors des nécropsies pour améliorer les mesures morphométriques et la documentation. En utilisant des outils de télédétection accessibles, y compris des téléphones mobiles équipés de capteurs LiDAR, cette étude évalue l'efficacité des reconstructions 3D sur dix espèces de mammifères marins dans des conditions environnementales variées. Les principales conclusions démontrent que la numérisation 3D non seulement complète les procédures de nécropsie traditionnelles en fournissant des données anatomiques précises et non invasives, mais révèle également des informations cruciales sur la santé et la pathologie des mammifères marins échoués, améliorant ainsi notre compréhension scientifique de leurs réponses aux stress environnementaux et anthropiques. La mise en œuvre de cette technologie facilite des évaluations rapides et accessibles, cruciales pour des actions de conservation immédiates dans les zones éloignées, en favorisant un engagement communautaire plus large et en encourageant la recherche collaborative et des stratégies de conservation efficaces. Cette recherche met en lumière le potentiel transformateur des technologies accessibles dans la conservation marine, suggérant des voies pour de futures avancées dans la recherche et la gestion des mammifères marins.

Acknowledgements

I would like to express my deepest gratitude to everyone who has supported and guided me throughout the journey of completing this thesis.

First and foremost, I extend my heartfelt thanks to my supervisor, Professor Dr. Margaret Kalacska at McGill University. Her unwavering support, insightful guidance, and encouragement have been instrumental in the successful completion of this work. I am immensely grateful for her mentorship and the invaluable knowledge she has imparted to me.

I am also profoundly grateful to Oliver Lucanus of the Applied Remote Sensing Laboratory. His expertise and assistance have been pivotal in the development and execution of this research. His dedication and willingness to help have been greatly appreciated.

A special thanks to Dr. Juan Pablo Arroyo-Mora, who works at the National Research Council of Canada at the Flight Research Laboratory. His support and contributions have been crucial to the progress of this project, and I am deeply thankful for his collaboration.

I would like to extend my sincere appreciation to Dr. Stephen Raverty, veterinary pathologist and adjunct professor at UBC, for his invaluable support in coordinating the necropsies of marine mammals. His expertise and dedication have been essential to this research.

My gratitude also goes to Taylor Lehnhart of the Department of Fisheries and Oceans for assisting with necropsy efforts. His assistance has been essential, and I am thankful for his dedication and hard work.

Finally, I would like to thank my friends and family for their unwavering support and encouragement throughout this journey. Their love and understanding have been a constant source of strength and motivation for me.

Thank you all for your support, without which this thesis would not have been possible.

Contribution of Authors

This thesis is presented in manuscript-based thesis format. It is arranged around one main results chapter (Chapter 3), which is written as a manuscript to be submitted for publication. The thesis also contains an introduction (Chapter 1) and literature review (Chapter 2) and a concluding chapter (Chapter 4). It is the original work of Brendan Cottrell with a few exceptions. I have developed the research objectives, carried out the data collection, analyzed the results and wrote the manuscript as the lead author. My supervisor Dr. Margaret Kalacska as well as Dr. Juan Pablo Arroyo-Mora provided expert advice on the development of the project from its inception as well as editing the manuscript and thesis. Data collection for all marine mammal necropsies was made possible by Dr. Stephen Raverty who also edited the manuscript. Oliver Lucanus provided insight into equipment use as well as editing the manuscript. Taylor Lehnhart and Paul Cottrell also assisted in conducting the necropsies that allowed for data collection to be possible.

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Chapter 1. Introduction

In the vast expanse of our changing oceans, marine mammals serve as critical indicators of ecosystem health (Dierauf et al. 2001). Their strandings, whether due to natural causes or human activities, provide invaluable insights into the intricate dynamics shaping marine environments and, by extension, the entire ecosphere. As we grapple with the challenges of climate change, ecosystem shifts, and human impacts on the biosphere, the study of marine mammal strandings emerges as an increasingly vital field of inquiry. Understanding the health of marine mammals and the causes of their strandings thus transcends mere scientific curiosity; it serves as a crucial gauge of oceanic well-being and resilience. This underscores the significance of necropsies, which offer direct insights into the causes of these strandings and by extension the broader health trends affecting marine populations. Leveraging advancements in remote sensing technologies, this research utilizes 3D reconstructions to enhance the effectiveness of these postmortem examinations for marine mammals, improving morphometric measurements and visualizations to better understand and manage these critical events.

1.1 Historical Context of Stranding Research

The study of marine mammals through their strandings has evolved dramatically over the centuries, marked by key discoveries and technological innovations. Early documentation in the time of antiquity by Pliny the Elder (Denson 2021) and Aristotle (Cordes 1982) provided initial insights, though steeped in the context of myth and observation without systematic study. This work evolved significantly during the Renaissance, with works in the 16th century by Pierre Belon and Guillaume Rondelet (Romero 2012) providing some of the first scientific descriptions of cetaceans and a variety of other marine mammals. These were early attempts to categorize and describe marine life based on observation and dissection, rather than relying solely on folklore or second-hand accounts.

The 19th century saw a profound expansion in marine mammal research, catalyzed by the commercial whaling industry. Although devastating, whaling expeditions gathered crucial data on marine mammal biology and facilitated the first systematic observations of mass strandings and overall abundance (Baker et al. 2004). These observations began to highlight the complex interactions between human activities and marine mammal populations, leading to the establishment of the International Whaling Commission (IWC) in 1946 (Gulland 1990). This was a pivotal moment that not only aimed to regulate whaling but also spurred international scientific cooperation and conservation efforts.

Technological advancements in the 20th century brought about significant changes in how strandings were studied. The development of satellite telemetry and geographic information systems (GIS) transformed the tracking and management of marine mammal populations, allowing researchers to identify stranding hotspots and respond more effectively (Citta et al. 2018). Notable events such as the 1989 Exxon Valdez oil spill underscored the importance of rapid response and accurate data collection, as researchers documented the long-term ecological impacts and recovery efforts of the event, which further influenced conservation policies (Peterson 2001; Peterson et al. 2003). The introduction of non-invasive imaging techniques like magnetic resonance imaging (MRI) and computed tomography (CT) scans in the late 20th century for zoological efforts (Stoskopf 1989) began to address some of the limitations in studying strandings, providing clearer insights into internal pathologies.

The 21st century has brought significant advancements in marine mammal research, particularly through the integration of new technologies. This period has been characterized by an interdisciplinary approach that merges traditional marine biology with technological innovations. Improved satellite tracking, remote sensing applications, and the use of non-invasive imaging techniques including Unmanned Aerial Vehicles (UAV) have particularly taken off in marine mammal research (Álvarez-González et al. 2023). Additionally, the application of molecular techniques has enabled researchers to study the genetic material of marine mammals from even small samples obtained from stranded individuals (Mancia 2018). The integration of artificial intelligence and machine learning in enhancing predictive modeling of marine mammal behaviors, population dynamics and stranding patterns is also poised to increase in scope and utility (Khan et al. 2023; Duc 2020). The development of more sophisticated bio-logging devices, which can record a wider range of data including physiological responses has improved our ability to study marine mammals in their natural environment (Ropert-Coudert et al. 2009). Furthermore, the growth of citizen science initiatives (Kelly et al. 2020; Pirotta et al. 2020; Stelle 2017) has democratized participation in marine mammal conservation, fostering a broader engagement across different cultures and communities worldwide. This global perspective has been crucial, as different regions face unique challenges that require tailored action and international cooperation towards marine mammal conservation and stranding response. In the context of strandings, the increasing capability to 3D reconstruct marine mammals holds some of the greatest modern potential in integrating new technology to increase the efficacy and data output of postmortem examinations.

1.2 Ecological Significance of Marine Mammals and Strandings

Marine mammals, situated at or near the apex of their ecosystems, play critical roles in maintaining the structural and functional integrity of marine environments. Their influence extends across nutrient cycling, predator-prey dynamics, and overall ecosystem resilience (Moore 2008). As major consumers, marine mammals regulate the abundance and distribution of prey species, directly shaping energy flows and nutrient pathways within marine food webs. As an example, sea otters serve as a critical component of the otter-urchin-kelp trophic cascade, with their population collapse resulting in explosions in sea urchin populations and the destruction of kelp forests (Fukunaga et al. 2020). Similarly, grey whale feeding significantly influences the structure of benthic invertebrate communities and may also boost the population size of various secondary prey species (Oliver et al. 1985).

The feeding activities and movements of marine mammals are essential for the redistribution of nutrients, enhancing primary productivity and supporting the proliferation of foundational species like phytoplankton (Moss 2017). The deposition of fecal matter by marine mammals introduces significant nutrients back into the ecosystem, catalyzing productivity and supporting a wide range of marine life (Roman et al. 2010). These roles position them as keystone species, where their presence or absence triggers cascading effects on ecosystem structure and stability.

Marine mammals also engage in complex interactions with other marine species, including cooperative feeding strategies and symbiotic relationships, which further influence ecological and evolutionary trajectories within marine ecosystems (Estes 2009). For example, in the western Arctic, walruses not only diminish prey biomass but also create pits in the substrate that gather detritus, thereby supporting a detritivore-based food web (Ray et al. 2006). The study of deceased marine mammals through strandings, therefore, not only sheds light on the health of individual species but also illuminates broader ecological patterns and challenges. This research underscores the importance of preserving marine mammal populations as indicators and regulators of marine health, pivotal for the sustainability of our oceans.

Strandings provide a direct window into these dynamics and help scientists observe the immediate and long-term ecological impacts of such events. The decomposition of stranded marine mammals also can create significant nutrient pulses that enrich local environments and temporarily alter the distribution and abundance of nearby marine organisms (Benbow et al. 2020). These events can serve as natural experiments, providing insights into nutrient cycling and the ecological importance of marine mammals. The absence of these high trophic level animals due to increased strandings can lead to overpopulation of prey species, disrupting traditional predator-prey relationships and potentially leading to imbalances that affect the stability of the whole marine ecosystem (McCauley et al. 2015). Through strandings, researchers gain invaluable data on how such disruptions can influence ecological resilience and stability. Further, the ability to reconstruct these animals and events in 3D provides a lesser explored improvement to what data can be collected and studied during these strandings.

1.3 Anthropogenic Impacts on Marine Mammals

Human activities exert significant pressures on marine mammal populations, profoundly impacting their well-being and increasing the incidence of strandings. Habitat destruction, a consequence of coastal development, maritime transport, and industrial activities, threatens critical marine mammal habitats such as breeding grounds, feeding areas, and migratory corridors (Harwood 2001). These disruptions force marine mammals into unfamiliar and often hazardous environments, increasing their vulnerability to strandings (Fleishman et al. 2016). Pollution poses another grave threat to marine mammals, with plastic debris, chemical contaminants, and noise pollution from shipping and industrial activities wreaking havoc on their health and behaviors. Due to their extended lifespans, central role in the food chain, and large lipid deposits, marine mammals are especially susceptible to serious health threats from the buildup of contaminants. Ingestion of plastics can cause internal injuries or blockages (Kühn et al. 2020), with the outcomes of microplastic exposure not yet fully understood. In one systematic review of microplastic research on marine mammals (Zantis et al. 2021), all but one of 30 studies found microplastics present in the gastrointestinal tracts of the specimens studied. Other contaminants such as persistent organic pollutants (POP) and heavy metals contribute heavily to declining marine mammal health, with an estimated 60% of all marine mammal species threatened by this pollution (Schaap et al. 2023).

Noise pollution from ships and other anthropogenic activity disrupts communication and foraging behaviors, disorienting marine mammals and increasing the likelihood of stranding events (Simmonds et al. 2014). The growing intersection of marine vessels and marine mammals also contributes to increased collisions which cause physical trauma or death (Schoeman et al. 2020). Overfishing exacerbates the challenges faced by marine mammals, depleting prey populations vital for their survival, with 60% of the world's exploited fish and shellfish stocks being either fished to capacity, overfished, or recovering from overfishing (Goñi 1998). As prey becomes scarcer if these fishing practices continue, marine mammals experience nutritional stress, reduced reproductive success, and heightened competition for limited resources (Trites et al. 1997; Moore 2013), making them more susceptible to strandings. Additionally, entanglement in fishing gear pose significant risks to marine mammals. This manifests not only as the increasingly recognized problem of bycatch (Reeves et al. 2013), but also in static gear such as buoy lines and traps (Hamilton and Baker 2019), and aquaculture pens (Storlund et al. 2024). Entanglement can result in severe injuries, drowning, or prolonged distress (De Vere et al. 2018), with the abrasive impact of fishing gear on tissues well characterized in for example large whales (Woodward et al. 2006). Climate change further compounds these threats by altering oceanic conditions, such as sea surface temperature, salinity, and ocean acidification, disrupting marine mammal habitats and food sources. Direct observations of various marine mammal populations have displayed responses to climate change (Simmonds et al. 2007). Some species and populations are particularly at risk, including those with restricted habitat ranges, such as the vaquita, and those that rely on sea ice as a crucial component of their habitat such as grey whales (Gailey et al. 2020). These anthropogenic impacts not only increase mortality rates but also contribute to the incidence of strandings as marine mammals struggle to adapt to changing environments. Understanding the intricate interactions between human activities and marine mammal populations is paramount for developing effective conservation strategies and mitigating the impacts of anthropogenic threats on these animals. This is also an especially important use case for 3D reconstruction, which provides a new opportunity to image animals that have been impacted directly by anthropogenic factors. The most outwardly severe of these being vessel strike and entanglement, further understanding of the dynamics between this human activity and marine mammals can be further improved with this technology and thus impacts mitigated.

1.4 Necropsies as a Tool to Monitor Strandings

Necropsies, also known as postmortem examinations, are indispensable for analyzing the health and determining the causes of death within marine mammal populations, which are inherently difficult to study due to their aquatic habitats and wide-ranging behaviors (Nowacek et al. 2016). These systematic procedures, conducted by trained veterinarians and researchers, involve detailed dissection and inspection of deceased animals, offering critical insights that are either challenging or impossible to obtain through live observation. The process includes a comprehensive examination of the animal's anatomy, meticulously documenting findings such as lesions, or other external and internal indicators of health. This data, combined with supplemental diagnostic tests like histopathology, microbiology, and serology, enhances the diagnostic accuracy of necropsies. These examinations are crucial for detecting trauma, abnormalities, and assessing the impacts of threats such as vessel strikes and entanglement in fishing gear (Rowles et al. 2001).

Beyond their diagnostic value, necropsies contribute significantly to scientific knowledge by advancing our understanding of marine mammal anatomy, physiology, and pathology. These examinations provide critical data on mortality factors and the impacts of various threats, including environmental contaminants and infectious diseases. “Forever” chemicals such as poly- and perfluoroalkyl substances (PFAS) are contemporary chemicals that have been detected during necropsies with emerging concern for adverse health impacts for both marine mammals and humans (Fair et al. 2018). Highly pathogenic viruses such as avian influenza have also been detected in marine mammals (Leguia et al. 2023), with this information vital to tracking the progression of these viruses through both different populations and species. These threats detected during necropsies are particularly significant as they not only affect marine life but also have the potential to impact human health. Necropsies thus play a pivotal role in safeguarding public health and environmental integrity by detecting and monitoring the presence of these transmissible diseases and contaminants. They are also crucial in legal contexts, where findings from necropsies provide essential evidence in investigations related to oil spills, entanglements, vessel strikes, and other anthropogenic impacts. Examples of evidence are findings such as the ingestion of fishing gear or plastics but also signs of interactions including lacerations or tissue damage that aligns with known types of trauma which can be plausibly linked to human interactions (Stolen 2021). This legal evidence is instrumental in shaping policies and litigation aimed at protecting marine environments.

By elucidating the mechanisms underlying mortality events, necropsies inform targeted conservation efforts and management strategies aimed at mitigating threats to marine mammal populations. For example, necropsy results were instrumental in identifying the specific toxins responsible for the mass mortality event of sea lions along the Californian coast, linking their deaths to domoic acid poisoning from algal blooms (Lefebvre et al. 1999). Such findings are essential for wildlife managers and conservationists to track health trends, detect emerging threats, and implement targeted conservation measures.

Despite the value of these examinations, challenges persist, particularly in diagnosing the causes of strandings accurately. Traditional necropsy methods are often hindered by the decomposition of specimens and logistical difficulties in accessing remote stranding sites. This not only makes the transportation and handling of carcasses cumbersome but also often leads to delays that can compromise the integrity of biological samples and the accuracy of subsequent analyses. The variability in expertise among responders also can affect the quality and consistency of data collected, leading to gaps in the standardized collection of information. This is compounded by the sporadic nature of strandings, which makes systematic study challenging and sometimes results in missed opportunities to collect valuable data. Another significant gap is the limited ability to detect and analyze sub-lethal pathologies and their long-term impacts on marine mammal health and populations, as current methods are often better suited to identifying immediate causes of death (Raverty et al. 2018).

To address these issues, recent years have seen significant advancements in postmortem examination practices of marine mammals. Key developments include the adoption of advanced imaging techniques such as MRI and CT scans, which provide detailed insights into the internal anatomy and pathology of marine mammals without the invasiveness of traditional necropsies. These non-invasive imaging techniques enable researchers to identify injuries, diseases, and other abnormalities with greater precision, facilitating more accurate diagnoses and formulation of specific treatment plans. For some examples these technologies have been used to accurately detect abnormal gas accumulations in cetaceans and pinnipeds (Dennison et al. 2012), as well as estimate the anatomy and brain volumes of living California sea lions (Montie et al. 2009). Additionally, portable diagnostic tools, such as handheld ultrasound devices, have begun to be used in field conditions, offering real-time insights that were previously possible only in laboratory settings. One notable example of this is the field identification of bubbles in tissues of beaked whales and dolphins stranded near sonar exercises or caught at depth and hauled to the surface (Dennison et al. 2011).

Another crucial advancement is the integration of molecular techniques into postmortem examinations, including polymerase chain reaction (PCR) and next-generation sequencing (NGS). These technologies enable researchers to detect pathogens swiftly, identify genetic markers associated with specific diseases, and assess the genetic diversity of marine mammal populations. By combining traditional pathological examinations with molecular analyses, researchers gain a comprehensive understanding of the underlying causes of strandings and their implications for population health. This technology has been used and developed to effectively detect emerging morbillivirus infections in marine mammals (Saliki et al. 2002), as well as investigate the use of environmental DNA (eDNA) to genetically monitor marine mammals (Foote et al. 2012).

Recent innovations also include the use of digital pathology tools and machine learning algorithms that help in the detailed analysis of tissue samples. Large-scale databases and digital pathology platforms enable researchers to efficiently catalog and share postmortem findings, facilitating data integration, comparison, and synthesis across different regions and time periods. An important element of this is the application of artificial intelligence and machine learning to improve data analysis methods. These technological innovations support more robust epidemiological studies, trend analyses, and predictive modeling efforts, enhancing our ability to monitor and respond to strandings and associated threats to marine mammal populations. This has been highlighted in recent research on harbour porpoise strandings that used machine learning methods to accurately predict cause of death categories (IJsseldijk et al. 2024).

This field has also benefited from a growing emphasis on collaborative efforts and interdisciplinary approaches, particularly evident in the response to significant recent events such as the mass stranding of pilot whales in New Zealand in 2017. This incident saw nearly 600 whales stranded on Farewell Spit, prompting an extensive rescue and research operation that required the expertise of professionals across various disciplines. Researchers from veterinary medicine, pathology, marine biology, and conservation science came together to address this crisis. This large-scale collaboration enabled a comprehensive analysis of the stranding (Stockin et al. 2022), combining insights on health assessments, environmental factors, and behavioral studies (Hunter et al. 2017). Such an interdisciplinary approach not only facilitated immediate rescue efforts but also enhanced the subsequent conservation strategies by integrating diverse perspectives and expertise, underscoring the importance of teamwork in responding to complex ecological emergencies involving marine mammals. This experience highlighted how collaborative efforts can lead to more thorough assessments of strandings and better-informed strategies to prevent future incidents.

Despite these advancements, there is still a pressing need for improved protocols, more mobile and adaptable necropsy tools, and enhanced training for first responders. There is also a crucial requirement for better integration of necropsy data into broader marine health monitoring frameworks, which could significantly enhance our understanding of the impacts of environmental changes and human activities on marine mammal populations. Addressing these gaps is essential for advancing marine mammal conservation and management strategies, ultimately helping to mitigate the frequency and severity of strandings.

The use of 3D reconstruction technology is one developing field that has the potential to alleviate some of these gaps in marine mammal stranding research and capacity. Discussed in detail later, this technology is capable of rapid, accessible reconstructions by and for a variety of users and provides a new useful data format for postmortem examinations that provides benefits current methods are unable to output reliably and consistently. As the field of marine mammal research evolves, continued improvements in the integration of necropsy methods with these emerging technologies remains essential. This evolution will ensure the ongoing progression of the field, leading to better conservation strategies and more effective interventions to protect marine mammals globally.

1.5 The Use of Remote Sensing Tools to Monitor Marine Mammals and Strandings

In the study of marine mammal strandings and marine mammals in general, remote sensing technologies have become indispensable tools, providing unique capabilities that greatly enhance our understanding of the factors influencing marine mammals. By tracking the movements, health, and behaviors of marine mammals over expansive and often inaccessible marine areas, researchers are better equipped to identify the ecological and anthropogenic pressures that contribute to strandings. As we continue to integrate and refine these tools, they hold the potential to revolutionize our approach to understanding marine mammal strandings and ensuring the health of marine ecosystems.

Satellite tracking and telemetry are pivotal in studying marine mammals, particularly for understanding their migration patterns, habitat use, and behavioral ecology. By attaching satellite tags to animals, researchers receive data on their movements over vast oceanic territories, which is invaluable for species that are otherwise difficult to track due to their elusive nature or remote habitats. This technology provides continuous, long-term location data, allowing scientists to monitor individual and group behaviors across different seasons and years, with early efforts of this for marine mammals beginning back in the 1970s and 1980s (Priede et al. 1991). More recently, integration of machine learning with higher resolution satellite imagery has allowed for marine mammals surveys and monitoring via satellite without the use of tags, with models learning from aerial images of animals or other location data (Borowicz et al. 2019; Kapoor et al. 2023). One massive advantage of this is the ability to automate detection and counting, which significantly reduces the manual input labour of scientists conducting these studies and has been applied successfully to many marine mammal species (Rodofili et al. 2022). Geographical Information Systems (GIS) are utilized to perform spatiotemporal analyses of this data, facilitating the mapping of migration routes, critical habitats, and areas of frequent stranding (Norman et al. 2012). GIS helps in identifying environmental variables that correlate with these patterns, such as sea surface temperatures, ice cover, and human activities like shipping lanes and fishing areas (Becker et al. 2010; Pennino et al. 2017; Laidre et al. 2005). The integration of satellite data and GIS continues to enable a detailed and dynamic understanding of marine mammal ecology, strandings, and interactions with humans, aiding in conservation efforts and management decisions.

The use of unmanned aerial vehicles (UAVs) or drones has revolutionized the monitoring of marine mammals, especially in terms of non-invasive data collection. Equipped with high-resolution cameras, UAVs are employed for many purposes, allowing researchers to obtain precise measurements of body size, shape, and health condition of marine mammals from aerial images, assess abundance and distribution, photo-identify animals, or even take cetacean blow samples (Álvarez-González et al. 2023). UAVs are increasingly used to measure populations (Fettermann et al. 2022), animal distributions (Hodgson et al. 2017), and population group sizes (Sweeney et al. 2016) often providing more accurate estimates than traditional boat-based or land-based methods. The perspective offered by UAVs enhances the detection of individuals in dense groups or underwater, significantly improving the accuracy and efficiency of these assessments and reducing availability bias. UAVs have been used to create extensive photo-identification catalogues of southern right whales (Johnston et al. 2022) and beluga populations (Ryan et al. 2022). Aerial images from UAVs are used extensively to obtain morphometric measurements of marine mammals (Dawson et al. 2017; Dickson et al. 2021; Groskreutz et al. 2019). These metrics are essential for assessing growth patterns, nutritional status, and reproductive health. Morphometric data has even been applied as partial justification for the determination of new species of killer whales in the eastern North Pacific (Morin et al. 2024). UAVs also facilitate the observation of marine mammal behavior without the disturbance that manned vessels may cause, thus enabling more natural behavior studies and insights into social structures and interactions, something particular useful for highly social marine mammals such as dolphins (Karnowski et al. 2016).

Further, UAVs have become invaluable in stranding research. They can quickly cover coastal and hard-to-reach areas, providing rapid assessments of stranded animals, which is critical for timely necropsy or live stranding rehabilitation efforts. UAVs also aid in the documentation of stranding events, capturing detailed images and videos that help determine the spatial distribution of strandings and possible environmental contributors. UAVs have been applied to detect stranded animals effectively in Brazil as a cost-effective alternative to traditional beach monitoring (Pontalti et al. 2022). This capability is crucial for identifying stranding patterns and potential hotspots. In addition, UAVs can monitor the progression and aftermath of stranding events, offering insights into survivorship and predator-prey interactions post-stranding.

Lastly, 3D reconstruction technology is a particularly promising remote sensing tool in enhancing necropsy efforts for marine mammals. This technology enables the creation of precise, three-dimensional models that provide a detailed view of anatomical features. By integrating this technology with traditional necropsy practices, researchers can achieve a more nuanced analysis of strandings, significantly improving the accuracy and depth of their examinations. This not only enriches our understanding of marine mammal anatomy but also serves as a valuable educational and research resource. The following text delves deeper into how 3D reconstruction operates, and how it specifically can further develop and support marine mammal necropsies.

1.6 The Current Scope of 3D Reconstruction Technology and Applications

The advent of 3D reconstruction technology has marked a significant milestone in the evolution of digital imaging and modeling, offering profound implications across various fields from archaeology and architecture to forensic science and biological research. At the core of this technological leap are several methods, notably LiDAR and photogrammetry, which use reconstruction algorithms that synergistically create highly detailed and accurate 3D models of physical scenes and objects, including animals.

LiDAR, or Light Detection and Ranging, is a cutting-edge remote sensing technology that has revolutionized the way 3D models are created across various fields (Dong et al. 2017). This technology uses a laser to reconstruct environments and objects, capturing fine details at great distances with remarkable accuracy (Wandinger 2005). The versatility and precision of LiDAR make it an indispensable tool in many industries, from urban planning and forestry management to autonomous vehicle development and archaeological research (Desai et al. 2021; Bauwens et al. 2016; Chio et al. 2021; Losè et al. 2022) .

LiDAR operates by emitting laser pulses (850-940 nm for terrestrial, 500-750 nm for bathymetry) toward the target area and measuring the time it takes for each pulse to reflect back to the sensor. This time-of-flight data is used to calculate distances, which are then compiled to produce a dense set of elevation points known as a point cloud. These point clouds provide detailed and accurate 3D representations of the scanned environment, capturing natural and manmade features with high fidelity (Lehtola et al. 2021; Askar et al. 2023; Slavík et al. 2023). Modern LiDAR systems are often integrated with GPS and IMU (Inertial Measurement Units) to enhance the accuracy of location and orientation data, enabling precise georeferencing of the point clouds (Lopac et al. 2022).

In environmental sciences, LiDAR technology excels in creating detailed 3D models of various ecosystems, facilitating enhanced study and conservation efforts. By generating accurate topographic maps and biomass assessments, LiDAR allows ecologists to conduct detailed analyses of habitat conditions, species distribution, and environmental changes over time (Guo et al. 2021; Simonson et al. 2014). This capability is crucial for monitoring deforestation, studying habitat fragmentation, and implementing restoration projects effectively. Furthermore, LiDAR is increasingly used to model complex natural objects and animal forms in their natural habitats, for example in morphometric measurements of horses and cattle (Pérez-Ruiz et al. 2020; Huang et al. 2018). Researchers use LiDAR to capture the intricate details of animal morphology, which is essential for biological studies and conservation planning. These models provide valuable insights into the physical characteristics and functional mechanics of different species, helping scientists to understand evolutionary processes and species-specific behaviors. This is particularly valuable in studying endangered species and rare creatures. LiDAR has been effectively utilised to create reference collections of an abundance of different modern animal skeletons (Niven et al. 2009). This application extends to paleontology where LiDAR helps in the 3D scanning of fossilized remains embedded in rock, allowing scientists to extract and study fossils without physical excavation that might damage the specimens, in addition to rendering volumetric reconstructions of long extinct animals such as dinosaurs (Bates et al. 2010). The precision of LiDAR models enables detailed anatomical studies and enhances our understanding of the physical structure and environmental adaptation of various species, both living and extinct.

Photogrammetry is the art and science of extracting reliable physical information from photographs. Structure-from-motion (SfM) photogrammetry is based on the principle that the three-dimensional coordinates of points on an object can be determined by measurements made in two or more photographic images taken from different positions (Turner et al. 2012; Eltner et al. 2020). By utilizing photographs taken from different angles, SfM, when combined with other algorithms such as Multi-View Stereo (MVS) (Xiao et al. 2016) enables the creation of precise three-dimensional models of physical objects and landscapes, bridging the gap between the real world and digital interpretation (Ullman et al. 1997). The process involves several stages, starting with the planning of the image capture to ensure comprehensive coverage of the subject. This is followed by the actual capture, where consistency in lighting and overlap between images are key factors. The images are then processed using specialized software that identifies common points between overlapping images and reconstructs the 3D coordinates of these points, forming a point cloud. This point cloud is then used to generate a mesh of polygons, often followed by texturing, which overlays the photographs' textures onto the mesh to create a realistic 3D model (Liu et al. 2023).

One of the main strengths of SfM photogrammetry is its versatility and accessibility, making it a valuable tool in ecological studies and wildlife research. It is widely used in ecology to create detailed models of natural habitats, allowing ecologists to study complex ecosystems and interactions without disturbing the environment. For example, SfM has been used to characterize the structural complexity of coral reefs in 3D (Burns et al. 2015). Similarly, in wildlife conservation, SfM photogrammetry allows for the non-invasive monitoring of animal populations, enabling researchers to measure and track changes in animal morphology over time. Terrestrial mammals from 16 different species have had their mass estimated effectively from 3D photogrammetry in one study from South Africa (Postma et al. 2015). SfM 3D reconstruction has been applied to many other live animals including frogs, turtles, and porpoises (Grayburn et al. 2019). In doing so, photogrammetry helps enhance our understanding of animal morphology, contributing to more effective data collection and conservation strategies.

Reconstruction algorithms are at the heart of 3D imaging technology, transforming raw data from various sensing technologies into detailed and actionable 3D models. These algorithms are critical in fields ranging from mobile device applications to large-scale environmental monitoring, each tailored to optimize data from specific sources such as LiDAR or SfM photogrammetric imagery.

Iterative Closest Point (ICP) is one of the fundamental algorithms used for aligning multiple 3D data sets, especially in LiDAR scanning (He et al. 2017). It works by iteratively adjusting the alignment of data points from different scans to minimize the total distance between corresponding points. This is essential in applications where multiple scans of an object or area are taken from different angles, as it ensures that the resulting 3D model is as accurate and coherent as possible. The ICP algorithm has been utilized effectively in cases such as monitoring the quality of livestock which are generally evaluated based on their body form and weight (Kwon and Mun 2022).

Simultaneous Localization and Mapping (SLAM), another sophisticated algorithm, is crucial for mobile 3D scanning applications, such as those used in newer smartphones equipped with LiDAR sensors. SLAM allows devices to build a map of an unknown environment while simultaneously keeping track of their own location within that map (Thrun 2008). This dual capability makes

SLAM ideal for mobile applications, augmented reality (AR) applications, and autonomous vehicle navigation, where real-time spatial awareness and processing are required.

Poisson Surface Reconstruction offers an approach to creating smooth, well-defined surfaces from point cloud data, which are often collected via photogrammetry or LiDAR. This algorithm excels in generating high-quality surfaces by interpolating a continuous surface across given 3D points and is particularly beneficial for creating naturalistic models from organic shapes, such as those found in marine environments or in anatomical studies in medical research (Hoppe 2008).

Despite their numerous applications and capabilities, these technologies face limitations that can impact their efficacy. Both LiDAR and SfM require substantial computational resources to process and manage the large datasets they generate, making them data-intensive and sometimes cost-prohibitive. SfM photogrammetry in particular depends heavily on the quality of the source images; factors such as poor lighting, lack of distinct textures, or highly reflective surfaces can introduce inaccuracies in the final 3D model (Shin et al. 2021). The high cost of LiDAR equipment poses a barrier to widespread adoption, with the technology's expense often limiting its use to well-funded projects. Additionally, the complexity of the subject's geometry being scanned by either technology can further complicate data collection and model accuracy. These challenges underscore the need for robust data management solutions and continued advancements in technology to enhance the accessibility and accuracy of 3D reconstruction tools and algorithms.

In its current state, 3D reconstruction technology can provide immense value towards postmortem examinations of marine mammals, primarily due to the advent of low-cost LiDAR sensors implemented on many mobile devices. These sensors can create high resolution 3D representations of stranded marine mammals to be used for diagnostic evaluations or for reliable morphometric measurements in the field. These two applications alone make this technology worth pursuing for this application, as well as the potential for educational studies of marine mammal anatomy. This technology would allow previously rarely seen animals such as large whales, dolphins and pinnipeds be available in an accessible environment to be viewed, studied, and learned from in a 3D environment web application or virtual reality (VR).

1.7 Research Objectives

This thesis explores the application and impact of 3D scanning technology in the assessment of marine mammal strandings, leveraging readily accessible tools like mobile phones to improve traditional necropsy procedures.

A key objective of my study is to explore the broader applications of 3D scanning in education and conservation. The research aims to validate and refine the data collection processes associated with 3D scanning to ensure they meet the demands of scientific research and necropsy measurement accuracy. By comparing these modern methods against traditional necropsy techniques, the study seeks to establish standardized practices that can be employed effectively in various environmental conditions and by different users. This is particularly important in resource-poor settings, where access to sophisticated equipment and specialized personnel is limited.

The integration of 3D reconstruction technology into marine mammal research and necropsy is proposed as a transformative approach that not only enhances the quality and quantity of data collected but also facilitates wider collaboration among diverse stakeholders in marine conservation, ensuring that efforts are inclusive and comprehensive.

In summary, this thesis highlights the use of 3D reconstruction technology in marine mammal stranding research, demonstrating its potential to improve postmortem examinations, educational outreach, and conservation practices.

Chapter 2. Literature Review: 3D Reconstructions of Marine Mammals

To evaluate the current research in this field of study, a search of the literature involving 3D reconstructions of marine mammals was conducted from 2004 – 2024 using SCOPUS. The literature search included the terms "marine mammal" and "3D" and "model" or "reconstruction" or "scan" included in the title, abstract, or keywords. The search provided 56 results which were filtered to exclude reviews, conference abstracts, and non-English language results. The remaining articles were reviewed manually to check whether the titles and abstracts were consistent with the search objective. In total, 16 publications were selected, with these works described in groupings according to their application and methods. The literature broadly followed four categories explored here in order: detailed skeletal reconstructions, reconstructions using medical imaging, non-invasive estimations of body mass and volume for free-ranging animals, and analyses of stranded specimens.

2.1 Skeletal Reconstructions and 3D Printing

The application of three-dimensional (3D) geometric morphometrics in marine mammal research has provided unparalleled insights into skeletal structure variations and evolutionary adaptations. A detailed study on the Eurasian otter utilized photogrammetry to create precise 3D models of otter skulls from different genetic clusters across Great Britain (Russo et al. 2022). These models have facilitated the examination of distinct morphological traits, correlating them with genetic data, dietary habits, and environmental factors. The significant variations in skull morphology—such as wider zygomatic arches and longer snouts in otters from the Shetlands—are revealed through advanced 3D reconstructions, highlighting their adaptive traits in response to geographical and ecological pressures, as well as the imaging technology that generates these results.

Research on narwhals, belugas, and their hybrids has employed detailed 3D photogrammetric data to explore interspecies breeding impacts within the *Monodontidae* family (Vicari et al. 2022). This approach effectively delineated clear morphological distinctions, providing a visual representation of the hybrids that combines traits from both parent species. This study involved capturing high-resolution images from multiple angles, which were then processed using the software Blender and Meshroom to generate comprehensive 3D models.

Another use of 3D modeling involved investigating the cranial anatomy of baleen whales. Through close-range photogrammetry, researchers created detailed 3D models of minke whale skulls to study a unique biomechanical adaptation in the maxillomandibular cam articulation (Lambertsen and Hintz 2004). This feature illustrates a specialized evolutionary adaptation to aquatic feeding, discovered through plotting and transformation of photogrammetric data into 3D reconstructions that provide a deeper understanding of the biomechanics of feeding strategies.

These skeletal reconstruction studies underscore the critical role of 3D modeling in understanding morphological adaptations, enhancing our ability to study complex anatomical structures non-invasively and with high precision. In all these studies, it is mentioned that ensuring consistency in the scaling and alignment of 3D models is essential for accurate morphological comparisons across different studies. This is particularly important in these contexts when the findings from such detailed comparative analyses contribute to our understanding of evolutionary adaptations and ecological strategies.

2.2 Medical Imaging for the Purpose of 3D Reconstruction

Medical imaging for 3D reconstruction represents a significant technological advancement in the field of marine mammal research, offering detailed insights into internal anatomical structures that are otherwise difficult to study. The primary advantage of using medical imaging techniques, such as CT scans and MRIs, lies in their ability to provide high-resolution, three-dimensional views of complex biological systems without invasive procedures.

One key study centered on the North Atlantic right whale utilized computerized tomography (CT) to investigate auditory capabilities (Parks et al. 2007), a novel approach given the typical challenges associated with behavioral testing in large marine mammals. The precision of CT scans enabled detailed morphometric analyses of the cochleae, revealing crucial insights into the auditory range of the whales. This is particularly important as a means of understanding and mitigating risks from human activities like shipping and naval exercises. However, the requirement for larger sample sizes to enhance the reliability of these findings underscores a common limitation in marine mammal research, where specimen availability often hampers extensive studies.

The innovative use of 3D-printed models in a study on the cookiecutter shark's feeding behavior (Grace et al. 2023) exemplified how 3D reconstructions can simulate and analyze specific biological functions which in this case is the mechanics behind the species' characteristic bite marks. Despite its successes, the study also notes the constraints of using static models to replicate dynamic biological processes, reflecting the inherent challenges of ensuring experimental fidelity in simulations.

Further, the use of 3D reconstruction to map the auditory cortex of the La Plata dolphin (Fung et al. 2005) highlighted the application's utility in neuroscientific studies, where traditional approaches may be impossible. By combining histological data with 3D imaging, researchers can achieve a comprehensive visualization of complex brain structures, essential for understanding sensory processing in aquatic environments. Similarly, a study examining the cranial endocasts in pinnipeds through CT and μCT scans illustrated the broader evolutionary insights of brains possible with 3D reconstructions (Loza et al. 2023). This approach allows for detailed comparisons of neuroanatomy across different species, revealing how evolutionary pressures shape physiological traits in response to ecological niches.

Distinguished from other types of 3D modeling, such as photogrammetry or LiDAR virtual reconstructions used for external measurements and visualizations, medical imaging-based 3D reconstructions delve into the intricate internal details that are crucial for biomedical research. These methods face unique challenges, including the need for high-resolution data to accurately render fine anatomical details and the complexity of interpreting these detailed images in meaningful ways. Moreover, medical imaging requires access to specialized equipment and expertise, at often a high cost, which can be a significant barrier compared to more accessible methods like photogrammetry. Despite these challenges, the non-invasive nature and depth of data provided make medical imaging an invaluable tool in the ongoing efforts to conserve and study marine mammals, offering insights that are often unattainable through other methodologies.

2.3 3D Reconstruction for Estimating Form of Free-Ranging Marine Mammals

The advent of 3D reconstruction technologies has also significantly advanced the study of marine mammal physiology and morphology, offering non-invasive and highly accurate methods to estimate body mass and volume. The presence of methodological diversity within this field provides a deeper understanding of the best practices of creating reconstructions, which results in improved overall output quality.

The use of 3D imaging technology combined with artificial neural networks (ANN) to estimate the body mass of southern elephant seals marked a significant development in pinniped research (Eder et al. 2022). By scanning the seals with an infrared light sensor and processing the data through ANN, researchers achieved a remarkably low mean percentage error of 4.4% in mass estimates. This method stands out for its minimal disturbance to the animals and its avoidance of the logistical challenges usually associated with such measurements.

Similarly, 3D modeling has proven beneficial in assessing the body condition and supporting biomechanical studies of harbor porpoises (Irschick et al. 2020). Utilizing a combination of photography, drone footage, and GoPro videos, researchers created detailed digital reconstructions that were validated against traditional physical measurements. These models not only facilitate the study of locomotion and body condition but also serve as valuable educational tools, demonstrating the practical applications of 3D reconstructions in marine mammal science.

In the study of humpback whales, researchers have utilized UAVs to capture detailed morphometric data which was then used to develop scalable 3D models for estimating body volume (Hirtle et al. 2022). This approach significantly refined the precision of traditional methods, which often rely solely on visible dorsal surface measurements from aerial images. By integrating UAV-derived data into 3D models, the research highlighted the potential of these technologies in conducting real-time field assessments of marine mammals. Similarly, the application of aerial photogrammetry to estimate the body mass of free-ranging southern right whales (Christiansen et al. 2019) further illustrated the effectiveness of 3D models in marine mammal research. By creating a volumetric model that conceptualized the whale's body as a series of ellipses, this method not only accommodated detailed measurements of body width and height but also enhances the accuracy of body mass estimates. The study underscored the importance of incorporating comprehensive body dimensions to better understand the physiological conditions of marine mammals through 3D reconstruction. Focusing on pilot whales, another study demonstrated that detailed 3D models provide more accurate representations of marine mammal morphology than traditional truncated cones methods (Adamczak et al. 2019). These models, particularly effective for larger individuals, offer more reliable estimates of surface area and volume, highlighting discrepancies that arise with conventional methods as the size of the animals increases.

Lastly, the use of 3D models for finless porpoises has shown how accurately these reconstructions can mimic actual biological structures (Zhang et al. 2023). Validated against traditional modeling techniques, these 3D models closely matched direct measurements, emphasizing their reliability and the potential for broader application in non-invasive morphometric studies. The potential of single image 3D modeling was also tested for finless porpoises (Zhang et al. 2023), where despite its lesser accuracy compared to multi-image techniques, points to the need for rapid and cost-effective assessment tools in marine biology. This method could be particularly useful in scenarios requiring quick and efficient responses, such as during brief sightings or in remote locations.

While these studies collectively demonstrate the integration of 3D modeling in marine mammal research, they also highlight areas for improvement, with main themes in the standardization of methodologies and the development of more accessible tools for widespread application. Future research should thus focus on enhancing the resolution and accuracy of 3D models and exploring their use in more dynamic and challenging environments.

2.4 3D Reconstruction of Stranded Marine Mammals During Postmortem Examination

The integration of 3D reconstruction technologies in the study of stranded cetaceans offers potential for further advancements in marine mammal research, enabling more precise morphometric analyses and visualization options for necropsies. Two studies exemplify this integration, firstly the use of photogrammetry in assessing a stranded fin whale in Campania, Italy (Del Pizzo et al. 2021), and secondly, the application of a "4D virtual necropsy" on a humpback whale in Alaska (Chenoweth et al. 2022).

The Campania fin whale study highlights the potential of photogrammetry to replace traditional morphometric data collection methods, which are often hindered by logistical challenges and the physical state of decomposing carcasses. By utilizing consumer-grade cameras and photogrammetric software, researchers created detailed 3D models from images taken around the whale carcass, facilitating accurate and undisturbed measurements of morphological features. This method proved not only comparable but occasionally superior to traditional measurements, suggesting that photogrammetry could greatly enhance the accuracy and efficiency of post-mortem examinations. The study advocates for the development of standardized photogrammetry protocols to improve data quality and accessibility, which could significantly advance the monitoring and understanding of cetacean health and conservation.

Similarly, the "4D virtual necropsy" utilized both LiDAR and photogrammetry to document the necropsy and decomposition of a humpback whale over several months. This innovative approach produced a publicly accessible digital necropsy, which has served educational and research purposes globally. The incorporation of time as a fourth dimension allows for dynamic observations of post-mortem decomposition, offering a unique educational tool that enhances the understanding of marine mammal anatomy and pathology without necessitating physical presence.

Despite these successes, the studies mention potential improvements in the research, particularly concerning the standardization of methodologies and the adaptation of these technologies to a wider range of species and environmental conditions. Future research should focus on refining these methods to ensure they are robust across different necropsy scenarios and can be seamlessly integrated into existing stranding response protocols. This would not only streamline data collection but also enhance the global capacity for marine mammal research and conservation efforts.

2.5 Current State of the Research and Gaps

One of the primary limitations evident across the studies is the inconsistency in methodological approaches. While diversity in methods can foster innovation, the lack of standardized protocols can hinder the comparability of results and scalability of technologies. For instance, the field would benefit from harmonizing techniques used in photogrammetry and CT scans to ensure that a larger breadth of data collected by different researchers or institutions can be accurately compared or integrated. This standardization is particularly critical in longitudinal studies or those spanning multiple geographic regions, where data consistency is paramount. Studies like the one on the North Atlantic right whale reconstruction and the cookiecutter shark bite provide critical insights but also highlight the need for broader sample sizes and the adaptation of experimental setups to better mimic natural conditions.

Despite the proven capabilities of 3D reconstructions in enhancing our understanding of marine mammal anatomy and behavior, their application in real-world conservation strategies remains limited. Research is needed to bridge the gap between academic findings and practical conservation tools, such as developing streamlined processes for deploying these technologies in the field and enhancing their affordability and accessibility for conservation practitioners. For example, the research on narwhals and belugas and their hybrids using 3D morphometrics illustrates the technology's capability to detail interspecies variations yet points to the need for further studies to explore the broader ecological and evolutionary implications of these findings.

In the specific context of necropsies and postmortem examinations, 3D reconstruction technologies hold tremendous promise for advancing our understanding of marine mammal pathology and mortality causes. However, several research gaps and challenges need to be addressed to fully leverage these technologies in postmortem studies. Firstly, there is a critical need for developing standardized protocols for 3D reconstructions during necropsies. Standardizing these methods would ensure consistency and comparability of postmortem data across different cases and institutions. This is particularly important for establishing baseline data on marine mammal health and for monitoring changes over time or across populations. The use of photogrammetry in assessing the fin whale in Campania, Italy, suggests that while 3D models can replace traditional methods and offer superior accuracy, there remains a substantial need for standardized photogrammetry protocols to improve data quality and accessibility universally.

Additionally, there is an opportunity to expand the use of 3D reconstructions to include a wider range of species and sizes of marine mammals. Most existing research focuses on larger cetaceans, while smaller species and less common marine mammals are underrepresented. Expanding the application of 3D reconstructions to include these groups could provide a more comprehensive understanding of species-specific pathologies and anatomical variations, which are crucial for tailored conservation strategies.

Another gap is the integration of advanced imaging techniques such as magnetic resonance imaging (MRI) and computed tomography (CT) with other forms of 3D reconstruction. These imaging modalities can provide detailed insights into the internal anatomy that are not possible with external scans alone. Research into hybrid techniques that combine these methods could enhance the depth and breadth of data collected during necropsies, offering more comprehensive insights into cause of death and disease processes.

Finally, enhancing the accessibility of these technologies for field-based necropsies is crucial. Many strandings and postmortem examinations occur in remote or resource-limited settings where sophisticated 3D scanning equipment is not available. Developing portable, cost-effective, and user-friendly 3D scanning solutions that can be deployed in these conditions would significantly advance the capacity for rapid and accurate postmortem examinations globally.

Chapter 3. 3D Reconstructions of Stranded Marine Mammals Using Accessible Remote Sensing Tools for Use in Morphometric Measurements and Visualizations

The literature review highlights significant advancements in the field of marine mammal research, particularly the integration of innovative technologies to enhance the accuracy and comprehensiveness of data collection. Traditional necropsy methods have been indispensable, yet they face inherent limitations due to logistical challenges, resource constraints, and the deteriorating condition of specimens. The emergence of 3D reconstruction technology, specifically through accessible tools like mobile phones equipped with LiDAR, represents a promising solution to these challenges.

Considering these advancements, my study explores the application of 3D scanning technology in marine mammal strandings. By leveraging readily available technology, I aim to improve the precision of morphometric measurements and enhance the documentation process during necropsies. This approach not only addresses the practical constraints encountered in the field but also opens new avenues for research, education, and conservation.

The following manuscript delves into the operational aspects and potential impact of utilizing 3D scanning tools in the assessment of marine mammal strandings. By focusing on the practicality and accuracy of these technologies, I aim to demonstrate their transformative potential in marine mammal conservation efforts.

Reference:

Cottrell B., Kalacska M., Raverty S., Arroyo-Mora J.P., Lucanus O., Cottrell P., Lehnhart T. 3D Reconstructions of Stranded Marine Mammals Using Accessible Remote Sensing Tools for Use in Morphometric Measurements and Visualizations. *Frontiers in Marine Science*.

Note: The heading, figure and table numbers for chapter 3 are adjusted to follow the table of contents for the thesis.

3.1 Abstract

This study investigates the practicality and potential impact of 3D scanning technology in assessing marine mammal strandings. Utilizing accessible tools like mobile phones, we evaluate the technology and its capability to accurately reconstruct strandings across diverse conditions and 10 marine mammal species. This process is validated by measuring an inflatable whale to an accuracy of less than 1%, with most marine mammals studied being measured to within 2% of manual morphometric measurements. Our findings demonstrate the adaptability of the technology in remote environments, particularly for large whale strandings, while showcasing its utility in measuring morphometrics and enhancing necropsy documentation. The study underscores the transformative role of 3D scanning in marine mammal conservation, offering avenues for improved research, education, and conservation practices. It emphasizes the importance of accessible technology in engaging communities and advancing wildlife conservation efforts globally.

3.2 Introduction

As sentinels of broader ocean health (Bossart 2011), marine mammals reflect the intricate balance of marine ecosystems and play a crucial role in providing insights into environmental changes (Simmonds and Isaac 2007; MacLeod 2009; Derville et al. 2019; Burek et al. 2008), pollution levels (Williams et al. 2023), and ecosystem dynamics (Bowen 1997; Rhodes-Reese et al. 2021). Studying marine mammals such as large whales, dolphins, and other pelagic creatures often poses significant challenges due to spending their lives underwater and their vast and remote oceanic habitats (Nowacek et al. 2016). Necropsies, the post-mortem examination of deceased animals, offer invaluable opportunities to assess marine mammal health, shedding light on both individual and population-level factors influencing their well-being (Küker et al. 2018). Necropsies not only provide insights into the cause of death but also offer unique glimpses into various other aspects of marine mammal health. Tracking emerging diseases (Waltzek et al. 2012; Leguia et al. 2023; VanWormer et al. 2019), assessing variations in body condition (Castrillon and Bengtson Nash 2020), and identifying trauma (Schoeman et al. 2020; Cassoff et al. 2011) are just some of the critical observations that can be made during necropsies. These examinations allow researchers to monitor seasonal changes (Wund et al. 2023), identify trends in mortality rates (Bogomolni et al.

2010), and assess the impacts of environmental stressors on marine mammal populations (Carrier-Belleau et al. 2021).

The progression of best practices in conducting necropsies worldwide continues to improve the information collected about marine mammal strandings and overall health. In remote areas where access to specialized equipment, personnel, and expertise is limited, it is difficult to extract a consistent level of detail from these examinations in comparison to resourced areas (Fitton et al. 2021). In regions like British Columbia, Canada, where expansive marine mammal populations thrive amidst hundreds of kilometers of remote coastline, the need for innovative approaches to necropsy procedures becomes increasingly relevant. Despite these challenges, extensive data has been compiled on stranding trends (Raverty et al. 2024; Barbieri et al. 2013), anthropogenic threats (Storlund et al. 2024), emerging diseases (Berhane et al. 2022; Teman et al. 2021; Rosenberg et al. 2016), and contaminant levels (Lee et al. 2023; Lee et al. 2023) of marine mammals in this region. Opportunity to improve the quantity and quality of data from postmortem examinations is of critical interest and can be developed in part by way of newly available imaging instruments and procedures (Tsui et al. 2020). Improved documentation and sample management has been an another identified need in improving necropsy procedure (Brownlie and Munro 2016).

The need for complementary methods to enhance necropsy data collection and analysis can be realized in part using rapidly developing 3D reconstruction sensors and technology (Bois et al. 2021; Farahani et al. 2017) . Continued advancements in this technology will further improve the accessibility and user-friendliness of 3D reconstruction tools. By providing detailed visualizations of marine mammal anatomy and pathology, these virtual reconstructions have the potential to enhance public engagement, interest, and education (Au et al. 2017). Virtual reality (VR) environments in particular offer immersive experiences (Cipresso et al. 2018) that will potentially allow users to explore reconstructed marine mammal specimens in unprecedented detail, fostering greater awareness and appreciation for these creatures and the challenges they face.

Models of marine mammals have been used successfully to estimate body size and morphology, often in the pursuit of understanding health and bioenergetics. Digital modelling combining photographs and select morphometric measurements have been successfully applied to create 3D models of pilot whales (Adamczak et al. 2019), finless porpoises (Zhang et al. 2023), and humpback whales (Hirtle et al. 2022), as well as many other animals (Irschick et al. 2022). These models are typically used as a proxy for live animals and animated for biomechanical analysis or to analyze body condition. Often these models are dependent on validation from stranded animals, which further justifies the need for continued and improved collection of morphometric data during necropsy of all marine mammal species. Digital imaging has also been combined with 3D printing to create high definition 3D printed specimen replicas of a killer and blue whale for use in a marine science center (Mills et al. 2022). In Alaska, a humpback whale was 3D scanned using an iPad in addition to Unmanned Aerial Vehicle (UAV) photogrammetry to create a “Virtual Necropsy” educational tool (Chenoweth et al. 2022). The use of accessible remote sensing tools has been shown to provide value for both education and in documentation of stranded animals in numerous occasions, although the technology must continue to be tested, improved, and implemented to provide long term value for marine mammal conservation. This includes being tested in time-constrained situations, non-ideal environmental conditions, by unfamiliar users and among varied specimens and species.

In this paper, we present a novel rapid approach for 3D reconstruction to complement traditional necropsy methods in marine mammal research in cases of various necropsy conditions and species. The primary purpose of our work is to showcase the current state of the technology in the context of marine mammal strandings and that it can be utilized by community partners to improve marine mammal stranding information collection in particularly challenging and resource-poor environments. This includes testing the feasibility of collecting 3D data in the typical (often poor) environmental conditions where marine mammals strand in British Columbia. This is particularly important for large whale strandings, or in cases where carcass transport from remote areas is not feasible and thus limited external examinations and sample collection must be done in place. We tested our methodology by collecting data from a diverse range of marine mammal specimens, including large whales, dolphins, pinnipeds, and sea otters, with a focus on accessible and user-friendly handheld devices equipped with LiDAR sensors. This was done in conjunction with the validation of the data collection process against an inflatable pilot whale used for live-stranding training. Additional auxiliary data including UAV photogrammetry was also collected, in the case of large whales to provide a comparison to LiDAR. In the cases where a full necropsy was completed, individual datasets of organ systems were collected when possible. These scans were processed and created into detailed virtual models for morphometric assessments, and/or as an education tool. These scans were also implemented in a web application and VR environment as an example of marine mammal stranding data visualization for multiple species. Through our study, we demonstrate the significant potential of 3D reconstruction technology with easily available sensors to enhance the study of marine mammal health and pathology. By providing detailed visualizations of marine mammal specimens and exploring the adoption of continued collection of this data, we offer researchers, community members, and educators valuable tools for documenting and understanding marine mammal strandings. We highlight the importance of innovation in necropsy procedures for advancing our understanding of marine mammal health and informing conservation efforts particularly in remote and challenging environments.

3.3 Materials and Methods

3.3.1 Study Area

The province of British Columbia, located on the westernmost edge of Canada, is renowned for its diverse and dramatic physical geography, particularly along its extensive coastline. Stretching over 27,000 kilometers, the coastline features a complex network of fjords, inlets, and islands, including the prominent Vancouver Island and the Queen Charlotte Islands (Haida Gwaii). The coastal waters are characterized by a mixture of cold, nutrient-rich currents that support a vibrant marine ecosystem including many marine mammals. There are 31 species of marine mammals that can be found in British Columbian waters, 25 cetaceans (whales, dolphins, and porpoises) and 6 species of carnivores (seals, sea lions and the sea otter) (Ford 2014).

Marine mammal strandings in British Columbia, are monitored province-wide by the British Columbia Marine Mammal Response Network (BCMMRN) coordinated by the Department of Fisheries and Oceans Canada (DFO). Necropsies for this study were conducted in cooperation with the provincial Animal Health Centre in Abbotsford, British Columbia.

Starting in May 2022, data were collected for strandings that were conducive to a postmortem examination and 3D reconstruction within the territorial waters of British Columbia. In this study, 10 species and 12 specimens were examined: 7 cetacean and 3 carnivore species (Table 1). The strandings where data collection occurred are labelled by species with locations displayed in Figure 1.

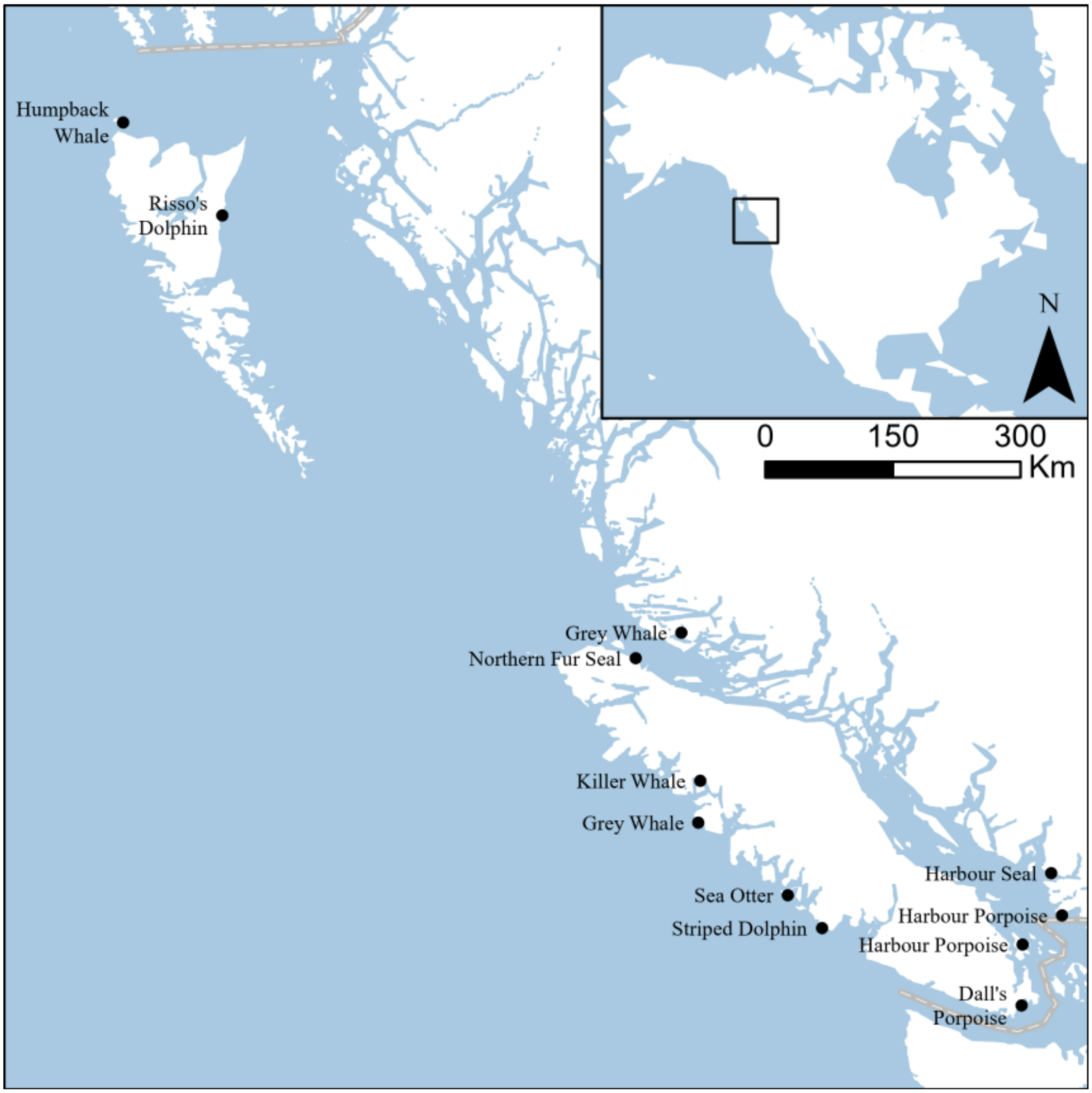

Figure 1: Map of study area on the west coast of Canada illustrating marine mammal strandings where 3D reconstruction data collection was performed.

3.3.2 3D Model Reconstruction Background

While in-depth descriptions of the background theory for the methods used can be found elsewhere (see Gomes et al., 2014; Kang et al., 2020; Ma et al., 2018; Zhou et al., 2024 among others), given the novelty of the application, a short overview is presented here.

Light Detection and Ranging (LiDAR) is a remote sensing technology that uses laser pulses to determine distance between the instrument and the object/surface of the Earth. The resulting point clouds are detailed three-dimensional representations of surfaces and objects (Wandinger 2005). By emitting laser pulses and measuring the time it takes for them to return after hitting an object, LiDAR generates precise distance data. Handheld LiDAR devices utilize this technology in a portable format, allowing for efficient 3D data collection in various environments (Bauwens et al. 2016; Chio and Hou 2021; Desai et al. 2021). The most common output from LiDAR is a 3D point cloud.

Structure-from-Motion Multi-View Stereo (SfM-MVS) photogrammetry is a technique used to create 3D models from 2D photographs (Eltner et al. 2020). By capturing a series of overlapping photographs from different angles, SfM software can identify common points within the images and reconstruct their three-dimensional positions. This process involves camera calibration, feature detection, and matching, followed by the generation of a sparse point cloud that represents the object's or scene's geometry (Fathi and Brilakis 2011). Further refinement through dense point cloud reconstruction is achieved through algorithms such as MVS (Strecha et al. 2012).

A 3D point cloud is a collection of discrete points in three-dimensional space, each representing a specific location on the surface of an object or scene. These points collectively describe the object's geometry but lack information about the surface's continuity (Liu et al. 2019). In contrast, a 3D mesh provides a more structured representation, consisting of vertices, edges, and faces that form a continuous surface (Rassineux 1997). Figure 2 shows what the two different formats of point cloud (a) and 3D mesh model (b) represent visually for reference on an inflatable test whale.

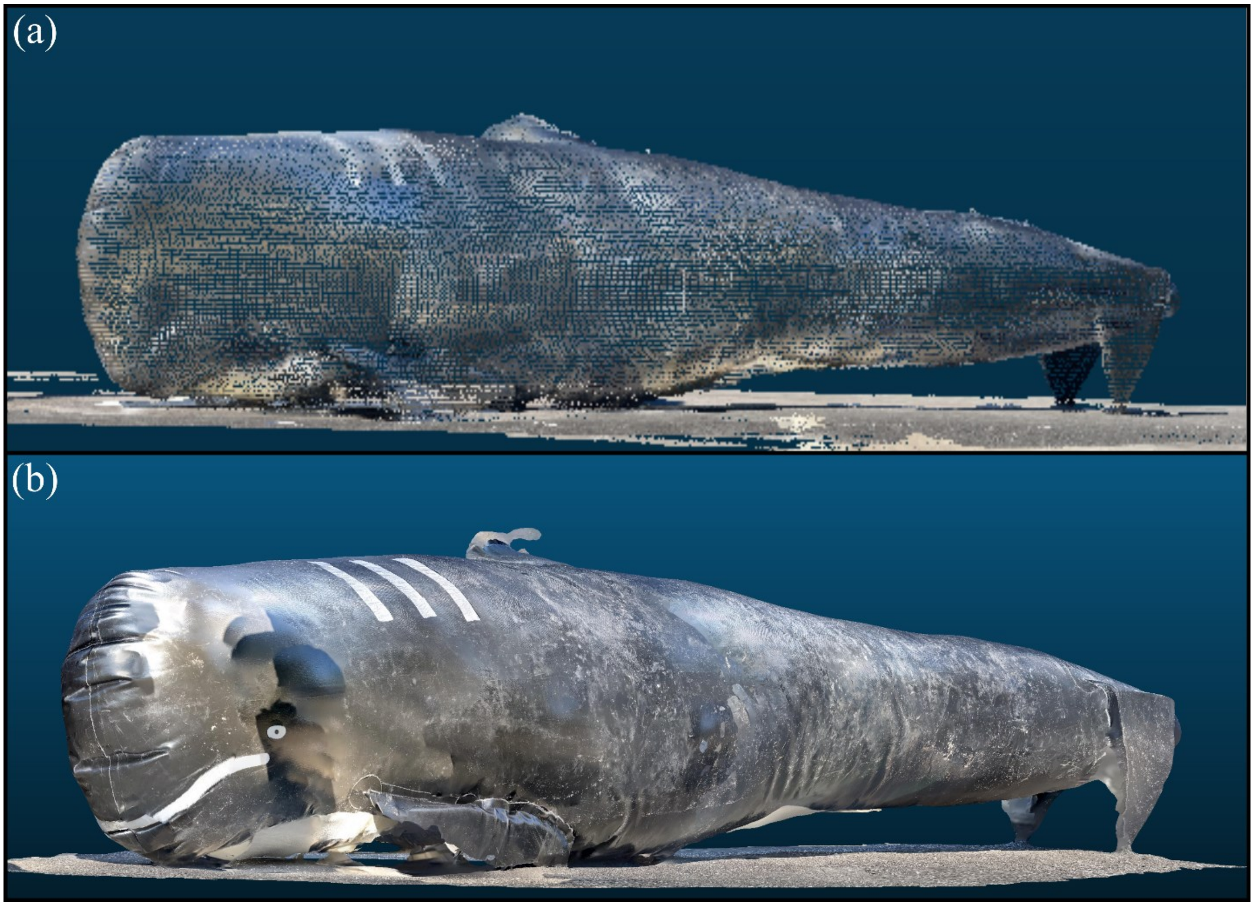

Figure 2: Point cloud representation of inflatable test whale collected from LiDAR (a), and the resultant 3D mesh model (b).

3.3.3 Marine Mammal Specimens Examined

Over the period of two years, twelve marine mammal specimens (ten species) were collected or examined for study, with a summarization of the stranding information and 3D data collection for each case in Table 1. The location of each specimen is shown in Figure 1. In addition to the specimens listed in Table 1, LiDAR and SfM data were also collected of an inflatable test whale (see section 3.3.3.1) in order to validate the process of data collection for real animals.

Table 1**:** Marine mammal specimens used to demonstrate 3D reconstruction capability.

Species	**Date Collected/Observed**	**Date Examined**	**Location**	**Age and Sex**	**Length (m)**	**Data Collected**
Grey Whale	August 2023	August 2023	Jarvis Inlet	Adult Female	12.30	Pre and post necropsy LiDAR
Grey Whale	June 2022	June 2022	Nootka Island	Adult Male	9.9	Pre and post necropsy LiDAR, UAV photogrammetry
Humpback Whale	May 2022	May 2022	Langara Island	Adult Female	12.2	Pre-necropsy LiDAR, UAV photogrammetry
Killer Whale	March 2024	March 2024	Zeballos	Adult Female	6.00	Pre-necropsy LiDAR
Risso's Dolphin	July 2023	August 2023	Daajing Giids	Juvenile Female	2.23	Pre-necropsy LiDAR
Striped Dolphin	August 2023	October 2023	Ucluelet	Adult Female	1.95	Comprehensive LiDAR including organ systems
Dall's Porpoise	May 2022	July 2023	Victoria	Adult Male	2.04	Comprehensive LiDAR including organ systems
Harbour Porpoise	May 2023	August 2023	Salt Spring Island	Adult Male	1.50	Comprehensive LiDAR including organ systems
Harbour Porpoise	July 2023	August 2023	Tsawwassen	Calf	0.83	Comprehensive LiDAR

						including organ systems
Sea Otter	March 2022	July 2023	Tofino	Subadult Male	1.14	Comprehensive LiDAR including organ systems
Northern Fur Seal	January 2021	July 2023	Port Hardy	Juvenile	0.80	Comprehensive LiDAR including organ systems
Harbour Seal	December 2023	January 2024	Vancouver	Calf	0.79	Comprehensive LiDAR including organ systems

3.3.3.1 Validation of Reference Measurements

In July 2022, 15 LiDAR datasets were collected of an inflatable pilot whale typically used for live stranding training (British Divers Marine Life Rescue, East Sussex, UK). These data were collected with ideal clear sky conditions at the DFO warehouse on Annacis Island, British Columbia. Multiple software settings were tested and scanning sequences were completed to determine what may work ideally in the field (see section 3.3.4). A 5.00-meter tape measure was set up as a ground reference to assess the accuracy of the reconstructed model. Three UAV flights to collect photogrammetry data were also performed (see section 3.3.5).

Standard photographs and morphometric measurements were collected for each stranding in accordance to normal marine mammal necropsy procedure which generally follows that of similar institutions such as that of the National Oceanic and Atmospheric Administration (NOAA) in the United States, and other stranding response protocols that are well established (Pugliares et al. 2007). This is done opportunistically with the maximum possible number of samples and measurements taken given the surrounding conditions and time limitations, resources, and personnel available for the postmortem exam.

3.3.3.2 Large Whale Specimens Collected

In May 2023, a 12.30-meter female grey whale (*Eschrichtius robustus*) and calf became trapped in a tidal lagoon at the end of Jarvis Inlet, an approximately two-hour boat ride from Port Hardy, B.C. Despite rescue efforts, only the calf was able to escape from the lagoon. The mother was found floating dead outside of the lagoon a few days after the final rescue efforts to free her in late August. The animal was presented in poor body and post-mortem condition due to emaciation from being trapped in the lagoon for four months. Four personnel were available to attend the necropsy where the animal was towed to a nearby inlet where a come along winch was used to move the animal as close as possible to shore at high tide. As the tide receded the animal became accessible to examiners where two 3D datasets of the animal were completed: one pre-necropsy, and one post-necropsy after the animal was sampled. Heavy rain during the postmortem examination precluded any UAV flights to collect photogrammetry data, however video was collected of the process of moving the whale to a location where a necropsy was feasible.

In June 2022, a 9.9-meter male grey whale (*Eschrichtius robustus*) presented stranded on the west side of Nootka Island. The animal was in fair to poor post-mortem condition (decomposition code 3.5 (Bogomolni et al. 2010)) and moderate body condition. The abdomen was moderately distended and firm. The Canadian Coast Guard (CCG) was able to bring three personnel to attend this necropsy via CCG helicopter. The animal was on shore at low tide allowing for examination during the half tidal cycle, which precluded any extended examination but allowed for a limited "windowed" approach, where a rectangular section of the abdomen is opened to allow access to some critical organs for examination. Two UAV flights (Supplementary Table 1) were completed to collect photogrammetry data and to take video of the pathologists sampling the animal. Two 3D datasets of the animal were completed: one pre-necropsy with the animal as it was stranded, and one post-necropsy after the animal was sampled.

In May 2022, a 12.2-meter female humpback whale (*Megaptera novaeangliae*) stranded on Langara Island, Haida Gwaii. The animal was in moderate body and fair post-mortem condition (decomposition code 3.5). The opportunity was available for three personnel to attend this remote necropsy, which consisted of a two-hour boat ride from the nearest settlement in Masset. The whale was floating in a narrow tidal gorge, precluding any meaningful necropsy but the decision was made to anchor the animal to shore as far up the inlet as possible at high tide. The following day at low tide the animal was on shore and the necropsy was completed during the half tidal cycle before the animal began to float again. Two UAV flights were completed with one to collect photogrammetry data and the other to take video of the pathologist sampling the animal. One 3D dataset of the animal post-necropsy was collected, which included stepping on the animal itself as the surrounding terrain was inaccessible. The animal's fluke and a portion of the tail was submerged during the examination, precluding that portion of the animal from being included in the 3D dataset.

3.3.3.3 Dolphin Specimens Collected

In March 2024, a 6.00-meter pregnant adult female and calf killer whale (*Orcinus orca*) became trapped in a lagoon, resulting in a live stranding event near Zeballos, B.C. Despite efforts to return the animal to the water, the adult female died later in the day. Multiple personnel were available to assist with this necropsy, with pre-necropsy 3D datasets being collected on both the adult and unborn fetus. Logistic and personnel challenges unfortunately precluded additional scans from being conducted.

In July 2023, a 2.23-meter juvenile Risso's dolphin (*Grampus griseus*) stranded on East Beach, Haida Gwaii. The animal was in poor body condition and very poor postmortem condition (decomposition code 4). The animal was subsequently frozen, and a necropsy was later conducted in August 2023 in Daajing Giids as part of a training course for community partners in marine mammal conservation. 3D datasets were collected of the animal pre-necropsy.

In August 2023, a 1.95-meter adult female striped dolphin (*Stenella coeruleoalba*) live stranded near Ucluelet, B.C. The animal was close to death when rescuers arrived and attempts to refloat the animal were unsuccessful. In October 2023, the animal had a full post-mortem exam at Annacis Island. This included collecting 3D datasets of the body pre and post necropsy, as well as organs and organ systems that were suitable for scanning.

3.3.3.4 Porpoise Specimens Collected

In May 2022 a 2.04-meter adult male Dall's porpoise (*Phocoenoides dalli*) was found floating dead near Victoria, B.C. The animal was found in moderate to poor body condition with larvae around the mouth and abdominal distention. The animal was frozen in Victoria and transported to Annacis Island for a full necropsy in July 2023. This included collecting 3D datasets of the body pre and post necropsy as well as suitable organs.

In May 2023 a 1.50-meter adult male harbour porpoise (*Phocoena phocoena*) was found stranded on Salt Spring Island, B.C in moderate body condition. The animal was frozen and stored at Annacis Island until it was possible to perform a full necropsy of the animal in August 2023. 3D datasets of the animal pre and post necropsy in addition to organ systems were collected.

In July 2023 a 0.83-metre harbour porpoise calf live stranded in Tsawwassen, B.C. Efforts were made to bring the animal to the Vancouver Aquarium's marine mammal rescue facility, but the animal died in transit. The animal was frozen at Annacis Island and a full necropsy was performed in August 2023. 3D datasets of the animal pre and post necropsy in addition to organ systems were collected.

3.3.3.5 Carnivore Specimens Collected

In January 2021 an 0.80-meter juvenile female northern fur seal (*Callorhinus ursinus*) was found stranded near Port Hardy, B.C. in poor post-mortem and fair body condition. The animal was frozen and transported to Annacis Island, where a full necropsy was performed in July 2023. 3D datasets of the animal pre and post necropsy in addition to organ systems were collected. In December 2023 a 0.79-meter harbour seal (*Phoca vitulina*) calf was abandoned in Vancouver. The animal was taken in by the Vancouver Aquarium's marine mammal rescue team but died in transit to the facility. The animal was frozen, and a full necropsy was conducted in January 2024 at Annacis Island. 3D datasets of the animal pre and post necropsy in addition to organ systems were collected. Lastly in March 2022 a 1.14-meter subadult male sea otter (*Enhydra lutris*) stranded near Tofino, B.C. in fair body and moderate postmortem condition. The animal was frozen and taken to Annacis Island for necropsy in July 2023. 3D datasets of the animal pre and post necropsy in addition to organ systems were collected.

3.3.4 LiDAR Data Acquisition and Processing

LiDAR data were collected using an iPhone 12 Pro (Apple, Cupertino, CA) using the free Scaniverse application (Niantic, San Francisco, CA). The LiDAR sensor is available on the Pro and Pro Max models of the iPhone 12 and later, in addition to iPad Pro models starting from 2020.

This was achieved by walking around the animal with the iPhone in hand, carefully covering the entire extent of the animal and ensuring to not exceed the adjustable LiDAR range (i.e., 0.3 meters – 5 meters) in distance from the animal while scanning. For large whales this took up to 10 minutes, where with the smaller marine mammals this process was completed in a maximum of 2-3 minutes.

The Scaniverse app collects both LiDAR and photographs from the phone's main camera. Processing through the application generates a realistic triangular 3D mesh as the primary output. The scanning systems on iOS device applications use a form of simultaneous localization and mapping (SLAM) which continuously tracks the sensor's position and orientation in three dimensions over time. SLAM relies on optical data overlaps, utilizing previously observed features to establish relative coordinates and maintain accurate image registration (Lehtola et al. 2021). Figure 3 displays the Scaniverse interface and an example workflow for marine mammal data collection and subsequent export capabilities using the Scaniverse application. Details on the processing within the application are provided in section 3.3.6**.**

3.3.5 Structure-from-Motion Photogrammetry Acquisition and Processing

For large whale necropsy conditions that allowed for collection of UAV photogrammetry, a Mavic Professional (Da-Jiang Innovations (DJI), Shenzhen, China) UAV was used. Data collection consisted of capturing photographs of the stranded whale and surrounding area. The UAV was flown manually as opposed to the widely used preprogrammed orthogonal flight path transects as no previous understanding of the stranding sites were available to create a detailed flight plan. During the manual flights the best effort was made to create orthogonal flight lines with high overlap (~ 80%). See Supplementary Table 1 for flight details. Pix4DMapper (Pix4D, Prilly, Switzerland) was used to implement the SfM-MVS workflow. The resultant 3D mesh output for these large whale cases were used primarily to provide additional context for the large whale strandings.

One important consideration in the creation of realistic models is the determination of scale. The LiDAR system measures distances accurately and therefore evaluates the appropriate scale of the models within Scaniverse without the need for input of a known reference measurement in the scene. In the case of UAV photogrammetry here, the geotagging of each image used to create the model provides this distance measurement within a scene that is required to produce accurate scale. For non-georeferenced images, a known reference measurement is required to add these scale constraints to the model.

3.3.6 Data Processing Workflow and Visualization

The marine mammal datasets acquired broadly follow two overall groups and use cases. The first is the application of 3D data collection in the instance of remote or inaccessible necropsies that benefit from the ease of use of these sensors and software. This is the case where regional partners are most likely to use this technology, to collect 3D reconstruction information in the field where the animal is too large (for large whales) or too remote to be transported for a full postmortem examination or for pathologists to be transported to the area. Here the ideal case is for the mesh output of the Scaniverse workflow from a handheld device (Figure 3) being an acceptable reconstruction without postprocessing. For large whales the use of UAV photogrammetry was implemented, when possible, to provide more environmental context and auxiliary data to the handheld LiDAR collection alone although this would only be done if appropriate personnel and equipment was available. The second case is more exploratory in using this technology in the context of animals that stranded or were transported to resourced areas where a full necropsy can be conducted, with all organ systems sampled and a 3D dataset collected. Both kinds of data collection followed a similar workflow, which is detailed in Figure 4.

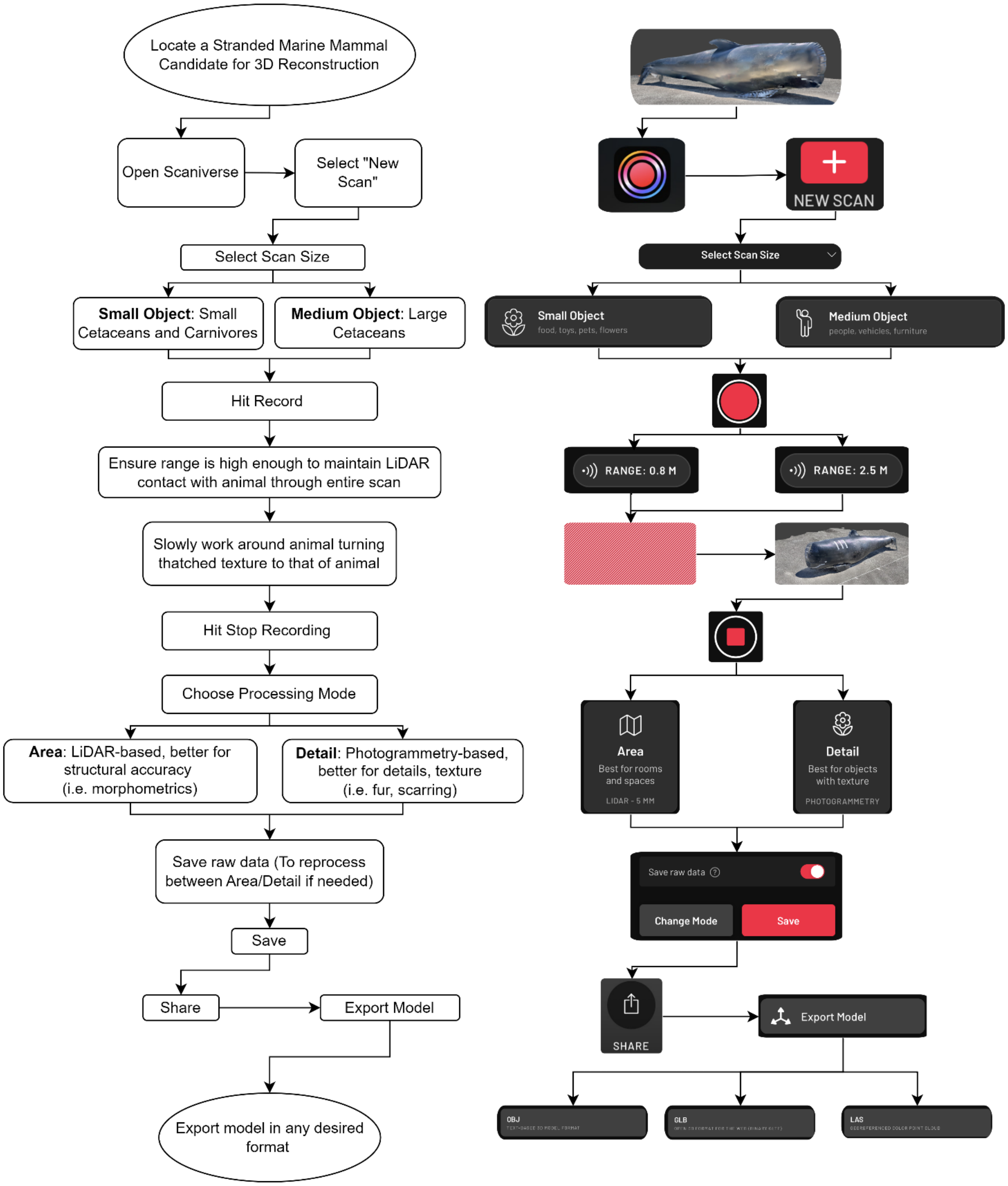

Figure 3: Workflow using the Scaniverse application for the purpose of collecting marine mammal scans. On the left is a written explanation of the processing steps. On the right is the same steps in pictorial form as would be viewed in the Scaniverse application.

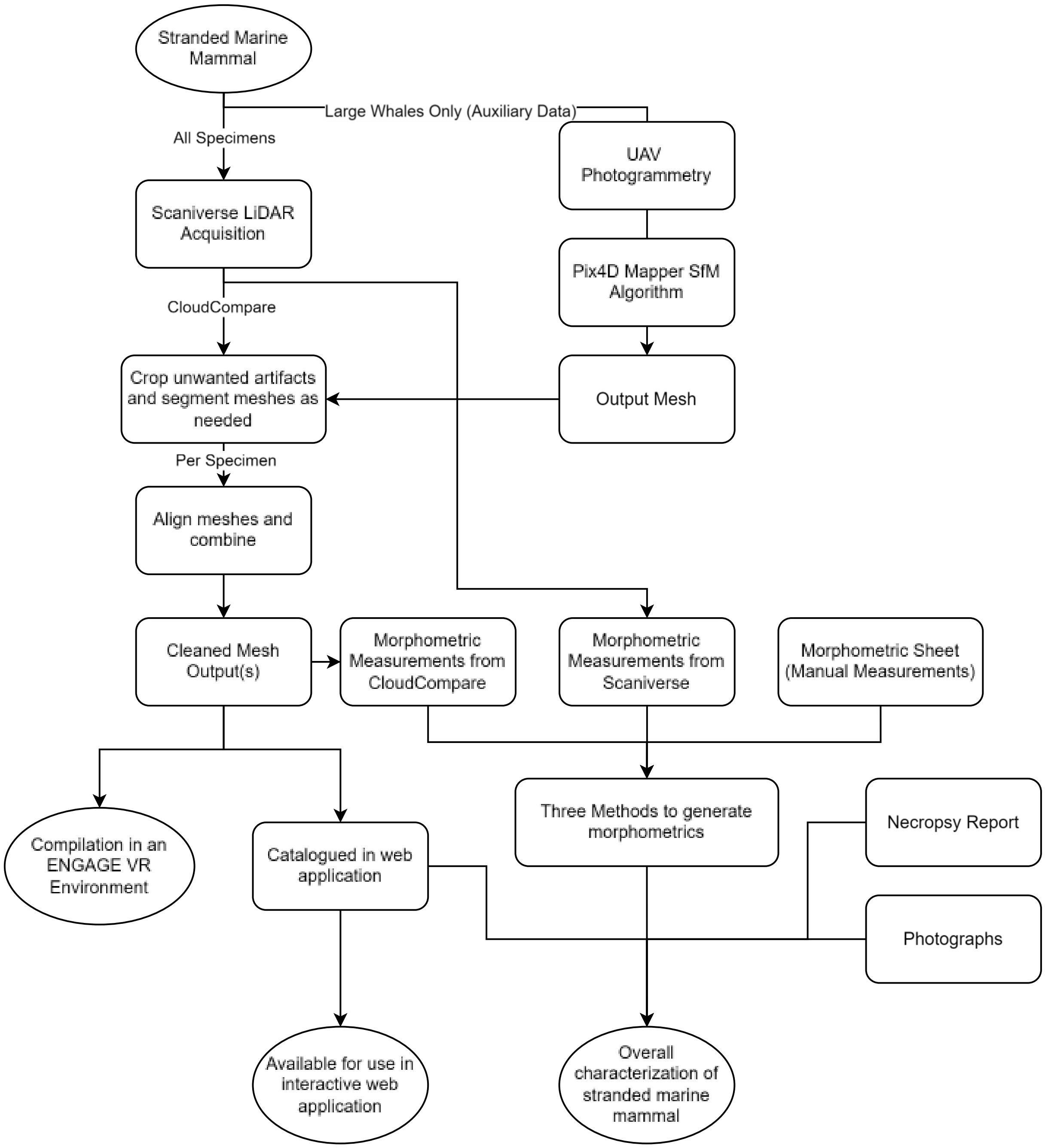

Figure 4: General workflow for all marine mammal scans collected.

Following processing and inspection of the resulting model, the meshes were exported to both .obj (geometry definition file format) and .las (RGB 3-dimensional point cloud data) files from the Scaniverse application to further refine in post-processing.

Post-processing the Scaniverse output was done using the free open-source 3D point cloud and mesh processing software CloudCompare Version 2.13. The two main tools used were to crop and segment data as well as merge multiple scans of the same specimen. For the cases where UAV photogrammetry data was taken, Pix4DMapper Version 4.8 was used to process the UAV data into meshes that could then be combined with the Scaniverse mesh outputs in CloudCompare.

3.3.7 Morphometric Measurements

For cetaceans, the key morphometric quantities of interest during postmortem exams (and in general) are straight-line length (from tip of upper jaw), appendage lengths, girth, and blubber thickness. There are 12 straight-line length measurements, 4 appendage measurements, 4 girth measurements, 2 throat pleat measurements (if applicable) and 9 blubber measurements typically taken for complete morphometric characterization during postmortem exams (Supplementary Figure 1). For carnivores, morphometric assessments typically include straight-line and curvilinear length (tip of snout to tip of tail), 2 appendage measurements, 3 girth measurements and 3 blubber measurements (if applicable).

For each stranding, digital morphometric measurements (Euclidean distance) were made in Scaniverse using a straight-line length or using a polyline measurement for curvilinear measurements of length or girth. For all specimens the multiple digital measurements are compared against the manually collected morphometric sheet as a proof of concept that these scans can be used to adequately describe the morphometry of the animal in various necropsy conditions, over species of varied size and form. One important consideration in this work is there is no way to verify the accuracy of the manual measurements, experienced personnel were primarily tasked with these measurements but there is an unquantifiable source of error intrinsic to manual measurements that must be mentioned, especially if these measurements are done in time constrained situations and difficult environments.

3.3.8 Web Visualization and Virtual Reality

The generated 3D reconstructions of the specimens collected, and auxiliary information was stored in an accessible web platform for visualization and further investigation. The exported .obj meshes were uploaded to a server using the open-source 3D Heritage Online Presenter (3DHOP) framework (Visual Computing Laboratory - ISTI-CNR, Pisa, Italy) for interactive web presentations of high-resolution 3D models.

Uploading and incorporating the models into virtual reality was implemented using the ENGAGE VR (Immersive VR Education, Ireland) platform. This platform allows for uploading of .glb files, which unlike .obj provides a packaged single file containing all textures and shaders of a model. Within the platform, a presentation was created to view the output of these scans in lifelike sizes, providing an opportunity to view what happens during a necropsy through virtual reality for multiple species types.

3.4 Results

3.4.1 Validation of Model Geometry with Inflatable Whale

The 5.00-meter measuring tape next to the inflatable whale was used as a reference and measured over 15 scan iterations within the Scaniverse app to be 4.99 ± 0.03 meters. This demonstrates that measurements achieved through reconstructions have approximately a 1% uncertainty, barring any obvious distortions, errors in scanning, or errors in using the measurement tool within Scaniverse. These three error sources must be closely monitored to obtain accurate measurements from a 3D reconstruction. An example of the reference measurement as well as three example morphometric measurements of the inflatable whale including dorsal fin height, flipper anterior length and half tail fluke width are shown in Figure 5. The proportions and overall shape of the inflatable whale are not entirely comparable to a real animal, however the reconstruction can clearly distinguish the structure of the fins, as well as the body shape.

During testing it was found that for most cases, using ‘detail mode’ (photogrammetry) for processing within Scaniverse can result in large artifacts (e.g., two tails) especially for the large whales while in ‘area mode’ the structural data provided from LiDAR allows for the best representation of true form in all cases. For smaller animals and organ systems, detail mode was able to provide better representations of texture, which is important for diagnostics.

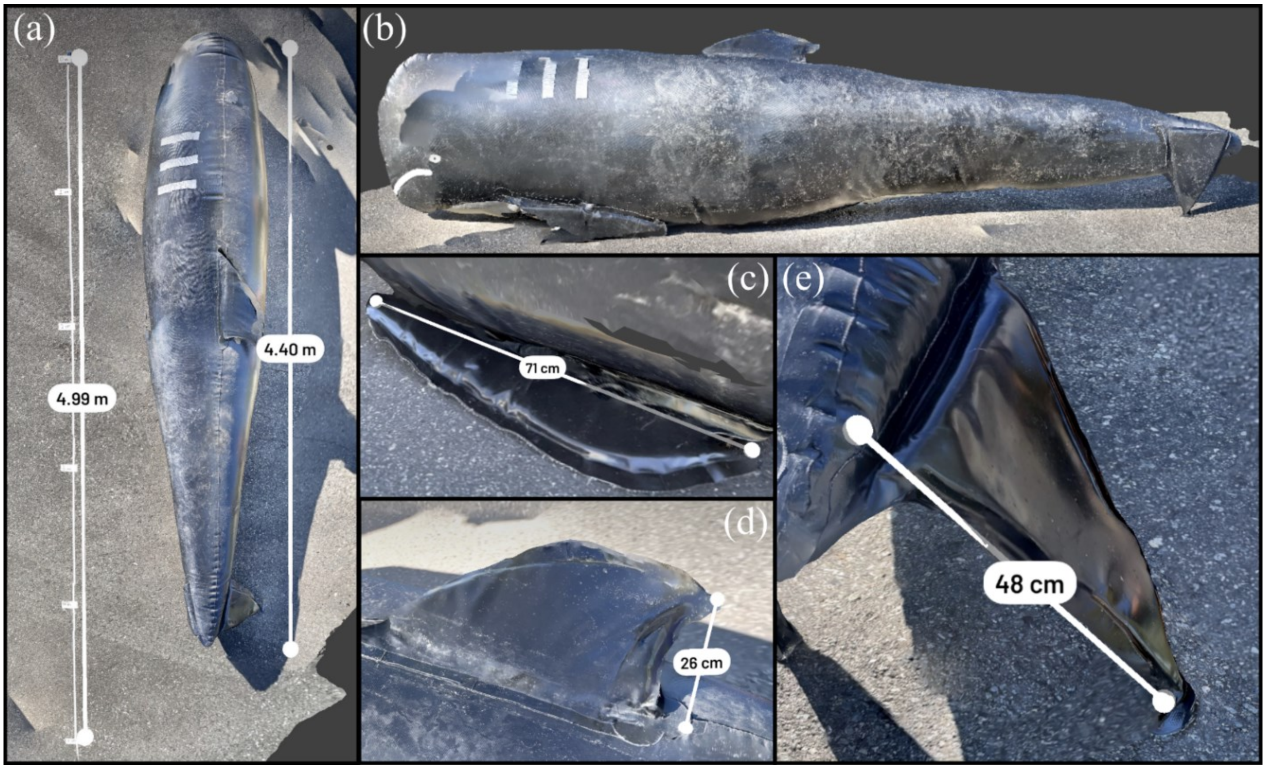

Figure 5: 3D model (generated from Scaniverse) of the inflatable pilot whale used for live stranding training. (a) Reference assessment against known length (5.00-meters), and straight-line measurement of the whale at 4.40-meters. (b) Side profile of whale for reference and display shape of inflatable. (c) Simulated measurement of anterior flipper length. (d) Simulated measurement of dorsal fin height. (e) Simulated measurement of (half) tail fluke width.

3.4.2 Large Whales

The grey whale that was stranded after being trapped in a lagoon for four months was severely emaciated. Pre-necropsy morphometrics via 3D data in addition to a post-necropsy representation of the animal that displays several internal organs are shown in Figure 6. With the entirety of the animal out of the water at the time of examination, an accurate straightline length can be determined directly from Scaniverse. The measured straightline length (12.35-meters) was < 1% different from the value measured manually in the field (12.30-meters). The axillary girth, doubled at half was different by a factor of 1.4%. This can partially be explained by the discrepancy when using a polyline measurement in Scaniverse as opposed to a tape measure that can adequately lie flush to the animal. Here polyline measurements at less than 10-centimeters between vertices were used. The tail fluke measurement had a discrepancy of 0.4-metres or approximately 10% if using a straightline fluke length, reduced to 2% using a 6-part polyline measurement. This is an important consideration in this case and other strandings where the animal's fluke rests in a curved shape, meaning a straightline length as shown in Figure 6 (b) will underestimate this value if the morphometric measurement was done with a tape measurer flush to the fluke length as was done here. A 13% discrepancy can be seen with the anterior flipper measurement as a small portion of the pectoral was still underwater, another consideration if taking morphometrics from 3D data. The animal was found to have marked reductions in subcutaneous and visceral adipose stores and the animal was poorly muscled, in addition to a salmon discolouration of the blubber. This emaciation manifests in a "peanut head" appearance which is readily apparent in the 3D representation of the animal Figure 6 (d) and (e). The salmon discoloration of the blubber has been observed in other grey whales and it is difficult to infer whether this may be related to dietary changes (abundant carotenoids), endogenous pigment production or some other process. The animal also had generalized sloughing of the skin.

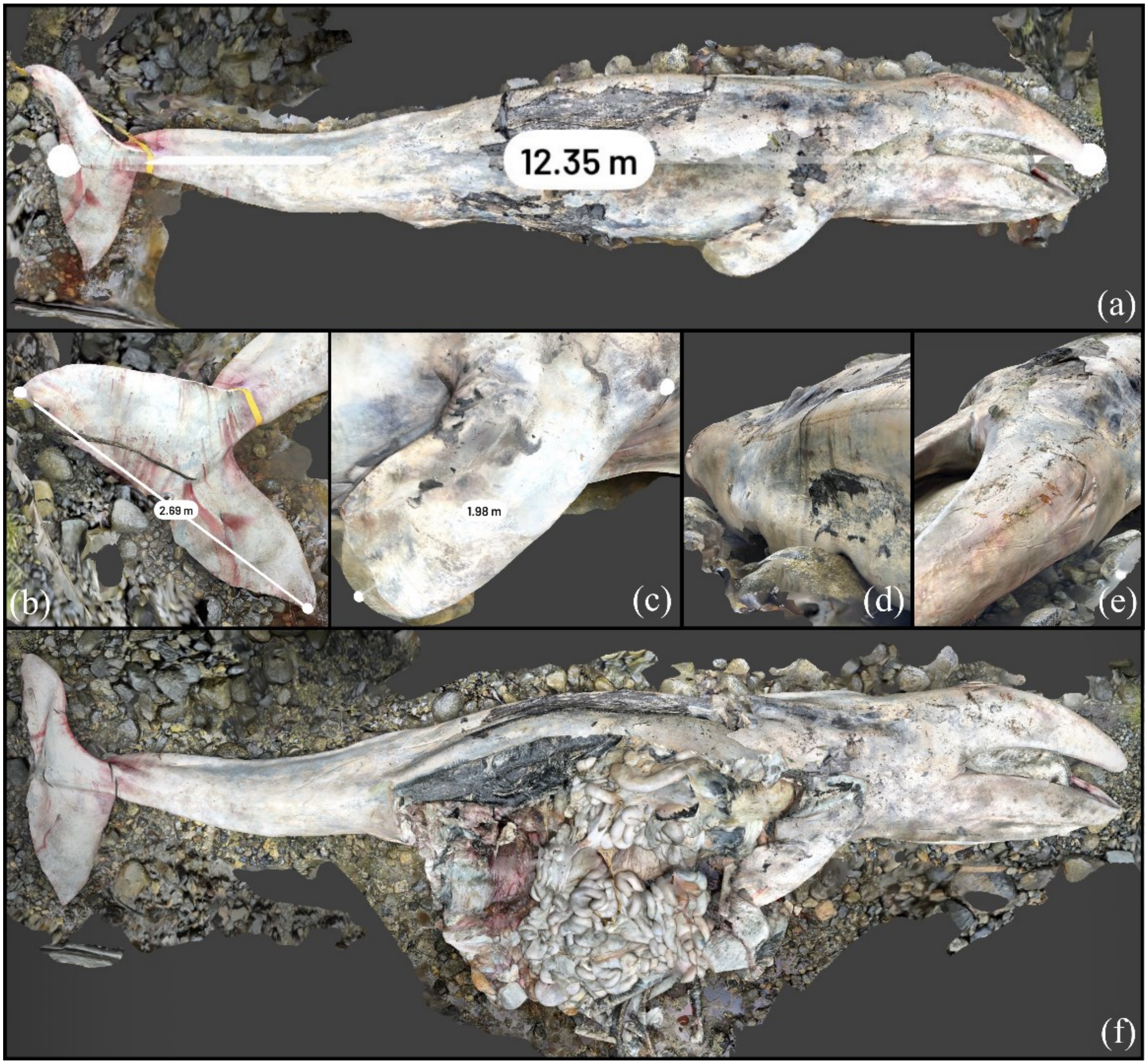

Figure 6: 3D reconstruction of grey whale stranded near Jarvis Inlet after being trapped in a tidal lagoon for 4 months. (a) Straightline length calculated in Scaniverse. (b) Tail fluke measurement (underestimated if straightline length used). (c) Anterior flipper measurement, underestimating by 10% due to water cutoff. (d) From mid dorsal looking towards head and (e) front dorsal towards tail obvious “peanut head” as a result of extreme emaciation before death captured in the 3D reconstruction.

The grey whale stranded on Nootka island was considerably bloated and upon incision of the abdominal musculature there was marked deflation of the abdominal cavity. Figure 7 displays the

UAV 3D model output collected during this necropsy and 3D dataset collection conducted pre and post necropsy. The animal's total length was estimated at 9.9-meters from nadir UAV photographs, as the fluke of the animal was still submerged at low tide. This includes a correcting factor given the estimated 20° decline of the tail in the water. An anterior flipper measurement from the prenecropsy LiDAR in Scaniverse was collected to be 1.44-meters, a difference of 2% from the manual measurement of 1.47-meters. In the post necropsy scan it is apparent that upon incision a moderate amount of brown-red fluid drained from the animal as a result of the poor postmortem condition. The small intestines and colon were taut, and gas inflated, well characterized by the 3D reconstruction. Of note, the post-necropsy dataset does not characterize the head well. This is due to the LiDAR collection losing contact (out of range) halfway through the scan. The processing software cannot register where the data is collected from and must re-register from a new reference point. This resulted in this scan essentially having two lower halves of the animal separated by approximately 15°, which was rectified in postprocessing via segmentation of the scan at the point of deviation and subsequent re-registration through the use of equivalent reference points that are present in both segments. Despite the visual success shown in Figure 7 (d), this scan would not be suitable for use in morphometric analysis, only a visual assessment.

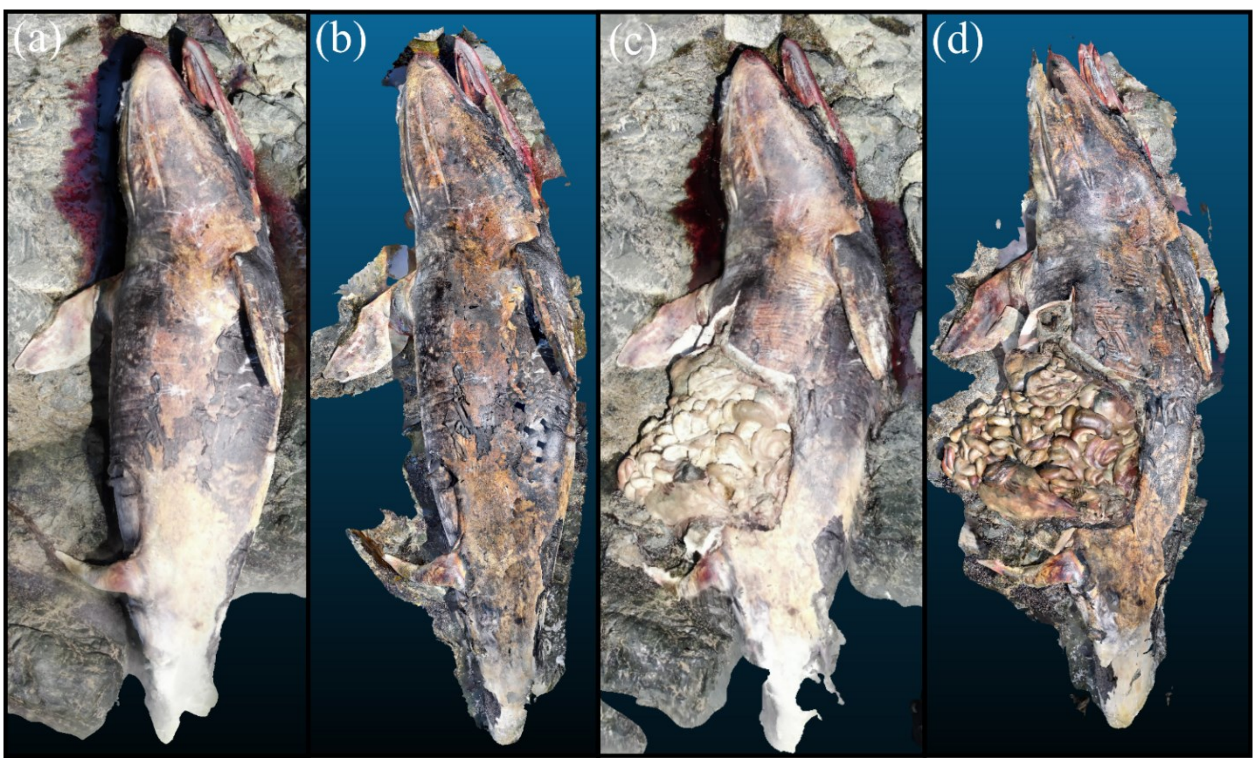

Figure 7: 3D reconstruction of grey whale stranded on Nootka Island. (a) UAV photogrammetry output pre necropsy. (b) LiDAR output pre necropsy. (c) UAV photogrammetry output post necropsy. (d) LiDAR output post necropsy.

The stranded humpback whale in Haida Gwaii is shown with the UAV photogrammetry and 3D dataset results in Figure 8. The UAV photogrammetry shown pre and post necropsy especially outlines the steep tidal gorge the animal was in that precluded much of normal necropsy procedure. LiDAR data only being collected post-necropsy shows that on incision of the musculature, multiple tense loops of gas inflated small intestine were extruded. The flukes and distal third of the peduncle were submerged, precluding safe access. The oral cavity as well was only partially exposed from the water. Morphometric measurements were collected solely through assessing the 3D reconstruction and UAV images due to the difficult environment, although some measurements such as that of the anterior flippers could be verified via manual measurements. With some areas of the animal inaccessible to the scanner being underwater, the straight-line length could not be calculated directly in Scaniverse. The animal's length was estimated at 12.2-meters from these scans and associated photographs in postprocessing. Other morphometrics were collected from Scaniverse including an example anterior flipper measurement at 2.47-meters, consistent with the manual measurement (2.50-meters) to within 2%. The 3D reconstruction adequately displays the animal's moderate body condition, prominent mammae and open abdominal cavity, including a moderate amount of ingesta primarily consisting of herring bones.

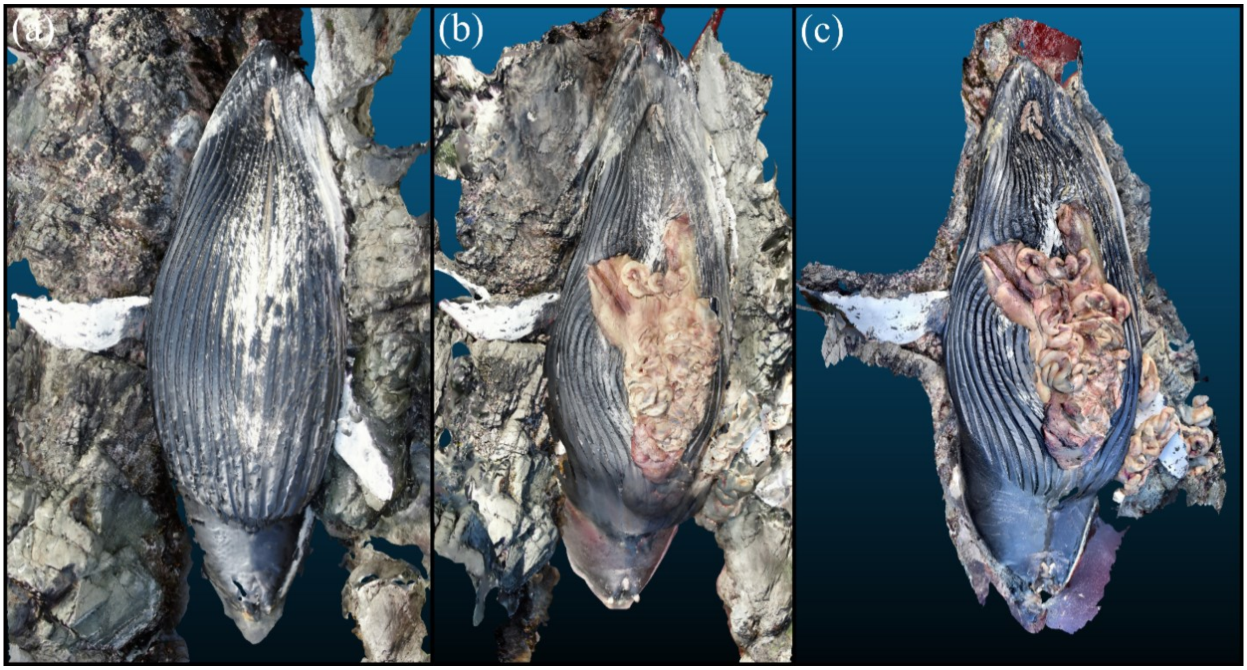

Figure 8: 3D reconstruction of humpback whale in Haida Gwaii. (a) UAV photogrammetry output pre necropsy. (b) UAV photogrammetry output post necropsy. (c) LiDAR output post necropsy.

3.4.3 Dolphins and Porpoises

Stranded killer whales are rare in B.C. relative to the large whales, providing a unique opportunity to showcase 3D reconstructions of this species. This is especially true for this specimen being in this good of condition due to being live stranded. Figure 9 displays the pre-necropsy scan of the killer whale as well as the unborn fetus that was present. Extremely wet conditions caused specular anomalies of the scanner operator and other surrounding areas being present on the surface of the whale in the 3D reconstruction. This did not impact the LiDAR information obtained from the scan (and thus ability to collect morphometrics). The straightline length is measured at 6.02-meters with 6.00-meters in the field. The straightline length of the fetus was measured to within 1% of the field morphometric measurement, with the 1.50-meter measurement in Figure 9 (e) comparable to the 1.53-meters measured in the field.

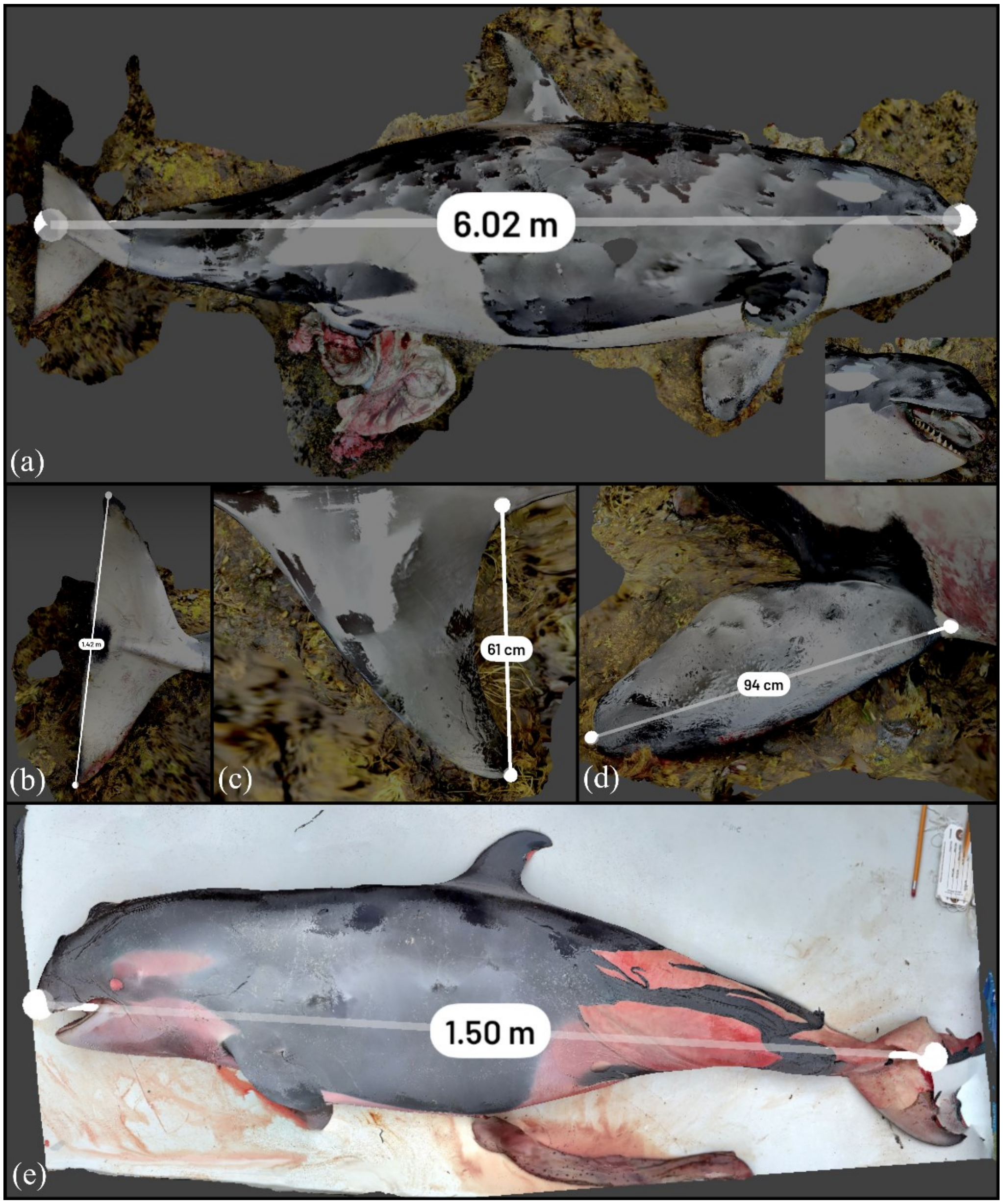

Figure 9: 3D reconstruction of killer whale stranded near Zeballos. (a) Straightline length calculated in Scaniverse. (b) Tail fluke measurement (underestimated if straightline length used). (c) Dorsal fin measurement (d) Anterior flipper measurement (e) Unborn fetus removed from the whale.

The Risso's dolphin specimen was found with extensive scavenging and poor postmortem condition, with extensive sloughing of the skin. The animal was measured at 2.21-meters in Scaniverse compared to 2.23-meters during the necropsy with a difference less than 1%. The pre-necropsy scan of the animal is shown in Figure 10. The suboptimal nutrition of this animal coupled with the lack of ingesta and blubber atrophy found during the necropsy are consistent with a negative energy balance would have been severe enough to cause the loss of this animal. There were no other apparent internal or external lesions.

Figure 10: 3D reconstruction of a Risso's dolphin with necropsy conducted as part of a training exercise with community partners. (a) Measurement of straightline length of the animal. (b) Animal laying on left side. (c) Animal laying on right side.

The live stranded striped dolphin that was euthanized is shown through its 3D reconstruction in Figure 11. The animal had superficial abrasions on the leading edge of the dorsal fin and edges of the tail flukes, possibly as a result of the live stranding event. The straight-line length of the animal was measured by Scaniverse at 1.91-meters, with the field measurement of 1.95-meters which is approximately a 2% discrepancy. This animal and the rest shown in this work were candidates for a full necropsy and thus all applicable tissues were scanned as was logistically feasible. The following strandings with full necropsies were less time and resource constrained and allowed for more focus towards a complete visualization of the stranded animal and associated internal anatomy. This allows for revisiting to the stranded animal as a 3D dataset to compare against different specimens or measure/visually assess areas again, including that of organ systems. The sequential removal of all tissues and organs during the full necropsy is displayed for a select few organs. The condition and structure of the organs and stomach, pluck including goosebeak and kidney captured well by the scan and are displayed for example. There were no significant lesions in the adipose tissue, peripheral vasculature, penis, urinary bladder, trachea, kidney, thyroid gland, adrenal gland, diaphragm, or liver.

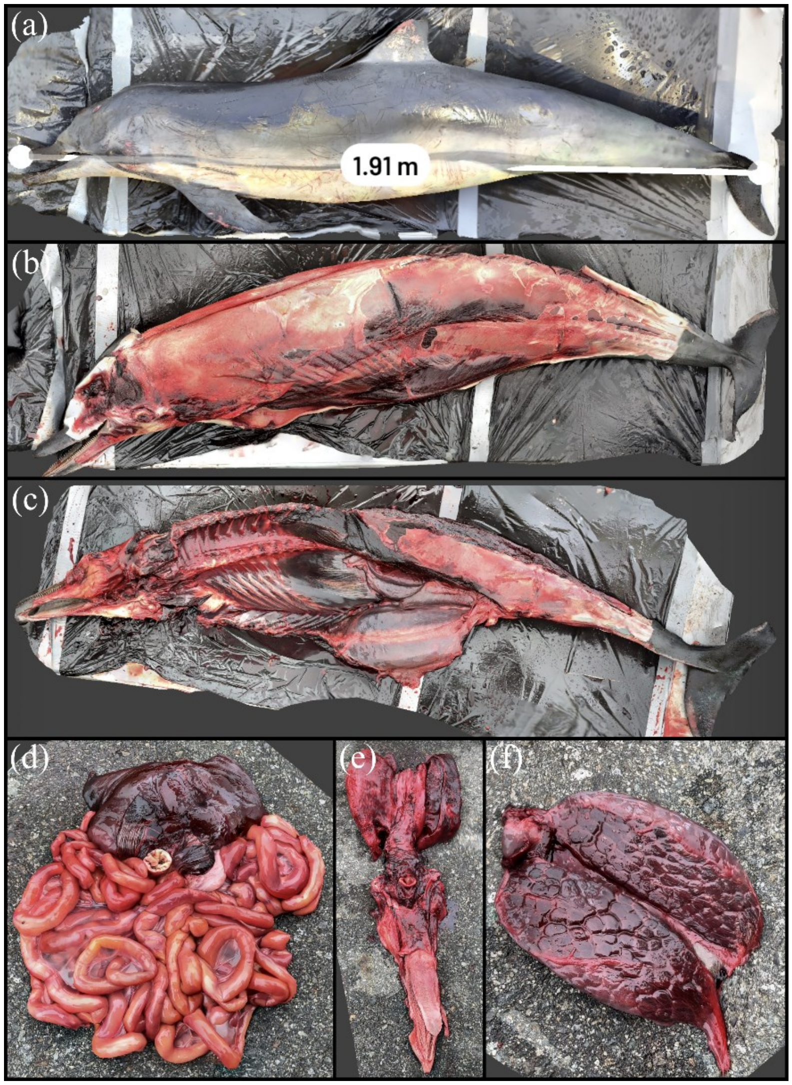

Figure 11: 3D reconstruction of a striped dolphin that live stranded in Ucluelet and was euthanized. (a) Measurement of straightline length of the animal. (b) Removal of external blubber layer. (c) Carcass with organ systems removed. (d) Digestive system. (e) Pluck including goosebeak. (f) Reniculate (lobed) kidney seen in marine mammals.

The stranded Dall's porpoise is shown via its reconstruction in Figure 12. The animal was measured to be 1.97-meters straightline length by Scaniverse, a difference of 3.5% from the manual measurement of 2.04-meters. The animal had reduced subcutaneous and visceral adipose stores, and the animal was fairly muscled. There were no apparent internal or external lesions that would have contributed to the loss of this animal. All organs were sampled with select scans of organ systems shown in Figure 12.

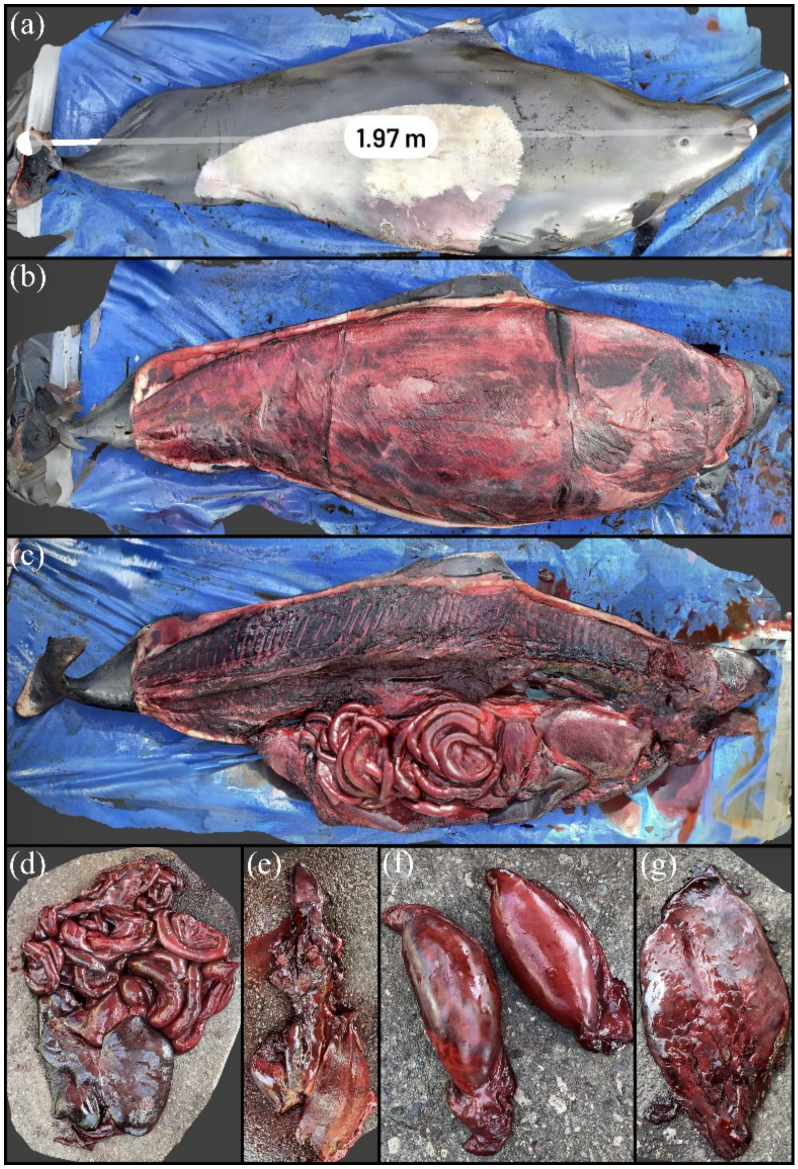

Figure 12: 3D reconstruction of a Dall's porpoise. (a) Measurement of straightline length of the animal. (b) Removal of external blubber layer. (c) Carcass with organ systems visible. (d) Digestive system. (e) Pluck including goosebeak. (f) Testes. (g) Reniculate (lobed) kidney seen in marine mammals.

Two harbour porpoise reconstructions are displayed in Figure 13. The adult was moderately fleshed with possible otisis interna. Incised cutaneous wounds are visible on this animal and suggestive of a possible vessel strike interaction. These wounds are visible on the scan and can be analyzed later using various characteristics of the injury (Byard et al. 2012). The animal was measured to have a straight-line length of 1.46-meters, within 3% of the manual measurement of

1.50-meters. All organs were sampled with select organ systems shown in Figure 12 (a-g). The harbour porpoise calf was in good condition with no apparent internal or external measurements. The animal was measured at a straightline length of 0.81-meters, within 2.5% of the manual measurement of 0.83-meters. Selected scans of the calf's overall body condition and organ systems are shown in Figure 13 (A-E).

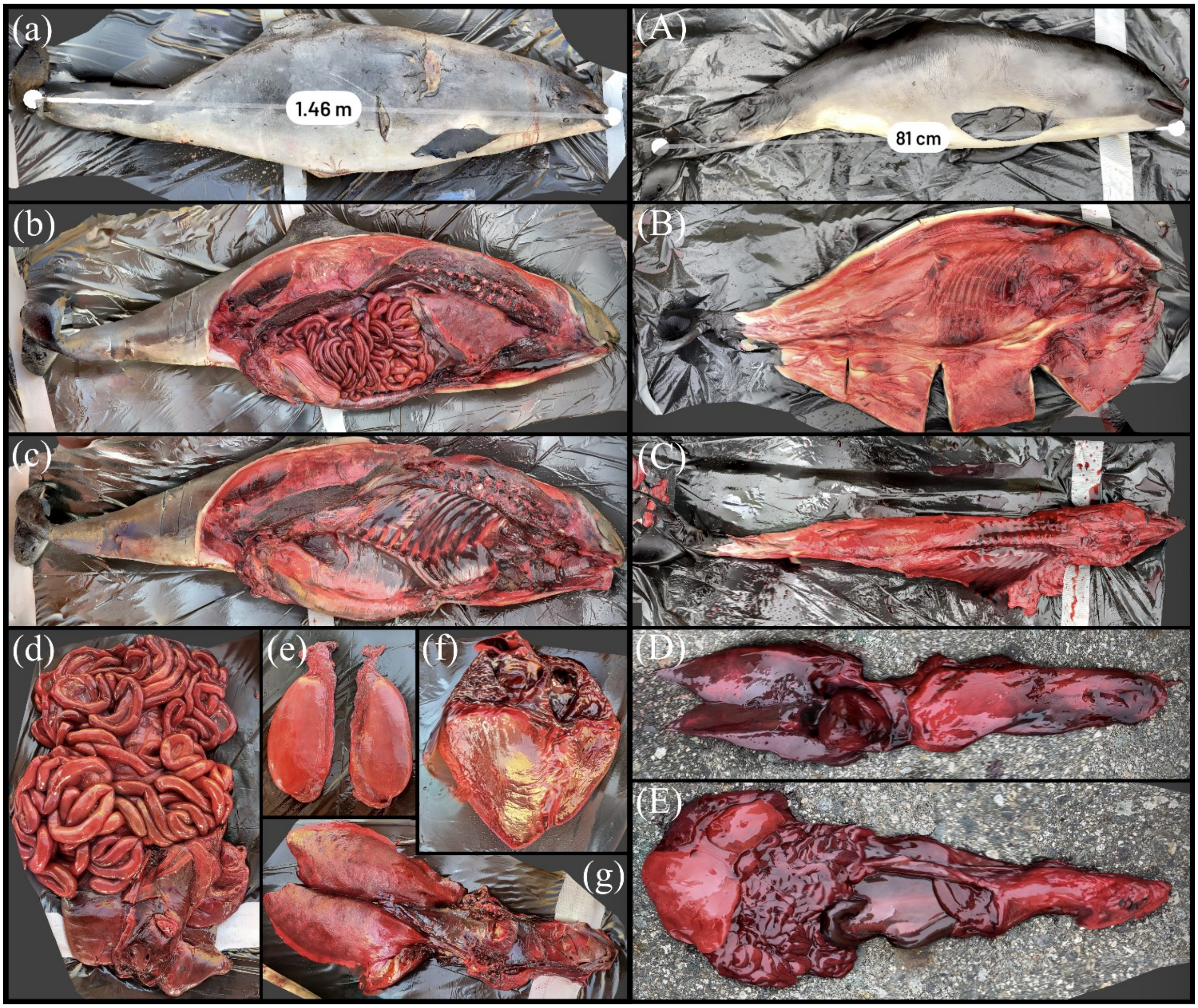

Figure 13: 3D reconstruction of an adult and calf harbour porpoise. (a) Measurement of straightline length of the adult harbour porpoise. (b) Carcass with organ systems visible. (c) Carcass with organ systems removed. (d) Digestive system. (e) Testes. (f) Heart. (g) Pluck including gooseback. (A)

Measurement of straightline length of harbour porpoise calf. (B) Carcass with blubber flensed. (C) Carcass with organ systems removed. (D) Pluck. (E) Digestive system.

3.4.4 Sea Otter, Northern Fur Seal, and Harbour Seal

All carnivore full-body reconstructions are displayed in Figure 14. The use of “detail” mode in Scaniverse allowed for improved resolution on the texture of the fur seen in some of the scans. The sea otter was in a state of advanced autolysis, with a pendulous fluid filled abdomen. Clearly visible in the reconstruction is the moderately distended abdomen, fluctuant with a prominent fluid line on ballottement as in Figure 14 (a). The straight-line length of the animal was measured to be 1.09-meters using the reconstruction, a difference of 4.5% from the manual measurement during the examination of 1.14-meters The subcutis is a dull pale green brown and tacky, and the liver is moderately enlarged. Oysters in the stomach contents can be viewed in a scan of the digestive system, along with scans of various organs presented in the web application (Supplementary Table 2). Unfortunately, postmortem change hampered a gross examination of the animal although the suspected cause of death is trauma to the head. The northern fur seal specimen was also in a state of advanced autolysis, although was fairly fleshed Figure 14 (A). There is mild swelling of the head and vulva and the lungs are mottled pale to dark red. The animal was measured at 0.77-meters, approximately a 4% difference from that of the manual measurement at 0.80-meters. The harbour seal pup is presented in Figure 14 (α) and is measured through the reconstruction as 0.78-meters at a difference of approximately 1% from the manual morphometrics measurement of 0.79-meters.

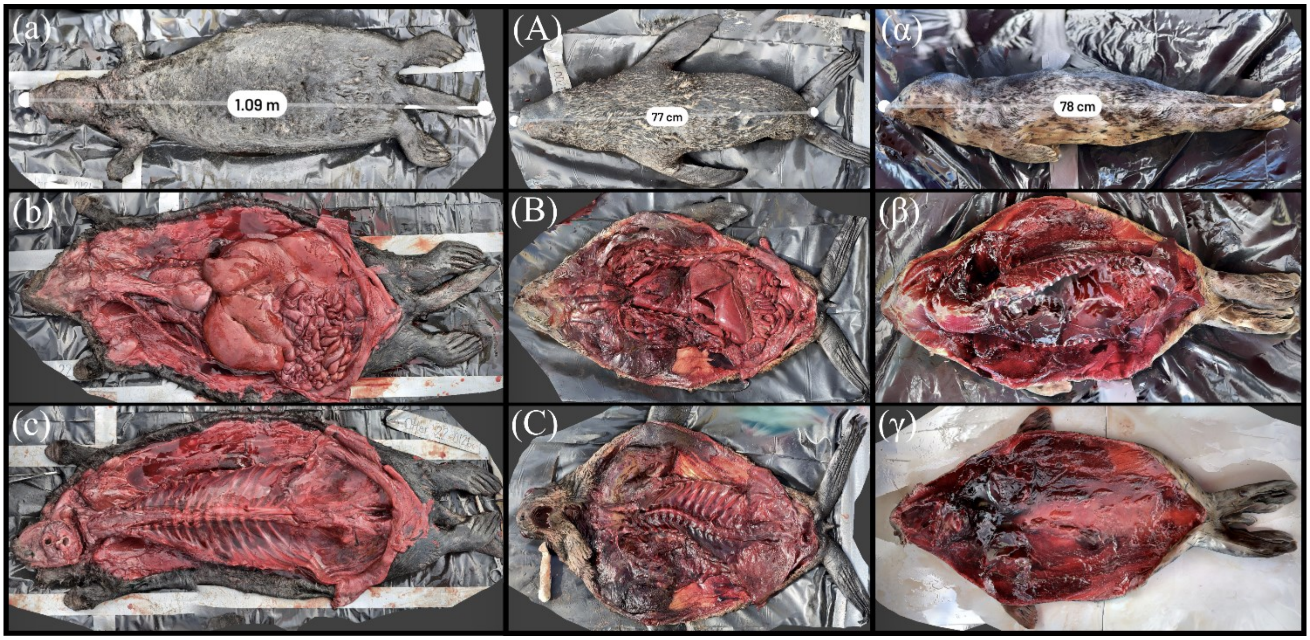

Figure 14: 3D reconstruction of an adult sea otter, juvenile fur seal and harbour seal pup. (a) Measurement of straight-line length of adult sea otter (b) Sea otter carcass with organ systems visible. (c) Sea otter carcass with organ systems removed. (A) Measurement of straight-line length of the juvenile fur seal. (B) Fur seal carcass with organ systems visible. (C) Fur seal carcass with organ systems removed. (α) Measurement of straight-line length of harbour seal pup. (β) Harbour seal carcass with organ systems visible. (γ) Harbour seal carcass with organ systems removed.

A summary of each specimen and associated measurement types, manual and model morphometrics and the percentage difference between the two is compiled in Table 2.

Table 2**:** Morphometric measurements of each specimen achieved manually and through measurement of the models.

Species	**Measurement Type**	**Manual Morphometric Measurement (m)**	**Model Morphometric Measurement (m)**	**Percentage Difference (%)**
Inflatable Whale	Straightline Length	4.41	4.40	0.23
	Anterior Flipper Length	0.72	0.71	1.40

	Dorsal Fin Height	0.27	0.26	3.77
	Tail Fluke Width (Half)	0.50	0.48	4.08
Grey Whale (Tsibass)	Straightline Length	12.30	12.35	0.41
	Axillary Girth (Doubled at Half)	5.64	5.60	0.71
	Tail Fluke Width	3.17	3.10	2.23
	Anterior Flipper Length	2.27	1.98	13.65
Grey Whale (Nootka)	Anterior Flipper Length	1.47	1.44	2.06
Humpback Whale	Anterior Flipper Length	2.50	2.47	1.21
Killer Whale	Straightline Length	6.00	6.02	0.33
	Tail Fluke Width	1.44	1.42	1.40
	Dorsal Fin Height	0.63	0.61	3.23
	Anterior Flipper Length	0.95	0.94	1.06
Killer Whale Fetus	Straightline Length	1.53	1.50	1.98
Risso’s Dolphin	Straightline Length	2.23	2.21	0.90
Striped Dolphin	Straightline Length	1.95	1.91	2.07

Dall's Porpoise	Straightline Length	2.04	1.97	3.49
Harbour Porpoise (Adult)	Straightline Length	1.50	1.46	2.70
Harbour Porpoise (Calf)	Straightline Length	0.83	0.81	2.44
Sea Otter	Straightline Length	1.14	1.09	4.48
Northern Fur Seal	Straightline Length	0.80	0.77	3.82
Harbour Seal	Straightline Length	0.79	0.78	1.27

3.4.5 Web Application and Virtual Reality

All the scans presented here in addition to those of other organ systems or stages of the necropsy are hosted according to Supplementary Table 2. Here the scans can be visualized, explored, and zoomed in to, as is the major advantage of 3D data versus a series of photographs. Further strandings where LiDAR or photogrammetry data are collected will continue to be added.

The virtual reality implementation of these scans was achieved through a short presentation in ENGAGE VR which highlights the importance of marine mammal necropsies, the possibility of virtual reality in improving the science and education of necropsies. The users within the virtual reality environment are able to walk around and experience several necropsies at close-to life size while a video of the stranding response and pathologists dissecting the whale is displayed above. The application provides a unique sense of the scale of necropsies, especially large whales to those that have never witnessed them in this context. An example screenshot of navigating the virtual reality environment is shown in Figure 15.

Figure 15: Navigation and example of the VR environment where students can investigate what conditions are like during a marine mammal necropsy. (a) The humpback whale shown in VR with the video outlining the necropsy playing above. (b) The grey whale from Nootka Island relative to a person navigating the VR environment.

3.5 Discussion

While all marine mammal 3D datasets were visually reconstructed well in the field, challenges such as water immersion affecting straight-line measurements for large whales were noted (Figures 6 and 7), prompting the need for complementary data integration methods like UAV photographs for large whale strandings for accurate measurements. Polyline measurements were utilized for curvilinear metrics such as girth or flukes that rested curved and showed good agreement to manual measurements (Figure 6). Specific organ system scans for smaller specimens including the striped dolphin, porpoises, and carnivores facilitated unique data collection opportunities, enhancing documentation and the ability to revisit interpretation of necropsy results, particularly concerning internal and external lesions (e.g., previous sign of vessel strike interaction in Figure 12).

The integration of 3D reconstruction technology into necropsy procedures offers several benefits that were conducted at no reduction in capacity to perform thorough postmortem examinations in the cases shown. This is despite the fact many of the remote necropsies were conducted by only 3-4 personnel. This technology enables the rapid collection of comprehensive data beyond what is achievable through photographs and morphometric data sheets alone. The detailed anatomical information obtained from 3D data facilitates more accurate assessments of causes of mortality and pathology when the physical specimen is not accessible, while also serving as datasets for morphometric analysis and virtual reconstructions. 3D reconstruction technology enables researchers to visualize and analyze remotely stranded specimens in ways that were previously impossible, opening new avenues for research and education. This enhanced documentation of a specimen's anatomy is useful in creating unique additions to permanent records of necropsy findings and simplifying data sharing with other researchers or regions for collaborative analyses. These 3D reconstructions can also be easily overlayed and compared between multiple specimens, enabling the identification of patterns, variations, and anomalies across different individuals or species. Where access to specialized equipment and facilities may be limited, handheld devices equipped with LiDAR sensors such as that of current iPhone models offer a cost-effective and portable solution for conducting necropsies and collecting this additional data. Although all scans can be subsequently processed post-data collection, the more accurate and representative the initial scans are the more likely community partners will be motivated to continue using and finding value in them. This reduces the effort and barriers to making the adoption of this technology standard for postmortem exams.

The findings suggest that the application of this technology is accessible to most users when the outlined instructions are followed diligently. It has demonstrated potential in supporting conventional necropsies, particularly in lesion identification, although histological assessment at time of examination is essential to ensure consistency, especially at adoption phase of this technology. The highest value of this technology is currently in scenarios where conventional necropsies are limited, such as with shown with large whales in Figure 6 and 7. Two primary use cases emerge: supplementing limited external examinations and complementing internal complete necropsies. The first case is shown to be essential for morphometric analysis where traditional measurements are not possible, and the identification of external lesions and signs of trauma. The second case enables later assessment of the form of internal lesions and organs. While all species are viable subjects, animals assessed in rainy conditions or with high specular reflection, such as the killer whale case here, may exhibit visual anomalies during the creation of the 3D mesh. The combination of LiDAR and photogrammetry during scans collected by Scaniverse is crucial for creating lifelike representations, with LiDAR data being particularly critical for accurate morphometric measurements.

The rapid advent of scanning technology in handheld phones has made this technology easily accessible in a broad range of applications primarily in mapping and geosciences (Tavani et al. 2022; Günen et al. 2023; Luetzenburg et al. 2021), and in fields such as human body measurement (Mikalai et al. 2022). The use of iOS-based LiDAR has been studied for repeatability and bias against reference values collected via manual measurements of a vehicle and filing cabinet (Heinrichs and Yang 2021). These scans are analogous in size to a large whale and smaller cetaceans/carnivores respectively, with their results also producing centimeter-level deviations from manual measurements as seen in these cases for marine mammals. These systems have also been used for cultural heritage applications, where different iOS scanning applications were tested against each other and distance metrics compared (Losè et al. 2022). This study outlines that although all iOS LiDAR sensors are the same, the choice of scanning application impacts the outcome of the scan due to dictating parameters such as scanning point density. In this work only Scaniverse was used and evaluated, although other applications such as 3DScanner, Polycam, and SiteScape perform similar functions. In one study comparing these applications point clouds against high-precision terrestrial LiDAR scanners (Askar and Sternberg 2023), it was shown that Scaniverse has a far lower density of points than any other application which makes on-site field processing far more rapid in Scaniverse. This is especially useful in the use cases outlined in this study for remote and inaccessible environments where quickly analyzing the scan output is important in ensuring the scan was captured properly. This does come at the expense of a less-dense point cloud, although in our examinations the meshes output by Scaniverse were within an acceptable margin of error for morphometric assessments, given these measurements in the field are subject to their own errors, especially in the large whale cases.

Previous studies that have investigated 3D reconstructions of stranded marine mammals primarily emphasize using this technology either for creating a digital collection of fossils or specimens for museums (Merella et al. 2023; Franci and Berta 2018; Niven et al. 2009), or for input into models that can estimate free-ranging animals body mass and volume for objectives such as bioenergetic analysis and swimming dynamics (Zhang et al. 2023; Irschick et al. 2022). The former cases have shown to create extremely detailed reconstructions that can be 3D printed and re-articulated into true representations of skeletons. The later purpose is rapidly developing and allowing for accurate determinations of many aspects of living marine mammals and progressing the ability to study and understand them in the wild. The only identified uses of this technology in assessing stranded marine mammals in the field is the case of the “Virtual Necropsy” conducted in Alaska (Chenoweth et al. 2022) as well as a fin whale reconstruction in Italy (Del Pizzo et al. 2021). The former appears to be the first time that this technology was used to generate a 3D reconstruction of a necropsy over the course of the animal decomposing. This work garnered broad interest and showcased the value of these scans for use in education, research, and public interest. In the fin whale case, the use of mobile phone photogrammetry to reconstruct a large fin whale was also successful. In this work we provide a complement and extension to this kind of data collection by providing scans from a variety of necropsy situations and species types and showcasing their utility as a documentation and visualization tool as this technology progresses.

The continued advancement of 3D reconstruction technology in the field of marine mammal strandings has significant implications for overall research and conservation efforts in this field. The morphometric and structural data obtained from 3D data offer invaluable reference and validation datasets for constructing accurate models of free-ranging cetaceans, crucial for bioenergetics and other physiological studies. This data also immortalizes these animals, enabling revisitation and improved documentation of rare events such as killer whale strandings. This is essential for monitoring causes of death and population health over time and providing context for future stranding events of all species. The collection of 3D data across populations also simplifies comparative studies in body condition, offering more nuanced methods of comparison beyond girth and straight-line length. The accessibility of this handheld technology allows non-experts and community members in remote or inaccessible regions to perform scans and engage actively in marine mammal conservation. Beyond British Columbia, this technology provides an opportunity for stranding programs globally with lower resources to collect more comprehensive data on marine mammal strandings by simply using their phone and downloading a 3D scanning application. An example of this is the recent Unusual Mortality Event (UME) for grey whales, where areas like Mexico reported almost half (44.9%) of all strandings in the Eastern North Pacific relative to 4.2% in British Columbia (Raverty et al. 2024). This area simply does not have the resources to collect extensive postmortem data on that many animals, however the utilization of simple accessible tools such as that presented here could serve to augment the data collected from these strandings going forward. Preserving this data for analysis by experts that cannot attend a necropsy is another particularly vital purpose of this technology as progressive decomposition from delayed examination limits the utility of a traditional assessment. Progressive decomposition also compromises the utility of measurements for validation of free-living animals as the animal decomposes, bloats, and changes shape (Christiansen et al. 2019). The fresher the specimen, the more likely both external and internal factors can be observed and determined to contribute to cause of death. These scan products when combined with rapidly improving tools such as virtual reality also present the potential to improve training the new generation of responders and volunteers in necropsy procedures, enhancing their preparedness for stranding events and improving examination efficiency and outcomes. The integration of website and virtual reality visualizations not only facilitates data compilation and dissemination but also ensures its longevity and accessibility to diverse user groups, including students, researchers, and conservation practitioners. The continued collection and use of data from 3D reconstructed marine mammals contributes to a growing integration of technology into wildlife conservation and ecological studies. Further work with this dataset will combine these reconstructions with that of medical imaging including computed tomography (CT) and magnetic resonance imaging (MRI) to showcase the ability of imaging products to improve the ability to diagnose, document and understand marine mammal health.

3.6 Conclusion

This study investigates the potential of 3D scanning technology within the domain of marine mammal strandings, aiming to assess its applicability, practicality, and consequential impact. By leveraging accessible LiDAR scanners present in mobile phones, we explored the technology's capacity to reconstruct marine mammal strandings with accuracy and consistency across varied postmortem conditions and ten species. Through our investigation, we have demonstrated the utility of 3D reconstructions in precisely measuring morphometrics in field settings, offering valuable supplementation to traditional field measurements and enhancing documentation practices. In most cases, discrepancies between manual morphometric measurements and that of the 3D reconstruction were less than 2%. The adaptability of this technology extends to educational realms, where it can be employed to train responders and volunteers in necropsy procedures, thereby improving stranding event preparedness and outcomes. The integration of virtual reality and web visualizations serves to disseminate this data effectively across diverse user groups and stakeholders in marine mammal health. Our research underscores the potential impact 3D scanning technology can have on marine mammal and ecological studies, offering a pathway for enhanced research, education, and conservation efforts.

3.7 Supplementary Information

Supplementary Table 1: Flight Details From four UAV Flights

Species	Flight Date	Location	Flight Time	Flight Lines	# Photographs
Inflatable Test Whale	June 2022	Annacis Island	3 minutes 24 seconds	3	58
Grey Whale	June 2022	Nootka Island	2 minutes 49 seconds	3	516
Grey Whale	June 2022	Nootka Island	3 minutes 5 seconds	3	430
Humpback Whale	May 2022	Langara Island	3 minutes 16 seconds	4	712

Supplementary Table 2: 3D Model Web Access and DOI's

Species	Location	Web URL (3DHOP)	DOI
Grey Whale	Jarvis Inlet	https://arls3d.geog.mcgill.ca/3dhop/GW1.html	https://doi.org/10.5683/SP3/MDFF93
Grey Whale	Nootka Island	https://arls3d.geog.mcgill.ca/3dhop/GW2.html	https://doi.org/10.5683/SP3/D0GJNL
Humpback Whale	Langara Island	https://arls3d.geog.mcgill.ca/3dhop/HBW.html	https://doi.org/10.5683/SP3/42ZNAS
Killer Whale	Zeballos	https://arls3d.geog.mcgill.ca/3dhop/KW.html	https://doi.org/10.5683/SP3/LFNPEQ
Risso's Dolphin	Daajing Giids	https://arls3d.geog.mcgill.ca/3dhop/RD.html	https://doi.org/10.5683/SP3/GIJNDX
Striped Dolphin	Ucluelet	https://arls3d.geog.mcgill.ca/3dhop/SD.html	https://doi.org/10.5683/SP3/3XEAUO
Dall's Porpoise	Victoria	https://arls3d.geog.mcgill.ca/3dhop/DP.html	https://doi.org/10.5683/SP3/P1Y5EY
Harbour Porpoise	Salt Spring Island	https://arls3d.geog.mcgill.ca/3dhop/HP1.html	https://doi.org/10.5683/SP3/VEGUB2
Harbour Porpoise	Tsawwassen	https://arls3d.geog.mcgill.ca/3dhop/HP2.html	https://doi.org/10.5683/SP3/P7N34H
Sea Otter	Tofino	https://arls3d.geog.mcgill.ca/3dhop/SO.html	https://doi.org/10.5683/SP3/VK8A0D
Northern Fur Seal	Port Hardy	https://arls3d.geog.mcgill.ca/3dhop/NFS.html	https://doi.org/10.5683/SP3/C7BKDB
Harbour Seal	Vancouver	https://arls3d.geog.mcgill.ca/3dhop/HS.html	https://doi.org/10.5683/SP3/8BUU1I

Fisheries and Oceans Canada | Pêches et Océans Canada | **File numbers:** DFO | Other:

MARINE MAMMAL INCIDENT RESPONSE FORM – *Page 2*

CETACEAN MORPHOMETRICS *Units:* cm *Side:* ◯*R* ◯*L*

Straightline length (from tip of upper jaw)

	1 To fluke notch *(total length)*
	2 To apex of melon
	3 To gape of mouth
	4 To centre of eye
	5 To centre of blowhole
	6 To anterior throat grooves *(if applicable)*
	7 To anterior insertion of flipper
	8 To anterior insertion of dorsal fin
	9 To dorsal fin tip
	10 To anterior genital slit
	11 To anus
	12 From fluke notch to anus

Appendages

	13 Dorsal fin height
	14 Flipper, anterior length
	15 Flipper, maximum width
	16 Tail fluke width

Girth ◯ *full* ◯ *doubling of half*

	17 At eye
	18 At posterior insertion of flipper
	19 At maximum: *location*
	20 At anus

Ventral throat pleats *(if applicable)*

	21 Number of throat pleats
	22 Length of longest throat pleat

Blubber

	23 Dorsal
	24 Lateral
	25 Ventral

PINNIPED/OTTER MORPHOMETRICS *Units:* cm *Side:* ◯*R* ◯*L*

Length

	1 Straightline – from tip of snout to tip of tail
	2 Curvilinear - from tip of snout to tip of tail

Appendages

	3 Front flipper, anterior length
	4 Back flipper, anterior length

Girth ◯ *full* ◯ *doubling of half*

	5 At posterior insertion of front flipper
	6 At maximum: *location*
	7 At anus

Blubber

	8 Dorsal
	9 Lateral
	10 Ventral

SEA TURTLE MORPHOMETRICS *Units:* cm

Carapace Length

	1 Straightline – head end of shell to tip of tail
	2 Curvilinear – head end of shell to tip of tail

Carapace

	3 Maximum width

ADDITIONAL COMMENTS

Supplementary Figure 16**:** Typical Marine Mammal Morphometric Sheet

3.8 References

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Chapter 4. Summary and Conclusions

4.1 Summary

By creating accurate 3D reconstructions of stranded marine mammals, it was shown that this technology can obtain precise morphometric data and visualizations, offering new tools for studying these animals' anatomy and health. This approach not only provides a simple means of gathering additional data but also has broader implications for conservation, enabling more detailed and accessible studies that can inform effective management and protection strategies for marine mammal populations.

The research primarily focuses on evaluating 3D scanning technology's accuracy and adaptability across diverse conditions in British Columbia and ten species of marine mammals. Notably, it assesses how effectively this technology performs in remote environments, which is particularly crucial for documenting large whale strandings. The findings demonstrate the significant potential of 3D scanning to enhance the documentation of necropsies and improve the precision of morphometric measurements directly in the field.

By fostering partnerships between local communities, indigenous groups, conservation organizations, and governmental bodies, the technology encourages a collaborative approach. The study underscores the importance of continuing to develop and implement advanced technological solutions to address the challenges faced in marine mammal conservation, particularly in remote and challenging environments.

4.2 Broader Discussion and Implications

Marine mammal conservation research has evolved significantly over the past two decades, driven by a growing understanding of the threats these species face and the need for effective conservation strategies. Researchers have employed and continue to develop various methodologies, including field observations (Southall et al. 2012), population modeling (Gormley et al. 2012), and genetic studies (Rosel et al. 2017) to monitor marine mammal populations and assess their health. This research has highlighted the critical impacts of pollution, climate change, and human activities such as shipping and fishing on marine mammal species, leading to the development of targeted conservation policies and mitigation measures.

Among the key methodologies, necropsies continue to evolve as an invaluable tool in marine mammal research. As mentioned previously, providing detailed insights into the causes of death, disease prevalence, and the effects of environmental contaminants, necropsies have enabled researchers to identify emerging health threats and understand their implications for marine mammal populations. The data derived from necropsies have informed regulatory measures (IJsseldijk et al. 2019), public awareness campaigns (Worthy 1999), and species recovery programs (Stacy et al. 2016), ensuring that conservation efforts are based on solid scientific evidence.

The integration of 3D reconstruction technologies like LiDAR and photogrammetry in marine mammal necropsies represents a paradigm shift in veterinary pathology and wildlife research. These technologies enable researchers to increase the ability to obtain high-resolution images and models of marine mammals, which are crucial for accurate post-mortem examinations. Traditionally, necropsy procedures, especially in large whales, are hindered by logistical challenges due to the size and the decomposed state of stranded specimens. 3D reconstructions allow for a non-invasive and simple method to conduct a detailed examination of the external and internal anatomy, preserving the physical state digitally before decomposition progresses. As just one example, marine mammals, particularly cetaceans, face a high rate of mortality due to bycatch in various fishing gears like purse seine, longline, and gillnets (Hutchinson et al. 2024). Improved necropsy imaging techniques such as 3D reconstruction technology can play a crucial role in addressing this issue by providing anatomical and physiological insights through a more accurate assessment of the injuries sustained and the potential causes of death. This has the consequence of enhancing our understanding of the impact of bycatch, ultimately helping to reduce mortality rates and improve the conservation of marine mammal populations.

3D technologies increase diagnostic precision by allowing pathologists to revisit the digital models at any point, offering opportunities for a more thorough analysis as new diagnostic information becomes available. For instance, in cases of stranded grey whales (Figures 6 and 7) displayed in this thesis, the use of 3D scanning has revealed intricate details about their physical conditions, such as the extent of emaciation or specific internal injuries that could be linked to ship strikes or entanglement. This provides concrete evidence that can lead to policy changes aimed at reducing such incidents. Anomalies visible in 3D scans might also point to nutritional deficiencies linked to overfishing or habitat degradation, which impact prey availability. There are many incidences of marine mammal skeletons being accurately 3D reconstructed for these kinds of purposes (Kot et al. 2020; Mills et al. 2022; de Vriend et al., 2018.), and the use of these models have been utilized effectively to simulate the physical impact of vessel strikes on large whales (Daume et al. 2023). Continuation of this research for not only skeletons but entire stranded animals can help elucidate these complex and often lesser understood interactions between vessels and marine mammals. These capabilities make 3D scanning a potent tool for proactive conservation efforts, allowing for the adjustment of management strategies in real time.

The detailed morphometric analysis enabled by 3D reconstructions studies in this thesis can also help in studying growth patterns, age-related changes, and species-specific anomalies. With a low margin of error, measurements from stranding data can improve from the opportunistic nature of measurement collection done currently to now having the capability to create accurate digital representations of the animal at the time of stranding. These insights are essential for managing and conserving these species, especially in remote environments such as that studied in British Columbia, in addition to rapidly changing environments such as the Arctic where these species face increased challenges from climate change and human activities (Laidre et al. 2015). The accumulation of 3D reconstructions and the subsequent improved ability to collect morphometrics presents a new method in digitally preserving the integrity of specimens as strandings occur. This also invites the potential to create a digital archive that can be revisited as new scientific techniques or insights emerge, not too dissimilar to for example the Warkins marine mammal sound database (Sayigh et al. 2017). Over time, the accumulation of 3D necropsy data can facilitate longitudinal studies of marine mammal populations, tracking health trends, and changes in response to environmental pressures more accurately than has been done previously.

Morphometrics estimations for live marine mammals have developed from basic estimations of body volume and mass (Hodgson et al. 2020), to truncated cone models (Shero et al. 2014) and most recently to models that take a series of many scalar morphometric measurements to generate an highly accurate 3D representation of an animal (Zhang et al. 2023). All these studies depend heavily on the “ground truth” of a real, often deceased animal that can be used to validate what these 3D models of live animals captures. The 3D reconstruction methods and techniques explored here provide a potential avenue to providing more accurate morphometric assessments of stranded animals not only for assessment of the strandings themselves but also provide the opportunity to improve the validation of 3D models of live animals, which are highly sought after for studying important quantities related to bioenergetics (Schmidt-Nielsen 1972), thermoregulatory demands (Gillooly et al. 2001), diving responses (Williams 1999) or other metrics otherwise unable to be collected.

The collection of 3D reconstructions themselves also does not necessarily have to be isolated to deceased animals. Some preliminary studies have been conducted to assess the ability to 3D reconstruct live marine mammals (MMRP 2021), which present more challenges with respect to data collection but if done correctly are obviously much more representative of the free-ranging animal than a 3D model generated from morphometrics of a deceased animal. The limitations of studying only dead animals through the impact of postmortem change to the carcass is one previously mentioned limitation of using the form of stranded animals as a proxy for live animals at least in the case of large whales (Christiansen et al. 2019).

Further, the utility of 3D technologies also has the potential to extend to the management of stranding events, where rapid diagnostic capabilities can significantly affect the outcomes for live-stranded animals. The need has been identified for example to include the use of advanced imaging technologies and post-release monitoring for live stranding events (Boys et al. 2022) By quickly creating a detailed model of a stranded marine mammal, rescuers and veterinarians can assess its physical condition accurately and make informed decisions about the necessary interventions and follow its recovery. This swift response can be the difference between life and death, especially in cases where rapid medical assessment and intervention are required.

On a policy level, the data derived from 3D models and the advancement of other monitoring techniques has the potential to significantly influence marine conservation laws and guidelines (Nelms et al. 2021). By providing undeniable evidence of the impacts of human activities on marine mammals, this technology supports stronger legislative measures for habitat protection, sustainable fishing practices, and the regulation of marine traffic. As international bodies look towards integrating science-based approaches into conservation (Svancara et al. 2005), 3D reconstructions offer a valuable tool for crafting effective and informed global strategies that address both local and worldwide threats to marine biodiversity. The introduction of accessible tools explored here to improve science-based approaches also allows for the increased involvement of local communities and the human dimension of marine mammal management which is an increasingly important intersection (Lovecraft and Meek 2011).

Similarly, beyond research and direct conservation applications, this 3D scanning technology also has significant implications for education and public engagement. Detailed models of marine mammals can be used in educational programs to interactively illustrate the complex anatomy and conservation issues surrounding these species. With increased awareness on the impacts on and subsequent reduction of marine mammals in captivity (Rose et al. 2006), this reduction of one of the main drivers of public awareness and engagement in marine mammal conservation has left a hole for younger generations especially (Jiang et al. 2007). By making these models accessible in digital or physical forms through 3D printing, institutions can enhance public understanding and support for marine conservation efforts. Such initiatives also foster a deeper connection between the public and marine environments, leading to increased support for conservation policies.

For 3D scanning technology to have a wide-ranging impact in marine conservation, it must be accessible not only in terms of cost but also in terms of usability. Simplifying the operation of these tools is crucial so that they can be used effectively by a wide range of individuals, from research scientists to local community members and volunteers participating in stranding networks. The use of these scanning applications on devices already owned by most people even in remote environments such as iPhones provides one such avenue to increasing the accessibility of this technology. By improving the development of intuitive user interfaces and possibly the integration of automated features that guide the user through the scanning process, reducing the likelihood of operator error and ensuring the quality of the data collected. As demonstrated here, even by following a simple step-by-step guide of the use of the scanning application can make this technology accessible to most people in places where marine mammals strand.

Going hand in hand with accessible technologies is proper training in the use of this 3D scanning equipment as a critical aspect to ensuring high-quality 3D reconstruction data collection. This training should cover not only the technical aspects of operating the scanners but also the interpretation of the data they generate. Workshops, online tutorials, and certification programs can be developed to equip users with the necessary skills and knowledge to implement this technology. Training workshops in marine mammal conservation have been shown to be successful (di Sciara et al. 2016; Clegg et al. 2021), indicating that integrating this kind of 3D reconstruction training with existing community training is possible. Additionally, creating standardized protocols for data collection and processing through training community partners can help maintain consistency across different users and locations, which is vital for longitudinal studies and large-scale monitoring efforts. To fully leverage 3D scanning technologies in marine mammal conservation, collaboration among these technology developers, research institutions, conservation organizations, and local communities is crucial, with shared resources like centralized databases and collaborative platforms enhancing data utility and providing a comprehensive view of marine mammal health and trends across regions.

The data collected from 3D scanners, particularly in complex field conditions, can be voluminous and complex, requiring significant processing and storage capabilities. Developing streamlined data processing software that can run on portable devices or through cloud-based platforms is one such development that could allow field researchers to analyze and interpret data on-site, making immediate decisions based on their findings. As shown in the thesis, Scaniverse can process such results within the application itself and usually at high quality. This capability is especially important in emergency stranding events where rapid response is crucial or the necropsy is limited by environmental or other factors.

Maintaining the reliability and accuracy of data in field conditions is another major challenge for scalability of 3D reconstruction technology for the purpose of analyzing marine mammal strandings. Environmental factors such as lighting, background interference, and the physical condition of the animal can affect the quality of 3D scans. This was seen in the killer whale scan explored in this thesis where specular reflections were clearly apparent on the scan and impacted the visual representation of the animal relative to what it looked like in reality. Advanced calibration techniques, error-checking algorithms, and artificial intelligence driven analysis need to be integrated into the scanning software to compensate for these variables. Part of this will improve as these scanning applications improve their algorithms, however regular testing, updates, and maintenance of the equipment is a critical component of ensuring consistent performance between scanners and operators.

4.3 Future Directions

Looking forward, the expansion of applications of 3D reconstruction beyond from where they are currently applied to include a broader range of aquatic and terrestrial wildlife is one pathway to improving the uptake in usage of this technology. This has been achieved for 3D models in general (Irschick et al. 2022), but incorporating the entire chain of accessible data collection with user-friendly equipment to processing and visualization would be a natural progression of this work. Comparative studies in the performance of reconstruction technology across different species and environments could uncover universal limitations to the scanning methodology and uncover further best practices while promoting the adoption of the technology.

Integrating 3D reconstructions and advanced imaging with other data types, such as genetic information and environmental data, represents the next frontier in wildlife research. For example, combining 3D scans of marine mammals with genetic data can help identify genetic markers associated with physical traits or disease susceptibility. Additionally, integrating 3D reconstructions with environmental data, such as ocean temperature, salinity, and pollution levels, can reveal how these factors influence the morphology and health of marine mammals. Currently the integration of marine mammal health data with environmental data focuses on climate change and habitat loss (Silber et al. 2017; Harwood 2001; Bruyn et al. 2009) or on anthropogenic impacts such as sonar effects (Pirotta et al. 2022). Genetic studies are also widely integrated into more holistic studies of biogeography and population recovery to improve the spatial scale of genetic data and place it in a broader ecosystem context (Stronen et al. 2022; Chen et al. 2018). Continuing to refine and expand these hybrid models can improve the ability to provide a holistic view of wildlife health and ecosystem dynamics, correlating morphological data with genetic markers or environmental conditions to offer insights into how external factors like climate change or habitat disruption impact species at a genetic and morphological level. This should be the end goal for all new technologies but especially 3D reconstruction technology in its early adoption phase.

Integration with existing datasets and established methodologies to quantify marine mammal health is critical, as a series of 3D reconstructions find little value if there is no ability to integrate them with other relevant data. To maximize the impact of multi-dimensional data, it is crucial to improve the integration and accessibility of data across different research platforms and stakeholders (Neves et al. 2023; Magera et al. 2013; Srinivasan 2018). Establishing shared databases and collaborative networks can facilitate the exchange of information and foster a collaborative approach to wildlife research and conservation. This environment would not only enhance the scope and depth of research but also accelerate innovation in conservation strategies, driven by a comprehensive understanding of wildlife health and ecosystem dynamics. Leveraging the comprehensive data provided by these integrated models, researchers can develop more accurate predictive tools that forecast changes in population health, distribution, and resilience (Kaschner et al. 2011). Predictive modelling in this space currently focusses on modelling marine mammal prey (Pendleton et al. 2020), extrapolating from bio-loggers (McClintock et al. 2013) or modelling other environmental variables to assess the extent and health of habitat (Palacios et al. 2013; Bailey and Thompson 2009). These tools are invaluable for conservation planning, allowing policymakers and conservationists to better implement proactive strategies based on predicted future conditions rather than rely on reactive measures. The use of 3D reconstruction technology to augment the data that is used as input parameters to these models has the capability to improve the validity of the model output thus increasing the accuracy of predictions and allowing for more focussed conservation efforts. This forward-looking approach is the key to enhancing the effectiveness of conservation efforts, ensuring that they are adaptive and robust and able to integrate new technological advancements quickly in the face of rapid environmental changes.

4.4 Conclusions

This study investigates the potential of 3D scanning technology within the domain of marine mammal strandings, aiming to assess its applicability, practicality, and impact. By leveraging accessible LiDAR scanners in mobile phones, we explored the technology's capacity to reconstruct marine mammal strandings accurately and consistently across varied postmortem conditions and species. Our findings demonstrate the utility of 3D reconstructions in measuring morphometrics in field settings, offering valuable supplementation to traditional measurements and enhancing documentation practices.

3D scanning technology proves adaptable in diverse and challenging environments, crucial for large whale strandings where logistical challenges can hinder thorough examinations. The ability to create detailed 3D models on-site allows for comprehensive examinations, capturing nuances that might be missed with traditional methods. This improved documentation facilitates better data sharing and collaboration among researchers, providing a valuable resource for future studies.

The educational applications of 3D scanning technology are also significant. By creating virtual models of marine mammals, educators can offer immersive, interactive experiences that foster a deeper understanding of marine mammal biology and conservation issues. These models can be used in virtual reality environments, enhancing public engagement and support for marine conservation efforts.

Our study highlights the importance of accessible technology in engaging communities and advancing wildlife conservation globally. Utilizing widely available tools such as mobile phones democratizes 3D scanning, allowing those in resource-poor environments to contribute valuable data. This approach empowers local communities and enriches the global dataset on marine mammal health and strandings.

Looking forward, integrating 3D reconstruction technology with genetic and environmental data represents a promising frontier in wildlife research. Hybrid models combining these data streams could provide comprehensive insights into the health and resilience of marine mammal populations facing climate change and habitat loss. Such models could predict future trends in population health and guide proactive conservation efforts.

In conclusion, 3D scanning technology offers significant potential for advancing research, education, and conservation efforts in marine mammal strandings and overall research. By providing detailed visualizations of marine mammal specimens, we offer valuable tools for documenting and understanding marine mammal strandings. As the technology evolves, its potential applications in wildlife research and conservation are likely to expand, offering new opportunities to protect and preserve marine mammal populations worldwide.

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