Journal homepage: www.fishtaxa.com

Virtual Reality Applications in Fish Morphology Study: Enhancing Taxonomic Data for Insights

Quinatana Borazon, Mikko Heino, Marion Glaser
[1] *Department of Fisheries and Apiculture University of Zagreb Zagreb, Croatia.*

Abstract
Virtual reality (VR) applications have become a ground-breaking tool in studying fish morphology, greatly increasing the collecting and processing of taxonomic data. An essential component of biology, fish morphology helps to classify species, explain their evolution, and guide conservation efforts. Fish morphology research has always depended on physical specimens, which have drawbacks in terms of accessibility, handling, and level of examination. The introduction of VR technology has completely changed this field by providing experiences that are immersive, interactive, and data-rich. Researchers may examine 3D models of fish specimens externally and inside using VR's improved visualization capabilities, revealing fine characteristics previously hidden in 2D photos. More thorough understandings of fish anatomy are made possible by this interaction, which also supports taxonomic organization and ecological study. Virtual reality specimens can be archived and preserved to maintain their long-term accessibility and lessen the dependency on physical collections. The protection of aquatic habitats is aided by AI integration, which speeds up species identification and data processing. The result found that VR applications in fish morphology raise the bar for research on fish taxonomy, biodiversity, and conservation. Scientists, educators, and environmentalists now have a fascinating new way to study and save the beauties of the undersea world due to this revolutionary technology.

Keywords: Virtual Reality (VR), Fish Morphology (FM), Taxonomic Data (TD), Applications (A).

Citation: Borazon Q et al. 2023. Virtual Reality Applications in Fish Morphology Study: Enhancing Taxonomic Data for Insights. FishTaxa 29: 47-57.

Introduction

Humans have been existing on Earth for a longer time and since then, they have been finding new ways to visualize the living world around them. From the microscope's early discovery that allowed the micro-world's visualization to the modern 2-D/3-D techniques for visualizing form and structure, every step has moved humans towards a better analyzation. Today, anthropogenic activities have covered the earth and its habitat, increasing the urgency of the need to visualize the shape and form of life around the earth. Because with an increase in human-based environment destruction, biodiversity is on the verge of breaching and this can only be overcome by outlining the form and shape of organisms. Since fish communities are more susceptible to the deadly fate, therefore their biodiversity can be saved by defining their morphological characteristics. For this sake, virtual reality has made successful rounds in the field for twenty-five years. Initially, only human responses were recorded using virtual reality, but later on, animal studies also took the lead.

To provoke responses in fish, virtual reality provides standardized stimulus and helps in learning their morphological potentials. These responses are visualized in a three-dimensional effect on display and, therefore, can be found effective in determining the taxonomic history of species. Fish are a group of diverse and numerous animals that live in aquatic habitats all over the world and have long captivated both scientists and naturalists. In order to fully comprehend the evolutionary origins and taxonomic categorization of these aquatic species, as well as to guide ecological and conservation research, it is essential to comprehend the fine aspects of fish morphology. A new era of scientific investigation has recently begun as a result of the fusion of virtual reality

Accepted: 16 December 2022; Published: 26 April 2023

(VR) technology and the study of fish morphology. This era is characterized by immersive, interactive, and data-rich experiences that have the potential to alter our understanding of fish biodiversity fundamentally. This introduction lays the groundwork for an investigation into how VR applications are revolutionizing research on fish morphology and enhancing taxonomic data to offer more in-depth perceptions of the undersea environment (Auster & Giacalone, 2021).

First, the necessity of identifying fish morphology needs to be justified. These days, biologists and evolutionists are finding ways to deduce genetic and developmental changes occurring in fish forms with time. If visual reality is used, they can easily focus on the outer features of fish assemblages and can read the dimensions of their head, body, axial arrangements, and limbs. This virtual representation not only allows the researchers to find out external characteristics of fish shape but also to find out the nature of fish interactions they have with the environmental drivers. For example, fish gills' movement, stream-like movement, temperature-oriented speed, body changes, and much more. Although internal body factors also affect such reactions, external features give us information about the locomotion of fish, which can easily be computer-analyzed by virtual reality robotics.

Morphological features help find out about the fish's size, weight, and health by analyzing the eye color or movement of gills. Therefore, image processing and machine learning techniques are combined in a visual reality system of displaying stuff. Numerous morphological features must be identified to estimate fish's nature and save their biodiversity. Out of these morphological potentials, fish length, width, caudal width, and length, the color of gills, the diameter of fish eyeballs, pelvic, spiny dorsal, soft dorsal, and anal fins, etc. are important to know. Additionally, VR is a potent teaching tool that enables researchers and students to collaborate remotely while participating in hands-on learning experiences. In VR settings, data gathering and annotation become more efficient, and the incorporation of artificial intelligence makes identifying species easier. VR is useful for comparative anatomy and taxonomy because it allows for the overlay of virtual specimens to highlight similarities and differences. Utilising VR's immersive experiences, public outreach and conservation initiatives raise awareness of the value of preserving aquatic habitats and species.

Until recently, these morphological features were being studied under invasive, costly, and time-consuming methods since fish needed to be taken out of water. But using virtual reality, the environments and stimulus under action, which fish need to be studied, can be set and visualized three-dimensionally. This makes structure study easier and conserves fish populations as they don't need to be used for experimental purposes. Similarly, fish trajectories can also be monitored by compiling computer vision techniques with virtual reality. For this, the behavior of fish is observed by computer vision and then later on, can be combined with virtual reality to analyze the retrieved images by considering the background water changes (Kaimal et al., 2020).

Different animal behaviors are related to the structure and shape that nature has granted to the fish assemblages. Such behaviors involve social behavior, predator-prey relation, foraging, habitat selection, and mate choice of a fish assemblage. To study these changes, first, the fish morphology needs to be understood, and later on, the behavioral responses can be deduced out of them. In previous days, live stimuli and environments were being used to study these features, but the responses faced diverse complications as neither the environment nor the stimulus could be controlled completely. Moreover, the use of live animals involved long preparations and limited the manipulations. Consequently, artificial stimuli are prepared in modern days using virtual reality techniques, which not only lowers the stimuli preparation cost but also allows the repetition of behavioral responses to deduce multiple manipulations.

Other than these applications, virtual reality has also helped in identifying morphological changes that fish larvae undergo. The marine fish larvae initially stay in a planktonic larval phase for many weeks. After that, a

new phase named the sedentary reef phase occurs that leads the larvae to develop into adult fish. The larvae thus produced are known to be very selective in choosing habitat. These larval changes directly influence the changes in morphology, metamorphosis, and physiology. Therefore, a virtual reality-based visualization is found to be very effective in finding out about these morphological changes. Because, through virtual reality, different sensory cues can be made artificially to study larvae's behavioral responses, which in turn provides insight into the undergoing morphological development.

Moreover, virtual reality's physical and digital 3-D scans can be assigned together to get a better view of fish form and structure. Physical scans can provide a better understanding of anatomy, and when these physical scans are linked to the 3-D scans, the three-dimensional representation of fish form allows the researcher to have a better view of color and posture.

Once these morphological changes are represented through visual reality techniques, they can also aid in taxonomic analysis. Because the morphological changes are occurring since fish larval stages and each change is habitual to the environment. Knowing these morphological traits, different fish assemblages can be related through their common pasts. This not only allows the researchers to study the taxonomic characteristics of fish species but also help save the biodiversity of different endangered fish species that are facing environmental degradation efforts of human. Conservation of susceptible fish species can easily be done by aligning the morphological traits of different fish groups and analyzing them through virtual reality techniques to learn their responses to different environmental factors and habitat-changing issues.

Literature Review:

Researchers claim that obtaining informational data related to marine biodiversity is a difficult and expensive process. understanding the patterns of aquatic biodiversity is a very time-consuming process. Using advanced technology like virtual technology helps in getting all the data about aquatic life in a short duration of time. The data about the spread of non-indigenous species in the Mediterranean Sea's ecosystem is obtained using technology-based data collection methods(Aglieri et al., 2023).studies reveal that communities of fish species possess a specific structural importance that is influenced by predation.to determine the predation interactions, the use of modern technology is made. Virtual reality technology-based cameras are used in marine ecosystems to assess the predator and prey interaction among fish species. studies reveal that our knowledge about the deep sea species is limited due to a lack of technology-based resources. Modern virtual reality-based technology provides a little insight into the species living in the deeper ocean(Błazewicz, 2022).

Studies explain that the applications of VR are found in several fields. The use of VR is made in the aquatic ecosystem to determine the various life-related aspects of aquatic organisms. combining AR and VR provides more advanced applications and improves the working mechanism of different aquatic fields(Genay, Lécuyer, & Hachet, 2021).studies suggest that evolutionary sciences provide data about the biological life found in aquatic ecosystems. The morphological and functional information about various species is explained through the use of 3D technology. The 3D models based on modern technology determine the morphology related to the organism and help in studying the life process of aquatic species(Irschick et al., 2022).studies determine the impact of stress on organisms using the virtual reality technique. In most health-related sectors, the use of VR is increasing at a rapid rate. studies predict that data related to the genetic analysis of microorganisms is a great tool for improving the monitoring technique. The cetaceans present in Chile are monitored using the standard monitoring technique based on the approach of genetic analysis(Kraft, Rodríguez, Olavarría, Poulin, & Pérez-Álvarez, 2023).studies claim that with the increased use of modern technology, the advancement in the mobile robotics system has been enhanced. tasks that are dangerous to perform by humans are done using robotics technology.Teleoperation techniques are employed in robotics to improve its functioning(Moniruzzaman,

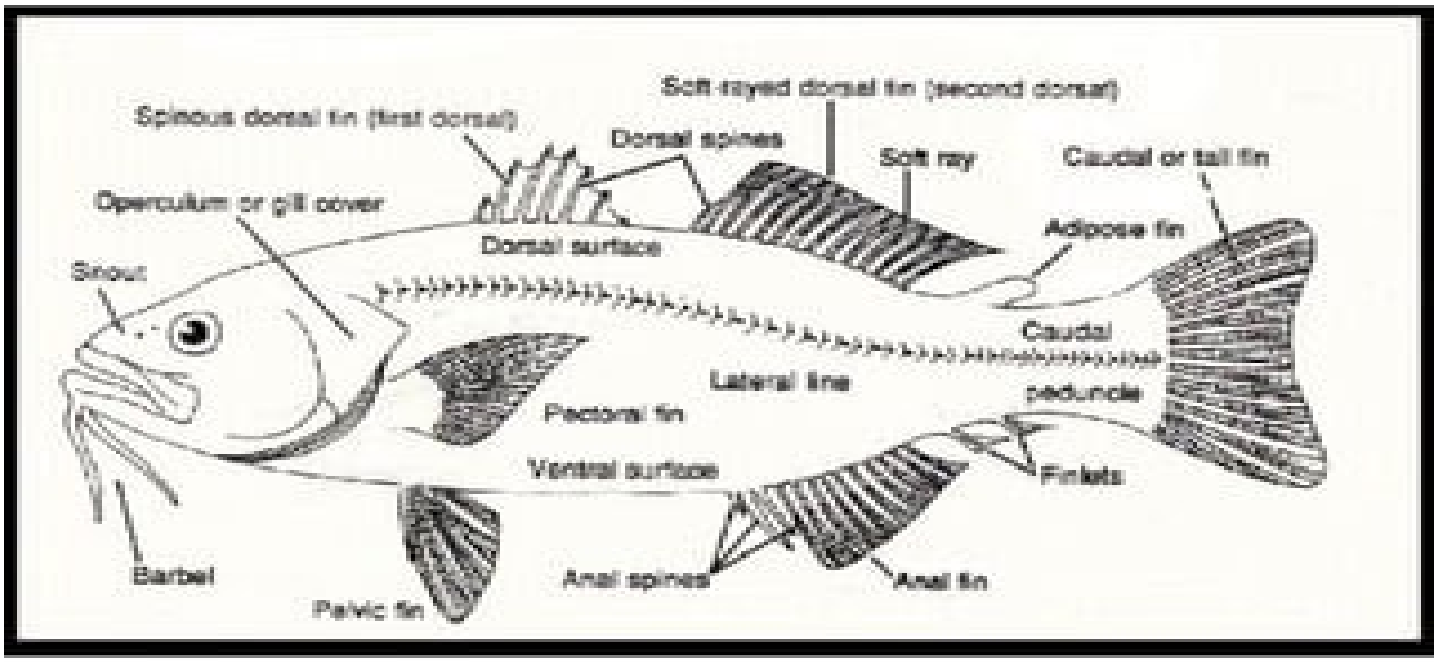
Rassau, Chai, & Islam, 2022).

Studies explain that the use of the paleontology branch is common for maintaining the information related to the earth. paleontology provides fossil records about the species on the earth's surface millions of years ago. for identifying which fossil records belong to which species, x-ray microcomputed technology is employed(Mouro et al., 2021).studies highlight that preserving the species that are at higher threat of getting extinct is done through the biomonitoring of fish species.to assess the species of benthic region, a lot of taxonomic problems occur. these problems are overcome using the biomonitoring system as this technology is involved in identifying species of benthic region (Ochieng, Okot-Okumu, & Odong, 2019).studies reveal that aquatic species use microalgae as a food .microalgae is among the most commonly available food sources for aquatic species. The production of microalgae is assessed through the evolutionary technology. The microalgae biomass has tremendous applications and provide potential benefits to aquatic species. studies show that with time, the aquaculture resources have increased. This increase in aquaculture resources provides great nutritional benefits. The data about the aquatic resources is determined through the use of next-generation technologies. this technology provides extensive detail about the oceanic data and provides data in a database (Rather et al., 2023).

Moreover, the aquaculture-based infrastructure is improved using advanced technological tools. These technology-based tools improve the conservation management process. Moreover, deep learning-based algorithms are used to determine the species' fauna in the freshwater ecosystems. The fish species present in Amazon seas are identified using next generation technology based deep leaning algorithms(Robillard et al., 2023).studies predicts that using machine learning technology provides useful data associated with complex systems .The machine learning approach is applied in numerous branches because of its tremendous applications. In the process of biological oceanography, the approach of MLT is implemented(Sadaiappan et al., 2023).studies show that cartilaginous fishes having jaw are characterized as Chondrichthyes. The population of this species is facing threat due to different factors.Their conservation process can be improved by assessing the genetic variation in Chondrichthyes species. The technology-based approach of biomedical sciences helps determine the evolutionary history associated with Chondrichthyes. This evolutionary history helps make effective conservation strategies for saving the Chondrichthyes from threat factors(Seixas, Domingues, & Antunes, 2023).studies show that aquaculture is a complex ecosystem that depends on the availability of water and minerals for its proper functioning.

Various enviromnetal factors disturb the data related to aquaculture. To improve the data quality of aquaculture, the use of a machine learning system is made. MLT provides the most accurate data about the various aspects of aquaculture(Sun, Yang, & Xie, 2020). Furthermore, for developing exceptional decisions for aquaculture maintenance, the fish metric calculation technique is employed. stereo vision is a technique used for assessing the size and distance traveled by fish species during their movement process. To improve the efficacy of underwater cameras, they are made using advanced technology. the underwater fish metric is determined using vision cameras(Ubina et al., 2022).studies reveal that using VR and other ‘advanced technology determines the interaction between humans and robotics systems.

Research studies on various fields become easy using the biotics system based on VR. The taxonomical background associated with the species of different ecosystems is explained through the effective use of VR and AR technology(Walker, Phung, Chakraborti, Williams, & Szafir, 2023).scholars explain that computer-based VR technology systems assess urban landscape design and its related information based on the concept of data fusion (Zhang, Fan, & Guo, 2022).scholars suggest that using MLT for the aquaculture digitalization process holds great importance in aquatic ecosystem. The fishery-based framing process get improved as a result of the digitalization of the aquaculture environment(Zhao et al., 2021).



Fish Morphology:

The term fish Morphology can be explained in these words "study which is related to structure, shape, type, form of parts of the fish body that are involved in the understanding of lifestyle and behavior of fish throughout life".

The following are important Morphological features for studying fish Morphology:

- Body length and width
- The caudal peduncle length
- The caudal peduncle width
- Eye diameter
- Pupil diameter
- Colour
- Shape and color of gills

Study of Fish Morphology:

It is very important to study fish Morphology because the study of fish Morphology helps in understanding the growth of fish, estimated or theoretical yield, ways of artificial breeding of fishes, and other investigations related to the population of fishes. In recent years, a variety of techniques have been used to study the structure of fish. These techniques include image processing technology, Virtual reality techniques, and others that are specifically related to the study of the Morphology of fishes.

Virtual reality:

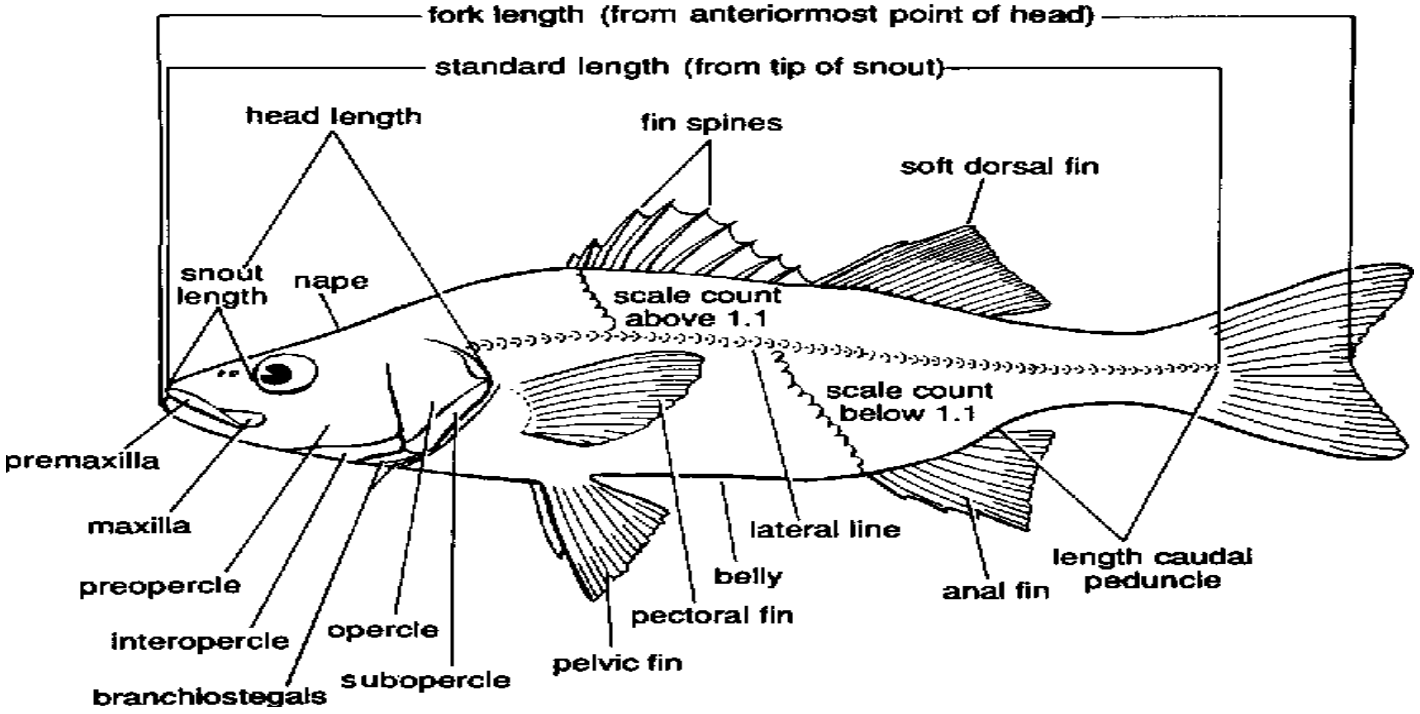
Virtual reality is a computer-generated three-dimensional image that is physically viewed by any person with the help of electronic equipment by creating virtual images such that these images seem to be real. The electronic equipment used for virtual reality includes a helmet with a screen and gloves fitted with sensors for observing

and understanding virtuality.

Virtual reality application in Fish Morphology study:

This virtual reality application is based on the research by National Manufacturing Institute Scotland with additional support from the Sustainable Aquaculture Innovation Centre. The techniques of 3D scanning and virtual reality have already been used in many sectors of life such as education, and industries like auroscopes and energy, the same technique can also be used to study the Morphology of fishes in modern times as well. The basic principle in virtual reality is that animals whose Morphology has to be studied are physically restrained compared to other electrophysiological methods that cannot apply to moving animals. The neural system of zebrafish was studied with the help of the virtual reality method on larval and embryonic stages up to almost seven days after fertilization. However, neural activity is very restrained and limited during the embryonic stage. For the study of the neural system of zebrafish, his head was fixed for proper study of Morphology. Virtual reality studies have shown that the skull of zebrafish is made up of five bone sets, out of five bones, four bones are very thin. But the fifth bone is quite hard and surrounds the brain ventrally and also laterally. In virtual reality, a small head bar was connected to this bone with the help of dental cement and glue. Then, this fish was introduced to a highly 3-dimensional virtual environment in a tank. There was little forward movement with asymmetrical tail and head movement. Then the behavior of zebrafish was also studied by creating 3 dimensional images and moves similar to other zebrafish in water. The behavior of fish was studied in such a way that there was a clear blank side of the environment and the other side had images of the other three zebrafish, the controlled zebrafish spent more time near that wall which had images of zebrafish. We have taken zebrafish for these studies because these are neither too small nor too large but an average perfect size for experiments. During these virtual reality experiments, it was observed that specific fractions of neurons in the forebrain showed quite prominent responses to the artificially created environment by virtual reality. This experiment explains that specific brain cells in mammals create a model inside the brain that responds to the external environment as well (Pascon et al., 2021). Virtually reality experiments can also be used to study the reproduction model of these fishes. Fishes are involved in external reproduction, which is a fusion of male and female gametes outside the body. When a virtual environment is created by virtual reality, such an environment can induce stimulus response in fishes to release their gametes outside the body for external fertilization. Virtual reality can also study hormonal changes in the fish's body during emergencies or the normal reproductive cycle. These hormonal changes are related to different responses to various stimuli in them. For example, when these fishes are under stress for example because of predators, the head bar attached to their brain can help to understand the level of hormonal changes during the state of fear. In the case of larval growth and development, these virtual reality techniques can also be used to study changes in them during the embryonic stage in adult fish. From the young stage of life to the adult stage of zebrafish, there are various changes in muscles and fins. These changes are also studied with the help of virtual reality techniques for more information about fish. The virtual reality technique can also be used to study the migratory behavior of fishes during different seasons. For example, during some time of year, fishes move from marine water to freshwater. The factors that are included for the migration of fishes from marine water to freshwater are studied thoroughly to create a virtual reality environment such as conditions of temperature, pressure, pH of water, salinity, and others. When all these factors are studied, the artificial environment is created with the help of virtual reality. For example, suppose some fish moves from marine water to freshwater because of high temperature. In that case, the artificial high temperature is created by virtual reality that allows fish to respond to this stimulus naturally thus migrating from marine water to freshwater. In the case of the stimulus of reproduction, the artificial environment for reproduction is created by the virtual reality that helps to study changes in the body of fishes during the period of preparation for

reproduction and caring for young larvae. Such techniques for studying the internal structure of fishes along other mammals can be effectively used for viewing internal structure. The virtual reality technique is quite helpful to study the structure and behavior of fishes which may be marine or freshwater fishes. There are different benefits of virtual reality, this application of virtual reality for studying the internal and external structure of fishes can yield better results for future horizons of information and research.



Considering Fish Morphology:

Fish, which have over 34,000 identified species, have an astounding variety of morphological characteristics and adaptations. Their skeletal architecture, body forms, fin arrangements, and scale patterns are the products of millions of years of evolution influenced by a variety of environmental influences. These morphological characteristics make morphology an essential part of fish taxonomy since they are critical diagnostic traits for categorizing and identifying fish species. knowing biodiversity begins with knowing taxonomy, the discipline of identifying, characterizing, and categorizing species. When discussing fish, taxonomy refers to the systematic division of species into hierarchical groups, starting with genera and progressing to families and orders. Inferring ecological roles within aquatic ecosystems and reconstructing evolutionary histories are all made possible by this categorization.

Additionally, fish morphology research goes beyond classification. Ecologists use morphological information to study how fish interact with other species, forage, and adapt to various environments. Conservation biologists use morphological data to recognize threatened species, track population health, and develop methods for their protection. Fish morphology essentially links our understanding of the shape and function of these aquatic animals and their ecological functions in the intricate web of life.

Applications:

Studies on the Evolution of Fish Morphology:

Fish morphology research has always depended on actual specimens that have been stored in natural history

collections and museums all around the world. Under a microscope, scientists carefully analyze these samples, noting their physical properties and taking measurements. Although this method has provided insightful information, it has drawbacks. First off, it's commonly difficult to find well-preserved specimens, especially for rare or freshly found species. Second, dealing with physical specimens can be time-consuming and dangerous, especially when dealing with delicate or fragile specimens. Third, employing conventional methods to analyze three-dimensional (3D) structures, such as skeletal configurations and interior organs, can take time and effort. A substantial advancement was made with digital imaging technologies, including high-resolution photography and computed tomography (CT) scanning. With the use of these instruments, researchers were able to take in-depth 2D and 3D pictures of fish specimens, improving visualization and minimizing the need to handle actual specimens. Even with these developments, the analysis's breadth and interactivity were constrained because most research on fish morphology was conducted in 2D displays.

Virtual Reality:

In the field of fish morphology research, virtual reality, a technology that has acquired significant acceptance in industries like gaming and entertainment, has changed the game. Using virtual reality (VR), it is possible to study fish morphology uniquely and engagingly by seamlessly fusing the physical and digital worlds. It allows researchers to go beyond the constraints of 2D displays and investigate the complex aspects of fish anatomy in a simulated aquatic setting.

Superior Visualization:

Giving improved visualization is one of VR's main advantages in fish morphology study. The underwater habitats where fish live may be accurately simulated in VR settings. By navigating these digital ecosystems, researchers may view fish in their native habitats. While doing so, learners may interact with 3D replicas of actual fish specimens by rotating, focusing on particular aspects, and even digitally dissecting them. The amount of interaction and realism present makes a greater grasp of fish morphology possible. It enables scientists to look at interior components like bones, muscles, and organs in addition to surface characteristics like scales, fins, and coloring. These understandings of fish shape and function are crucial for the taxonomy of taxa and ecological research.

Training and Interactive Learning:

VR offers enormous promise for teaching and training, not just for experts in the field. Virtual fish morphology laboratories might be developed to instruct pupils and aspiring taxonomists about fish anatomy and categorization. Without the use of actual specimens, students may participate in hands-on activities through VR, practicing dissections and polishing their identification abilities. Additionally, VR breaks down geographical barriers, allowing for online learning and collaboration. In a virtual classroom or laboratory, students and researchers from all around the world may come together to exchange ideas and further our understanding of fish morphology.

Information Gathering and Annotation:

Data gathering and annotation are more simplified and effective in the virtual reality environment. Researchers may use VR technologies to measure virtual specimens, make notes, and add information. The correctness and consistency of the data are ensured by this computerized record-keeping, lowering the possibility of human mistake. Furthermore, automated data extraction using AI algorithms may be accomplished using VR systems. These algorithms can identify and classify morphological characteristics, possibly speeding up the taxonomy identification process.

Taxonomy and Anatomy Comparison:

To classify and taxonomize fish species, it is crucial to compare their morphologies. Virtual specimens may be easily overlaid in VR, enabling researchers to spot morphological similarities and differences. The categorization of novel species and the improvement of current taxonomic categories are both aided by this comparison method. VR can also make exploring the evolutionary connections between different fish species easier. Researchers can learn more about the evolutionary history of fish and the forces that have created their variety by digitally recreating the morphological changes that have taken place through time.

Public Education and Environmental Awareness:

VR's immersive features make it a good tool for education and environmental conservation. It is possible to build virtual reality experiences that highlight the richness and beauty of fish species, increasing public awareness of the value of aquatic ecosystems and the necessity of their preservation. Imagine a virtual aquarium where visitors may swim alongside various fish species and closely examine their morphology and behaviors. Such adventures increase one's appreciation of the undersea environment and instill a sense of duty towards its preservation.

Preservation and Archiving:

The scientific community may access and long-term preserve digital specimens produced in VR by archiving them in digital repositories. Researchers may quickly access a wide range of fish morphology data due to the benefit of rapid specimen retrieval and sharing provided by virtual archives. This openness encourages cooperation and hastens scientific advancement.

Integration of AI and Species Identification:

The combination of AI and machine learning techniques with VR in the age of big data offers enormous promise for fish taxonomy. Artificial intelligence (AI) systems can examine digital photographs of fish specimens and make automatic recommendations for taxonomic coding. This speeds up fish identification and makes it easier to manage vast databases of fish morphology. Machine learning algorithms may be trained to identify certain morphological characteristics, such as the caudal fin's form or the configuration of the lateral line scales. Then, by employing these algorithms on VR fish species photographs, taxonomists' workload is lightened and the discovery rate is sped up.

Consequences for conservation:

The uses of VR in fish morphology go well beyond classification and teaching; they have significant conservation-related ramifications. Knowing the physical traits of different fish species Finally, the integration of virtual reality (VR) technology with the study of fish morphology is a paradigm-shifting advancement in our effort to solve the secrets of the undersea world. The immersive and interactive features of VR apps have enhanced, and in some cases outperformed, the conventional techniques of studying physical specimens. This progression has great potential to improve taxonomic data collecting, categorization, and analysis, which will ultimately result in better understandings of fish biodiversity and its wider ecological consequences. It is impossible to overestimate the significance of fish morphology in the areas of taxonomy, ecology, and conservation.

Conclusion:

Scientists can decipher fish species' evolutionary histories, ecological functions, and conservation status due to their distinctive morphological traits. We provide researchers with tools that improve visualization, engagement,

and effectiveness by enhancing our taxonomy data through VR. In addition to giving researchers a fresh method to see and interact with fish specimens, virtual reality also makes it possible to design immersive instructional experiences. Virtual reality (VR) democratizes access to the undersea environment from schools to research laboratories, allowing learners, scientists, and hobbyists worldwide to investigate fish morphology without being constrained by geographical constraints. Additionally, VR streamlines the study process by bringing unprecedented efficiency to data collecting and annotation. By incorporating AI algorithms, we may use machine learning to automate the recognition of morphological traits, speeding up fish species identification and relieving taxonomists of some of their work. VR's comparative capabilities makes a greater comprehension of fish variety and evolutionary links possible. Scientists can dissect and examine virtual specimens with remarkable accuracy, revealing information on the alterations and adaptations that have sculpted fish anatomy over millions of years.

VR experiences highlighting the beauty and significance of fish species are extremely beneficial to public outreach initiatives and environmental awareness campaigns. While promoting the preservation of aquatic ecosystems, these immersive experiences have the potential to motivate the next generation of scientists and environmentalists. The digitalization of fish morphological data using VR increases its accessibility and lifespan in terms of archiving and preservation. Virtual repositories turn become knowledge vaults that encourage global research cooperation and information exchange. A revolution in fish taxonomy is anticipated as a result of the combination of VR, AI, and machine learning. These technologies not only improve the speed and precision of species identification, but they also offer up new possibilities for the analysis of huge information and the discovery of hidden correlations and patterns.

In the end, VR applications in fish morphology have effects that go beyond scientific research. They have significant effects on maintaining fish populations sustainably and conserving aquatic environments. By improving our knowledge of fish anatomy and taxonomy, we can better address the problems caused by habitat destruction, overfishing, and climate change, all of which endanger the delicate balance of aquatic life. We must approach this exciting venture into the world of virtual reality in fish morphology research with a dedication to cooperation, openness, and appropriate technology use. The future health and vibrancy of our seas and freshwater ecosystems will ultimately depend on how we use the information we get from using virtual reality to explore the depths of knowledge and conservation. In conclusion, the use of virtual reality in fish morphology research is a promising new field that has the potential to fundamentally alter how we think about fish biodiversity, taxonomy, and conservation. Technology and science working together in this project have the potential to provide new insights, promote international cooperation, and motivate future generations to value and safeguard our planet's aquatic beauties. We set out on a voyage that may transform our relationship with the undersea environment and propel us to new levels of exploration and conservation as we delve further into this virtual universe.

Reference

Aglieri, G., Quattrocchi, F., Mariani, S., Baillie, C., Spatafora, D., Di Franco, A., . . . Milazzo, M. (2023). Fish eDNA detections in ports mirror fishing fleet activities and highlight the spread of non-indigenous species in the Mediterranean Sea. *Marine Pollution Bulletin, 189*, 114792.

Auster, P. J., & Giacalone, L. (2021). Virtual Reality Camera Technology Facilitates Sampling of Interactions Between Reef Piscivores and Prey. *Marine Technology Society Journal, 55*(2), 54-63.

Błazewicz, M. (2022). Challenges and Advances in the Taxonomy of Deep-Sea Peracarida: From Traditional to Modern Methods. *Recent and Emerging Innovations in Deep-Sea Taxonomy to Enhance Biodiversity Assessment and Conservation*.

Genay, A., Lécuyer, A., & Hachet, M. (2021). Being an avatar “for real”: a survey on virtual embodiment in augmented

reality. *IEEE Transactions on Visualization and Computer Graphics, 28*(12), 5071-5090.

Irschick, D. J., Christiansen, F., Hammerschlag, N., Martin, J., Madsen, P., Wyneken, J., . . . Siler, C. (2022). 3D visualization processes for recreating and studying organismal form. *Iscience*.

Kaimal, G., Carroll-Haskins, K., Ramakrishnan, A., Magsamen, S., Arslanbek, A., & Herres, J. (2020). Outcomes of visual self-expression in virtual reality on psychosocial well-being with the inclusion of a fragrance stimulus: A pilot mixed-methods study. *Frontiers in Psychology, 11*, 589461.

Kraft, S., Rodríguez, F., Olavarría, C., Poulin, E., & Pérez-Álvarez, M. J. (2023). Genetic Analysis as a Tool to Improve the Monitoring of Stranded Cetaceans in Chile. *Biology, 12*(5), 748.

Moniruzzaman, M., Rassau, A., Chai, D., & Islam, S. M. S. (2022). Teleoperation methods and enhancement techniques for mobile robots: A comprehensive survey. *Robotics and Autonomous Systems, 150*, 103973.

Mouro, L. D., Vieira, L. D., Moreira, A. C., Piovesan, E. K., Fernandes, C. P., Fauth, G., . . . Baecker-Fauth, S. (2021). Testing the X-ray computed microtomography on microfossil identification: An example from Sergipe-Alagoas Basin, Brazil. *Journal of South American Earth Sciences, 107*, 103074.

Ochieng, H., Okot-Okumu, J., & Odong, R. (2019). Taxonomic challenges associated with identification guides of benthic macroinvertebrates for biomonitoring freshwater bodies in East Africa: A review. *African Journal of Aquatic Science, 44*(2), 113-126.

Pascon, G., Messina, M., Petit, L., Valente, L. M. P., Oliveira, B., Przybyla, C., . . . Tulli, F. (2021). Potential application and beneficial effects of a marine microalgal biomass produced in a high-rate algal pond (HRAP) in diets of European sea bass, Dicentrarchus labrax. *Environmental Science and Pollution Research, 28*(44), 62185-62199.

Rather, M. A., Agarwal, D., Bhat, T. A., Khan, I. A., Zafar, I., Kumar, S., . . . Qadri, T. (2023). Bioinformatics approaches and big data analytics opportunities in improving fisheries and aquaculture. *International Journal of Biological Macromolecules*, 123549.

Robillard, A. J., Trizna, M. G., Ruiz-Tafur, M., Dávila Panduro, E. L., de Santana, C. D., White, A. E., . . . Deichmann, J. L. (2023). Application of a deep learning image classifier for identification of Amazonian fishes. *Ecology and Evolution, 13*(5), e9987.

Sadaiappan, B., Balakrishnan, P., CR, V., Vijayan, N. T., Subramanian, M., & Gauns, M. U. (2023). Applications of Machine Learning in Chemical and Biological Oceanography. *ACS omega, 8*(18), 15831-15853.

Seixas, M. J., Domingues, R. R., & Antunes, A. (2023). Decoding the Transcriptome of Sharks, Rays, and Chimaeras: Insights into Their Physiology, Morphology, Evolution, and Biomedical Applications. *Fishes, 8*(5), 271.

Sun, M., Yang, X., & Xie, Y. (2020). Deep learning in aquaculture: A review. *J. Comput, 31*(1), 294-319.

Ubina, N. A., Cheng, S.-C., Chang, C.-C., Cai, S.-Y., Lan, H.-Y., & Lu, H.-Y. (2022). Intelligent underwater stereo camera design for fish metric estimation using reliable object matching. *IEEE Access, 10*, 74605-74619.

Walker, M., Phung, T., Chakraborti, T., Williams, T., & Szafir, D. (2023). Virtual, augmented, and mixed reality for human-robot interaction: A survey and virtual design element taxonomy. *ACM Transactions on Human-Robot Interaction, 12*(4), 1-39.

Zhang, X., Fan, W., & Guo, X. (2022). Urban landscape design based on data fusion and computer virtual reality technology. *Wireless Communications and Mobile Computing, 2022*, 1-14.

Zhao, S., Zhang, S., Liu, J., Wang, H., Zhu, J., Li, D., & Zhao, R. (2021). Application of machine learning in intelligent fish aquaculture: A review. *Aquaculture, 540*, 736724.