

Computer vision and deep learning for fish classification in underwater habitats: A survey

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Abstract

Marine scientists use remote underwater image and video recording to survey fish species in their natural habitats. This helps them get a step closer towards understanding and predicting how fish respond to climate change, habitat degradation and fishing pressure. This information is essential for developing sustainable fisheries for human consumption, and for preserving the environment. However, the enormous volume of collected videos makes extracting useful information a daunting and time-consuming task for a human being. A promising method to address this problem is the cutting-edge deep learning (DL) technology. DL can help marine scientists parse large volumes of video promptly and efficiently, unlocking niche information that cannot be obtained using conventional manual monitoring methods. In this paper, we first provide a survey of computer visions (CVs) and DL studies conducted between 2003 and 2021 on fish classification in underwater habitats. We then give an overview of the key concepts of DL, while analysing and synthesizing DL studies. We also discuss the main challenges faced when developing DL for underwater image processing and propose approaches to address them. Finally, we provide insights into the marine habitat monitoring research domain and shed light on what the future of DL for underwater image processing may hold. This paper aims to inform marine scientists who would like to gain a high-level understanding of essential DL concepts and survey state-of-the-art DL-based fish classification in their underwater habitat.

KEY WORDS

Computer Vision, Deep Learning, Fish Habitat, Monitoring

1 | INTRODUCTION

Understanding and modelling how fish respond to climate change, habitat degradation and fishing pressure are critical for environmental protection and are crucial steps towards ensuring sustainable natural fisheries, to support ever-growing human consumption (Zarco-Perello & Enríquez, 2019). Effective monitoring is a vital first

step underpinning decision support mechanisms for identifying problems and planning actions to preserve and restore the habitats. However, there is still a gap between the complexity of marine ecosystems and the available monitoring mechanisms.

Marine scientists use underwater cameras to record, model and understand fish habitats and fish behaviour. Remote underwater video (RUV) recording in marine applications (Zarco-Perello &

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Enríquez, 2019) has shown great potential for fisheries, ecosystem management and conservation programmes (Piggott et al., 2020). With the introduction of consumer-grade high-definition cameras, it is now feasible to deploy a large number of RUVs or autonomous underwater vehicles (AUVs) to collect substantial volumes of data and to perform more effective monitoring (Pope et al., 2010; Rasmussen & Morrissey, 2008; Thorstad et al., 2013). However, underwater habitats introduce diverse video monitoring challenges such as adverse water conditions, high similarity between fish species, cluttered backgrounds and occlusions among fish. In addition, the volume of data generated by deployed RUVs and AUVs rapidly surpasses the capacity of human video viewers, making video analysis prohibitively expensive (Konovalov et al., 2019a). Moreover, humans are more prone to error than a well-designed machine-centred monitoring algorithm. Therefore, an automated, comprehensive monitoring system could significantly reduce labour expenses while improving throughput and accuracy, increasing the precision in estimates of fish stocks, fish distribution and biodiversity in general (Hilborn & Walters, 1992). Implementing such systems necessitates effective computer vision (CV) processes. As a result, significant research has been conducted on implementing monitoring tools and techniques that build upon CV algorithms for determining how fish exploit various maritime environments and differentiating between fish species (Zion, 2012).

In image analysis and CV domains, deep learning (DL) approaches have consistently produced state-of-the-art results in a variety of applications from agriculture (Olsen et al., 2019) to medicine (Azhgadi et al., 2020; Saleh et al., 2021) using deep neural networks (DNNs) (Miikkulainen et al., 2019; Montavon et al., 2018; Zheng et al., 2020). Notably, a video is inherently composed of images or frames, which are processed using image analysis techniques. Therefore, image- and video-based monitoring tasks can be done using DL models such as convolutional neural networks (CNNs) that receive an image (frame) as their input. Therefore, the methods mentioned for image-based tasks are useful for both images and videos.

Many DNN-based approaches outperform conventional methods in marine applications, including ecological and habitat monitoring, using video trap data (Tabak et al., 2019; Willi et al., 2019). DL is a technique that mimics how people acquire knowledge by continuous analysis of input data. The main drivers of DNN success over the past decade have been architectural progress by a large community of computer scientists, more powerful computers and processors, and access to massive amounts of data, which is critical for developing successful generalizable DL applications.

Deep neural networks have been successfully employed in many CV applications such as object classification, identification and segmentation as a result of the invention of CNN. CNN is a class of DNN, most commonly applied to visual analyses. For instance, CNNs have been successfully used for analysis of fish habitats (Konovalov et al., 2019a; Pope et al., 2010; Xu et al., 2019). In comparison with other image recognition algorithms, CNNs have the significant benefit that they require limited pre-processing. CNNs are not hand-engineered

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but uncover and learn hidden features in the data on their own. They learn level by level with various levels of abstraction. For instance, they learn simple shapes (edges, lines, etc.) in the first few layers, understand more sophisticated patterns in their next layers, and learn classes of objects in their final layers.

A putative challenge with CNNs is that they require a large number of images to be fully trained and generalize their learning

to unseen scenarios. On the contrary, CNNs have an interesting and powerful feature that enables transfer of their learning and knowledge across different domains. This means that they can be fine-tuned to work on new data sets (e.g. fish data sets) other than the one that they have been trained on (e.g. general objects). However, fine-tuning with annotated data sets specific for a given domain implies cost/effort/time needed to generate the annotations and also requires a larger set of data, which may not always be available.

Equipping CV algorithms with the powerful learning and inference capabilities of CNNs can provide marine scientists and ecologists with powerful tools to help them better understand and manage marine environments. However, although DL and its variants such as CNNs have been applied to various applications across a multitude of domains (Deng & Yu, 2013; Min et al., 2017; Pathak et al., 2018), their use in conjunction with computer vision for marine science and fish habitat monitoring is not broadly appreciated, meaning they remain underutilized. To address this, in this paper, we introduce key concepts and typical architectures of DL and provide a comprehensive survey of key CV techniques for underwater fish habitat monitoring. In addition, we provide insights into challenges and opportunities in the underwater fish habitat monitoring domain. It is worth noting that our article is written to provide a general and high-level, as opposed to detailed, introduction of deep learning and its relevant contexts for marine scientists. This is useful in understanding the follow-up discussions on the use of deep learning in the marine task of underwater fish classification.

Although a recent survey reviews deep learning techniques for marine ecology (Goodwin et al., 2022) and briefly discusses DL-based fish image analysis, to the best of our knowledge, no comprehensive survey and overview of deep learning with a specific focus on fish classification in underwater habitats currently exists. Our paper tries to address this gap and to facilitate the application of modern deep learning approaches into the challenging underwater fish images analysis and monitoring domains. We do this by comprehensively reviewing and analysing the literature by providing information about the DL model the previous works have used, their training data set, their annotation techniques, their performance and a comparison with other similar works. This detailed analysis is not provided in Goodwin et al. (2022).

In addition, another survey (Li & Du, 2021) exists that focuses on five different tasks of classification, detection, counting, behaviour recognition and biomass estimation. Compared with Li and Du (2021), we provide a different analysis and review of the literature because we mainly focus on the classification of fish in underwater images. Li and Du's work (Li & Du, 2021) fits mostly in the domain of aquaculture, while our paper is mostly a review of 'fish classification techniques in underwater habitats' and the challenges they bring. Li and Du introduce a background to many different DL architectures, one of which is CNN, which is the focus of our paper. Also, the challenges and opportunities that Li and Du introduce are different to our paper, which is mainly about underwater fish classification in their natural habitat.

Furthermore, we provide a historical review of the CV and DL research using underwater cameras for fish classification and analyse how their accuracy has evolved over years. This is not covered by previous works including Goodwin et al. (2022) and Li and Du (2021).

2 | BACKGROUND TO COMPUTER VISION AND MACHINE LEARNING

Humans have a natural ability to comprehend the three-dimensional structure of the world around us. Vision scientists (Oomes, 2001) have spent decades attempting to understand how the human visual system functions (Wang & Weiland, 2017). Inspired by their findings, CV researchers (Ballard & Brown, 1982; Huang, 1996; Sonka et al., 2008) have also been working on ways to recover the 3D shape and appearance of objects from photographs. The automatic retrieval, interpretation and comprehension of useful information from a single image or collection of images can be referred to as CV. In another definition, CV is a field of artificial intelligence (AI) that focuses on training computers to detect, recognize and understand images similar to processes used by humans. This necessitates the development of logical and algorithmic foundations for automated visual understanding (Mader et al., 2018). This understanding can include image classification, object localization, object recognition, semantic segmentation and instance segmentation, as shown in Figure 1. Today, computers with CV powers can extract, analyse and interpret significant information from a single image or a sequence of images.

Despite this progress, the goal of making a computer to understand a picture at the same level as a two-year-old child remains unattainable. This is due, in part, to the fact that CV is an inverse problem in which we attempt to recover specific unknowns despite having inadequate knowledge to completely describe the solution. In CV applications, the cause is usually an exploration process, while the effects are the observed data. The corresponding forward problems then consist of predicting empirical data given complete knowledge of the exploration process. In some sense, solving inverse problems means 'computing backwards', which is usually more difficult than forward problem-solving (Hohage et al., 2020).

The problem of backward computation was eased by the introduction of ML techniques more than six decades ago. However, in conventional ML approaches, the majority of complex features of the learning subject must be identified by a domain expert in order to decrease the complexity of the data and make patterns more evident for successful learning (see Figure 2, top). However, DL offered a fundamentally new method to ML. Most DL algorithms possess the ground-breaking ability of automatically learning high-level features from data with minimal or no human intervention (see Figure 2, bottom).

Deep learning is based on neural networks, which are general-purpose functions that can learn almost any data type that can be represented by many instances. When you feed a neural network a large number of labelled instances of a certain type of data, it will be

able to uncover common patterns between those examples and turn them into a mathematical equation that will assist in categorizing future data. Empowered by this fundamental feature, DL and DNN have progressed from theory to practice as a result of advancements in hardware and cloud computing resources (Azghadi et al., 2020). In recent years, DL approaches have outperformed previous state-of-the-art ML techniques in a variety of areas, with CV being one of the most notable examples.

Before the introduction of DL, the capabilities of CV were severely limited, necessitating a great deal of manual coding and effort. However, owing to improved research in DL and neural networks, CV is now able to outperform humans in several tasks related to object recognition and classification (Qin et al., 2016; Salman et al., 2016; Sarigül & Avci, 2017; Sun et al., 2017). CV equipped with DL is being used today in a wide variety of real-world applications that include, but are not limited to:

- Optical character recognition (OCR) (Permaloff & Grafton, 1992): automatic number plate recognition and reading handwritten postal codes on letters;
- Machine inspection (Park et al., 2016): fast quality assurance inspection of components using stereo vision with advanced lighting to assess tolerance levels on aircraft wings or car body parts, or to spot flaws in steel castings using X-ray technology;
- Retail (Trinh et al., 2012): object detection for automatic checkout lanes;
- Medical imaging (Erickson et al., 2017): registration of preoperative and intraoperative imaging or long-term analyses of human brain anatomy as they age;
- Automotive safety (Falcini et al., 2017): detection of unforeseen objects such as pedestrians on the street (e.g. fully autonomously driving vehicles);
- Surveillance (Brunetti et al., 2018): monitoring of trespassers, studies of highway traffic and monitoring pools for drowning victims;
- Fingerprint recognition and biometrics (Kim et al., 2016): for both automatic entry authentication and forensic software.

This demonstrates the significant impact of DL on CV and demonstrates its potential for marine visual analysis applications.

3 | THE EVOLUTION OF COMPUTER VISION APPROACHES TO FISH CLASSIFICATION

The last two decades have witnessed the emergence of novel computer vision approaches for fish classification including the design and evaluation of complex algorithms that could not be applied before and became possible with the availability of sufficiently large data and the use of powerful graphical processing units (GPUs). Here, we perform a systematic literature review of the evolution of computer vision applications and their different approaches over the past two decades.

3.1 | Search and selection criteria

We systematically reviewed the literature for underwater fish classification using computer vision from 2003 to 2021. The search terms used included 'underwater fish classification', 'Deep Learning', 'Computer Vision' and 'Machine vision'. The databases searched included Wiley Online Library, IEEE Xplore, Elsevier/ScienceDirect and ACM Digital Library. We believe that combining these four databases accurately represents global research on this topic.

We divided the search into two stages. First, we queried the databases for articles with the above-mentioned keywords in their titles and contents. Secondly, we independently reviewed the titles and abstracts of each article in order to check its relevance to our research topic. After the individual title and abstract reviews, we considered 64 articles for full-text reading. In the full-reading phase, we extracted information relevant to our research topic. In this phase, it became clear that 21 papers were not relevant to our work and therefore were excluded. This left us with 43 papers for fish classification, 26 of which were classical computer vision methods, and 17, deep learning papers. Figure 3 presents an overview of the methods used in the identified studies and classifies them into several groups, based on their classification algorithms that can be categorized into two general category of conventional CV and modern DL models.

3.2 | The evolution of fish classification algorithms over two decades

The publication trend for fish classification studies is summarized in Figure 4. The figure shows the cumulative number of publications and how the studies evolved over the past two decades. It is evident that the number of publications has been gradually increasing, but in 2016, when the first few studies using deep learning were combined with CV methods, the study numbers have seen the highest increase and a fast upward trajectory for a few years (2015–2019) after DL burgeoned in fish classification, and before slowing down.

Figure 4 also shows the highest classification accuracy achieved in each year, as a quality assessment metric. It is evident that since 2016, when DL techniques were first proposed for fish classification, the accuracy has seen its highest value. At the same time, it can be seen that there are large differences in the accuracies achieved over years. The main reasons for this difference include (i) using different classification and CV methods, and (ii) using different fish image sources that were captured differently and in different environments. These bring huge variations among studies, such as different image resolutions and inconsistent resolutions and image qualities across time. For example, some fish image data sets are in greyscale (Chuang et al., 2014, 2016; Kartika & Herumurti, 2017), while others are in colour (Shafait et al., 2016; Zion et al., 2007, 2008). Some data sets contain only images (Islam et al., 2019; Kartika & Herumurti, 2017), while others include videos (Cutter et al., 2015; Hossain et al., 2016; Lopez-Villa et al., 2015). Also, some data sets (Huang et al.,

2014) used low-quality images from the Internet, which negatively affects the accuracy, due to their wide range of resolutions, colours and angles. They are also taken at random locations. Due to these factors in various studies, direct comparison of accuracy values is unfeasible, though the accuracy trend can be still observed in Figure 4.

Computer vision for fish classification in the early 2000s and up to 2016, when first DL works started, has been mainly to manually extract fish features and then build classifiers that recognize these features. These conventional studies are listed, in a chronological order, in Table 1. Although there are many existing models, most of the classical non-DL models are based on local and engineered features. These include works using Haar features (Mutneja & Singh, 2021), scale-invariant feature transform (SIFT) (Lindeberg, 2012) and histogram of oriented gradient (HOG) (Dalal & Triggs, 2005), which need hand-engineered algorithms. Because these algorithms are not suitable for recognizing images of untrained animals and cannot capture fish features from complex backgrounds, they usually use a large number of manually extracted samples to build classifiers.

As shown in Table 1, support vector machines (Chuang et al., 2016; Fouad et al., 2014; Hossain et al., 2016; Hu et al., 2012; Huang et al., 2014; Islam et al., 2019; Ogunlana et al., 2015; Rova et al., 2007; Wang et al., 2017a) were one of the most commonly used classifiers for fish recognition, but they are prone to overfitting when trained with too many samples. This problem limits the scale of application. Another popular classification technique used in early works was backpropagation to train a simple feed-forward shallow neural network (Alsmadi et al., 2010, 2011; Badawi & Alsmadi, 2014; Boudhane et al., 2016; Pornpanomchai et al., 2013). Although this technique can handle simple samples, it is difficult to scale because of the neural network shallow layers, which will be explained in the next section. Naive Bayes (Kartika & Herumurti, 2017; Nery et al., 2005; Zion et al., 2007, 2008) have also been used to classify fish since the early 2000s and up to 2017. The technique does not require much training data, and as shown in Table 1 can reach good accuracy levels. Table 1 also shows some other CV classification techniques, which, while not as popular as the above-mentioned methods, could demonstrate good performance. However, it should be noted that most of the CV techniques in Table 1 were carefully engineered for their target data sets and are not capable of showing a similar performance level if used for another similar data set. They will perhaps require an overhaul in their design, starting from manual feature engineering to designing the detailed classification models.

In contrast, deep learning can extract features and perform classification tasks automatically. The features are invariant to data

scaling, translation, rotation and distortion. Because these features are better for classification, the classification performance can be better than that conventional CV tasks using manually designed features. Also, DL classification models, compared to traditional CV one, usually require a simpler redesign procedure to work on a new similar data set, due to the ability to extract features on their own.

Although DL emerged in 2012 (Krizhevsky et al., 2012), its first use for underwater fish classification was in 2016 (Salman et al., 2016). After that, 16 other works also used DL and its CNNs, as shown in Figure 3, to develop models that learn features from large amounts of data without manual interference. These studies have shown that, by using deep learning, some of the usual fish image classification challenges such as image noise reduction, classification of difficult or rare-seen fish, and classifying small fish can be solved.

In the following parts of this paper, we mainly focus on deep learning, how it works and how it can be applied to develop efficient and high-performance underwater fish classifiers. We will also critically analyse the 17 DL studies found as part of our systematic literature review described earlier.

4 | BACKGROUND TO DEEP LEARNING

Deep Learning (DL) (Goodfellow et al., 2016; LeCun et al., 2015) is a subset of ML algorithms that employs a neural network with several layers to very loosely replicate the function of the human brain by enabling it to 'learn' from huge quantities of data. The learning happens when the neural network extracts higher-level features from input training data. The term 'deep' refers to the usage of several layers in the neural network. Lower layers, for example in image processing, could detect edges, whereas higher layers might identify parts of the object.

4.1 | How deep learning differs from machine learning

Machine learning (ML) is usually referred to as a class of algorithms that can recognize patterns in data and create prediction models automatically. Deep learning (DL) is a subclass of standard ML because it uses the same type of data and learning methods that ML applies. However, when dealing with unstructured data, for example text and images, ML usually goes through some pre-processing to convert it to a structured format for learning. DL, on the contrary,

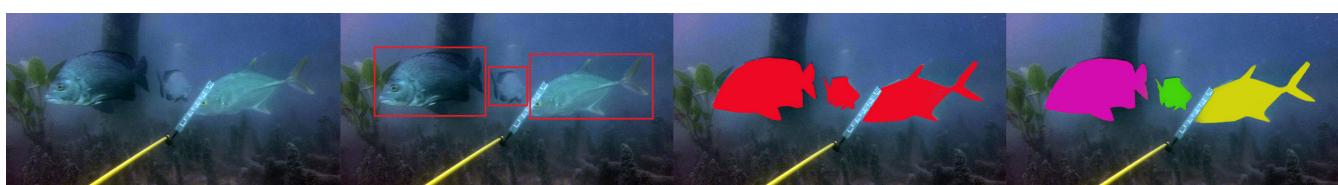


FIGURE 1 Illustration of four typical types of CV tasks (from left): image classification (i.e. is there a fish in the image, or what type (class) of fish is in the image?), object detection/localization, semantic segmentation and instance segmentation

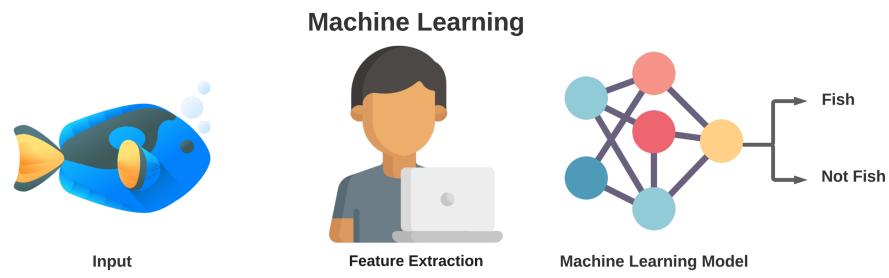
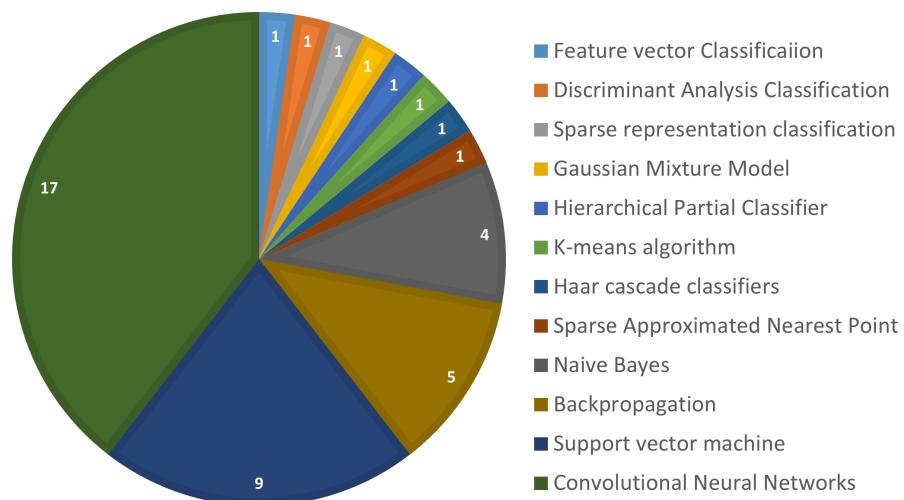
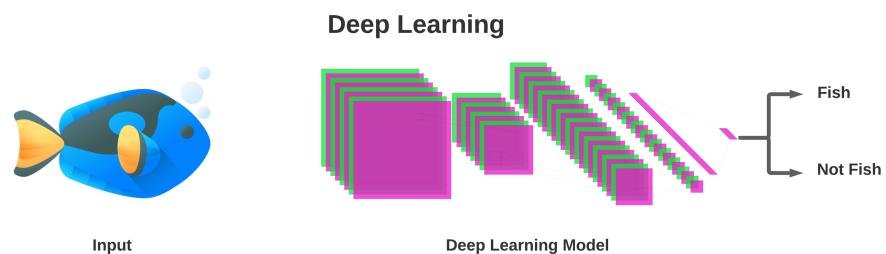


FIGURE 2 Comparison between machine learning (ML) and DL. In ML techniques, the features need to be extracted by domain expert, while DL relies on layers of artificial neural networks to extract these feature



does not usually require the data pre-processing needed by ML. It is capable of recognizing and analysing unstructured data, as well as automating feature extraction, significantly reducing the need for human knowledge (see Figure 2, bottom).

For example, to recognize fish in an image, ML requires that specific fish features (such as shape, colour, size, and patterns) be explicitly defined in terms of pixel patterns. This may be a challenge for non-ML specialists because it typically requires a deep grasp of the domain knowledge and good programming skills. DL techniques, on the contrary, skip this step entirely. Using general learning techniques, DL systems can automatically recognize and extract features from data. This means that we just need to tell a DL algorithm whether a fish is present in an image, and it will be able to figure out what a fish looks like given enough examples. Decomposing the data into layers with varying levels of abstraction enables the algorithm to learn complex traits defining the data, allowing for an automatic learning approach. DL algorithms may be able to determine which features (such as fishtail) are most important in differentiating one animal from another. Prior to DL, this feature hierarchy needed to be determined and created by hand by an ML expert.

4.2 | How deep learning works

Deep neural network (DNN), also known as artificial neural network, is the basis of deep learning. DNNs use a mix of data inputs, weights, and biases to learn the data, by properly detecting, categorizing and characterizing objects in a given data set of interest. DNNs are made up of several layers of linked nodes, each of which improves and refines the network prediction or categorization capabilities. For instance, Figure 5 shows a popular DNN architecture for image processing, called UNET (Ronneberger et al., 2015). UNET, which is a fairly complex deep learning architecture, is composed of a few different components and layers, to achieve a specific learning goal, that is to segment fish body in an input image.

Any DNN is composed of three types of layers, namely input, output and hidden layers. The visible layers are the input and output layers (see Figure 6). The DL model gets the data for processing in the input layer, and the final prediction or classification is generated in the output layer. In a typical neural network, including a DNN, the learning happens through two general processes, that is forward and backward propagations. Forward propagation refers to the propagation of input data through the network layers to generate

FIGURE 3 Overview of the methods used for fish classification using different computer vision techniques from 2003 to 2021. It is evident from the graph that DL and its CNNs have attracted more attention than classical ML methods

a prediction or classification result. Backward propagation or, backpropagation in short, is where the learning happens in the network. Backpropagation uses a training model that determines prediction errors and then changes the weights and biases of the neural network by going backwards through its layers. Forward propagation and backpropagation work together to allow a neural network to generate predictions and reduce the network errors. Through many iterations of backward and forward propagation, the neural network prediction or classification accuracy improves.

Almost all DNNs work on and through the same principles described above. However, different DL networks and architectures are used to solve different tasks. For instance, CNNs, which are commonly used in computer vision and image classification applications, can recognize characteristics and patterns within an image, allowing tasks such as object detection and recognition to be accomplished. However, in tasks with a different nature, such as natural language processing, speech recognition or time-series forecasting (Jahanbakh et al., 2022), recurrent neural networks (RNNs) are commonly employed. Despite the differences in their architectures, many DL techniques use the concept of supervised learning to process their input data and accomplish different tasks.

4.3 | Supervised learning

Supervised learning is a method used to enable finding and optimizing a function that maps an input to its corresponding output in an input–output object pair, also known as training example (Kotsiantis, 2007). Supervised learning uses a set of training examples based on manually labelled training data prepared by human observers or ‘supervisors’, hence the name for the learning method.

The aim of supervised learning is to generate an inferred function, f , that maps to the training examples, and can then be used to

map to new examples outside of the training examples. In order to accomplish any general task, a computer can be programmed to find function f to map X to Y , that is ($f : X \mapsto Y$), where X is an input domain and Y is an output domain. For example, in an image classification task, X is the data set of images and Y is a set of corresponding classification labels, which determine whether an object is present in the respective image in the data set or not.

To determine the function f that can recognize, for instance, a fish in an image using DL, one solution is to do feature engineering. However, it is usually very difficult to perform this, that is hand-pick features of the fish, based on the domain knowledge that comes from the training data set. In addition, most of the time, the hand-picked features need to be pruned to reduce their pixel dimensionality. Comparatively, it is often more feasible to collect a large data set of $(x, y) \in X \times Y$ to find the mapping function f , and this affords supervised learning advantage as an alternative mapping technique compared with direct feature engineering. Specifically, in the fish classification task, a large data set of fish images is collected, where each image x is labelled with y that shows the presence or absence of a fish, without the need to hand-pick its features.

One of the main supervised learning approaches is training a neural network, which is the foundation of deep learning, especially for computer vision applications such as fish image processing. We therefore dedicate the next subsection to neural networks and their underlying working principles.

4.4 | Neural networks

A ‘neural network’ (Cook, 2020) is a computer program originally conceived by mimicking actual cerebral neural networks that make up the brain’s grey matter. A computer’s neural network, a.k.a. an artificial neural network, ‘learns’ to do a specific task by using a large amount

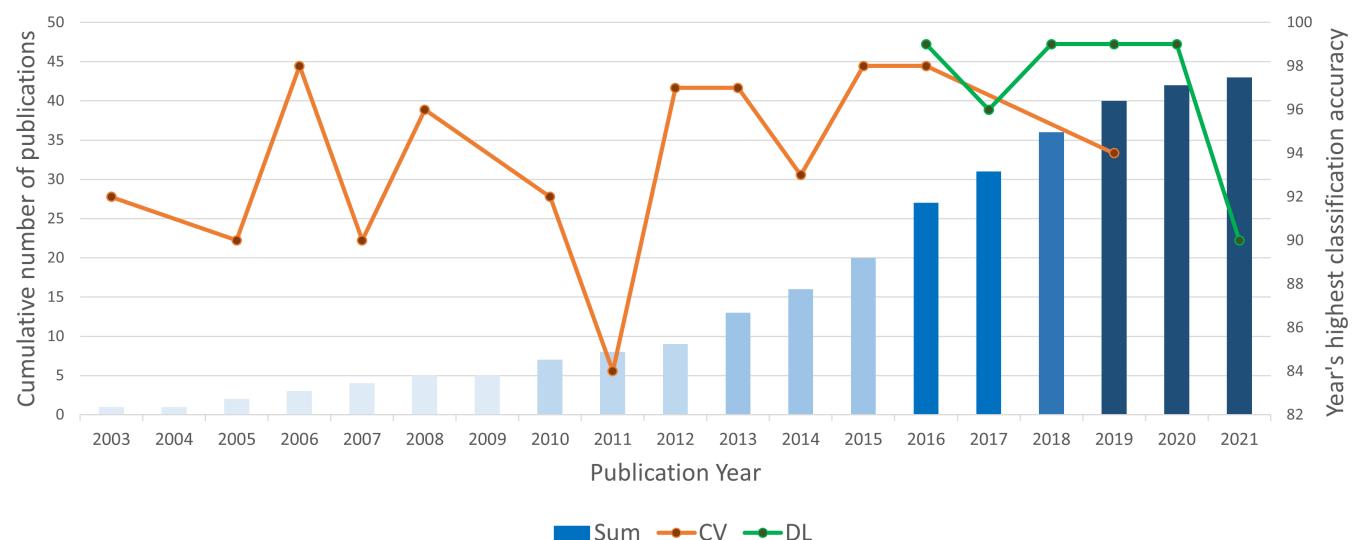


FIGURE 4 Overview of the publication trend and performance of an extensive range of fish classification computer vision (CV) and deep learning (DL) models from 2003 to 2021. Here, the bars show the cumulative number of publications over years and the growth thereof, while the line graphs demonstrate the highest classification accuracy in each year in literature on the right-hand-side vertical axis

TABLE 1 List of computer vision studies for underwater fish classification between 2003 and 2021 using conventional classifiers and based on engineered features

Article	Year	Classification method	AC
An automated fish species classification and migration monitoring system (Lee et al., 2003)	2003	Feature vector classification	92
Determining the appropriate feature set for fish classification tasks (Nery et al., 2005)	2005	Naive Bayes	90
Real-time underwater sorting of edible fish species (Zion et al., 2007)	2006	Naive Bayes	98
One fish, two fish, butterfish, trumpeter: recognizing fish in underwater video (Rova et al., 2007)	2007	Support vector machine	90
Classification of guppies' (<i>Poecilia reticulata</i>) gender by computer vision (Zion et al., 2008)	2008	Naive Bayes	96
Automatic fish classification for underwater species behavior understanding (Spampinato et al., 2010)	2010	Discriminant analysis classification	92
Fish recognition based on robust features extraction from size and shape measurements using neural network (Alsmadi et al., 2010)	2010	Backpropagation	86
Fish classification based on robust features extraction from color signature using back-propagation classifier (Alsmadi et al., 2011)	2011	Backpropagation	84
Fish species classification by color, texture and multi-class support vector machine using computer vision (Hu et al., 2012)	2012	Support vector machine	97
Real-world underwater fish recognition and identification, using sparse representation (Hsiao et al., 2014a)	2013	Sparse representation classification	81
A research tool for long-term and continuous analysis of fish assemblage in coral-reefs using underwater camera footage (Boom et al., 2014)	2013	Gaussian mixture model	97
Automatic Nile Tilapia fish classification approach using machine learning techniques (Fouad et al., 2014)	2013	Support vector machine	94
Shape- and texture-based fish image recognition system (Pornpanomchai et al., 2013)	2013	Backpropagation	90
A general fish classification methodology using meta-heuristic algorithm with back propagation classifier (Badawi & Alsmadi, 2014)	2014	Backpropagation	80
GMM improves the reject option in hierarchical classification for fish recognition (Huang et al., 2014)	2014	Support vector machine	74
Supervised and unsupervised feature extraction methods for underwater fish species recognition (Chuang et al., 2014)	2014	Hierarchical partial classifier	93
A feature learning and object recognition framework for underwater fish images (Chuang et al., 2016)	2015	Support vector machine	98
A novel tool for ground truth data generation for video-based object classification (Lopez-Villa et al., 2015)	2015	K-means algorithm	93
Automated detection of rockfish in unconstrained underwater videos using Haar cascades and a new image dataset: labeled fishes in the wild (Cutter et al., 2015)	2015	Haar cascade classifiers	89
Fish classification using support vector machine (Ogunlana et al., 2015)	2015	Support vector machine	79
Fish identification from videos captured in uncontrolled underwater environments (Shafait et al., 2016)	2016	Sparse approximated nearest point	94
Fish activity tracking and species identification in underwater video (Hossain et al., 2016)	2016	Support vector machine	91
Koi Fish Classification based on HSV Color Space (Kartika & Herumurti, 2017)	2016	Naive Bayes	97
Optical fish classification using statistics of parts (Boudhane et al., 2016)	2016	Backpropagation	95
Shrinking encoding with two-level codebook learning for fine-grained fish recognition (Wang et al., 2017a)	2017	Support vector machine	98
Indigenous fish classification of Bangladesh using hybrid features with SVM classifier (Islam et al., 2019)	2019	Support vector machine	94

Note: The last column presents the work's achieved accuracy.

of data, usually through supervised network training that does not involve any task-specific rules. As briefly mentioned, a neural network is constructed from three types of layers: an input layer, hidden or

latent layers, and an output layer (see **Figure 6**). These layers include processing neurons within them (coloured circles in **Figure 6**), and connecting synapses (weights) between them (edges in the figure).

The input layer is the gate to the network. It provides information to the network from outside data, and no calculation is made in this layer. Instead, input nodes pass the information on to the hidden layer. This layer is not visible to the outside world and serves as an abstraction of the inputs, independent of the neural network structure. The hidden layer (layers) processes the data received from the input layer and transfers the results to the output layer. Finally, the output layer brings the information that the network has learned into the outside world.

Learning in a neural network happens through minimizing a loss function. Generally, a loss function is a function that returns a scalar value to represent how well the network performs a specific task. For example, in image classification, the network is expected to correctly classify all the images containing a fish as fish, and all those not including a fish, as no fish, returning a loss value of zero. During learning, the network receives a large amount of input data, for example thousands of fish images, and eventually learns to minimize the loss between its predicted output and the true target value. In the case of supervised learning, these true target values are provided to the network, to find function f described in the previous section, to minimize the loss function. This minimization happens through optimizing f using an algorithm such as stochastic gradient descent (SGD) (Loshchilov & Hutter, 2017) that helps find network weights/parameters that minimize the loss.

4.5 | Convolutional neural network

Convolutional neural networks are probably the most commonly used artificial neural networks. They have been the dominant deep learning tool in computer vision and have been widely used in underwater marine habitat monitoring (Saleh et al., 2020). CNNs are broadly designed after the neuronal architecture of the human cortex but on much smaller scales (Schmidhuber, 2015). A CNN (LeCun et al., 1998) is specifically designed for dealing with data sets that have some spatial or topological features (e.g. images, videos), where each of the neurons is placed in such a manner that they overlap and thus react to multiple spots in the visual field. A CNN neuron is a simple mathematical design of the human brain's neuron that is utilized to transform non-linear relationships between inputs and outputs in parallel. There are two primary layer types in a CNN, that is convolutional layers and pooling layers, which generate feature maps, as explained in the following subsections.

4.5.1 | Convolutional layer

In this layer, the convolutional processes (i.e. the multiplication of a small matrix of the input neurons by a small array of weights called filter) are used on limited fields (which depend on the size of the filter) to avoid the need to learn billions of weights (parameters), which would be required if all the neurons in one layer are connected to all the neurons in the next layer. This excessive computation is avoided through the weight-sharing of convolutional layers combined with

filters for their corresponding feature maps. In a convolution operation, a small matrix of the input neurons is multiplied in its same-sized matrix, called a filter. In a convolutional layer, this convolution operation happens by sliding the filter on the entire input neurons, generating a feature map. Filters work on a reduced area of the input (convolutional kernel). Convolutional layers can either use the same kernel size, or they can use different kernel sizes, which makes it possible to extract complex features from the input using fewer parameters. In addition, weight-sharing is useful in avoiding model overfitting, that is memorizing the training data (Abdel-Hamid et al., 2013), while also reducing computing memory requirements and enhancing learning performance (Korekado et al., 2003).

4.5.2 | Pooling layer

This layer is used to reduce the spatial dimension (not depth) of the input features and add control for avoiding overfitting by reducing the number of representations with a specified spatial size. Pooling operations can be done in two different ways, that is max and average pooling. In both methods (see Figure 7), an input image is down-scaled in size, by taking the maximum of four pixels and downsampling them to one pixel. Pooling layers are systematically implemented between convolutional layers in conventional CNN architectures. The pooling layers work on each channel (activation map) individually and down-sample them spatially. By having fewer spatial information, pooling layers make a CNN more computationally efficient.

4.5.3 | Feature maps

Feature Maps, also called Activation Maps, are the result of applying convolutional filters or feature detectors to the preceding layer image. The filters are moved on the preceding layer by a specified number of pixels. For instance, in Figure 8, there are 37 filters of the size 3×3 that move across the input image with a stride of 1 and result in 37 feature maps.

The majority of CNN layers are convolutional layers. These layers are used to apply the same convolutional filtering operation to different parts of the image, creating 'neurons' that can then be used to detect features, like the edges and corners. A collection of weights connects each neuron in a convolutional layer to the preceding layer's feature maps, or to the input layer image. The feature maps help visualize the features that the CNN is learning to give an understanding of the network learning process, as shown in Figure 8.

5 | APPLICATIONS OF DEEP LEARNING IN FISH-HABITAT MONITORING

In a recent special issue titled 'Applications of machine learning and artificial intelligence in marine science' published in the International Council for the Exploration of the Sea (ICES) journal of marine

science (Proud et al., 2020), many uses of deep learning and CNNs have been shown. These include identifying the species of harvested fish (Lu et al., 2020), analysis of fisheries surveillance videos (French et al., 2020) and natural mortality estimation (Liu et al., 2020). Other published works have used CNN for other marine applications such as automatic vessel detection (Chen et al., 2019), and analysis of deep-sea mineral exploration (Juliani & Juliani, 2021). However, in this paper we focus on using CNNs for CV tasks.

These tasks are mainly designed to extract knowledge from underwater videos and images. Despite the recent use of CNNs for various visual analysis tasks such as segmentation (Alshdaifat et al., 2020; Garcia et al., 2020; Islam et al., 2020; Zhang et al., 2022), localization (Jalal et al., 2020; Knausgård et al., 2021; Su et al., 2020) and counting (Ditria et al., 2021; Schneider & Zhuang, 2020; Tarling et al., 2021), the most common and the widest studied CV task in underwater fish habitat monitoring has been classification. Therefore, in this paper, we focus mainly on classification of underwater fish images. We survey some of the latest works on fish classification and provide a high-level technical discussion of these works.

The task of classification is defined as classifying the input samples into different categories, usually based on the presence or absence of a certain object/class, in binary classification; or the presence of several different objects belonging to different classes, in multiclass classification (Ismail Fawaz et al., 2019). Similarly, image classification is concerned with assigning a label to a whole image based on the objects in that image. Conceivably, an image can be labelled as fish, when there is a fish present in it, or negative when no fish is present. Similarly, images of different species should be automatically assigned to their respective classes or given a label representing their class.

Classification is a difficult process if done manually, because an image may need to be categorized into more than one class. In

addition, there may be thousands of images to be classified, which makes the task very time-consuming and prone to human error. Consequently, automation can help perform classification quicker and more efficient.

In the context of fish and marine habitat monitoring, CV offers a low-cost, long-term and non-destructive observation opportunity. One of the initial tasks performed using deep learning on CV-collected marine habitat images is fish classification, which is a key component of any intelligent fish monitoring systems, because it may activate further processing on the fish image. However, underwater monitoring based on image and video processing poses numerous challenges related to the hostile condition under which the fish images are collected. These include poor underwater image quality due to low light and water turbidity, which result in low resolution and contrast. Additionally, fish movements in an uncontrolled environment can create distortion, deformations, occlusion and overlapping. Many previous works (Boom et al., 2012; Martinez-de Dios et al., 2003; Takada et al., 2014) have tried to address these challenges. Some of these works focused on devising new methods to properly extract traditional low-level features such as colours and textures using mean shift algorithm (Boudhane & Nsiri, 2016), in the presence of the challenges. However, these works have not been very successful compared with DL approaches.

With the inception of CNNs, many researchers utilized them to extract both high-level and low-level features of input images. These features, which can be automatically detected by the CNN, carry extensive semantic information that can be applied to recognize objects in an image. In addition, CNNs have the ability to address the challenges outlined above. Therefore, they are currently the main underwater image processing tool in literature for fish classification, as shown in Tables 2 and 3. These tables list some of the latest

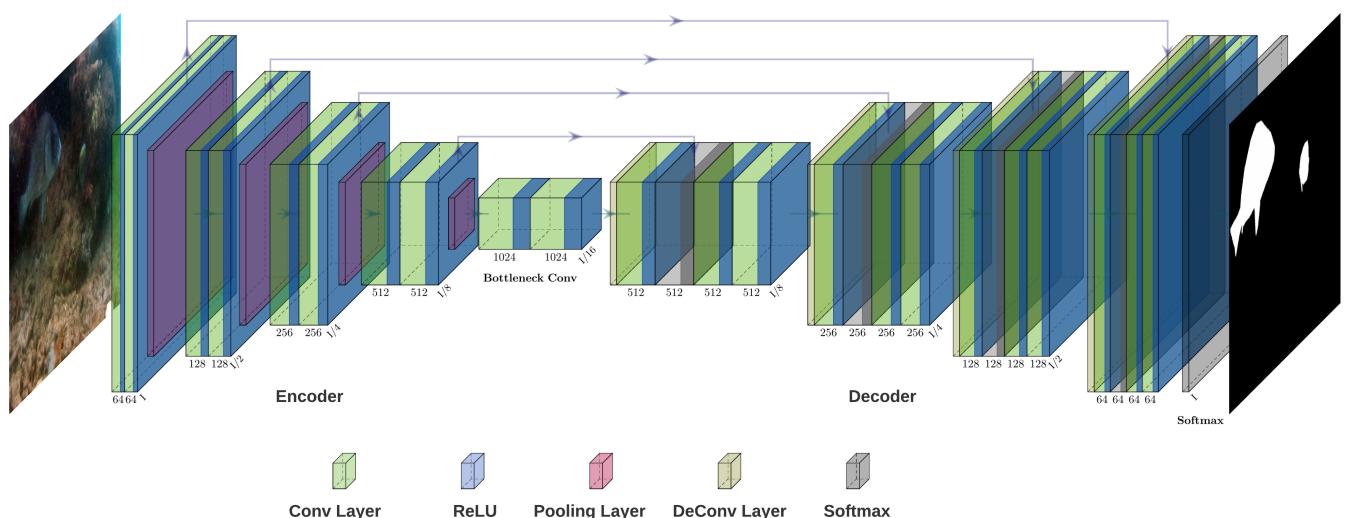


FIGURE 5 Popular CNN architecture, named UNET (Ronneberger et al., 2015), is demonstrated. The first component of UNET is the encoder, which is used to extract features from the input image. The second component is the decoder that outputs per-pixel scores. The network is composed of five different layers including convolutional (Conv Layer), rectified linear unit (ReLU), pooling, deconvolutional (DeConv) and SoftMax. Here, the task of the DNN layers has been to give a high score to only the pixels in the input image that belong to the fish body, resulting in the demonstrated white blobs output, showing where the fish are

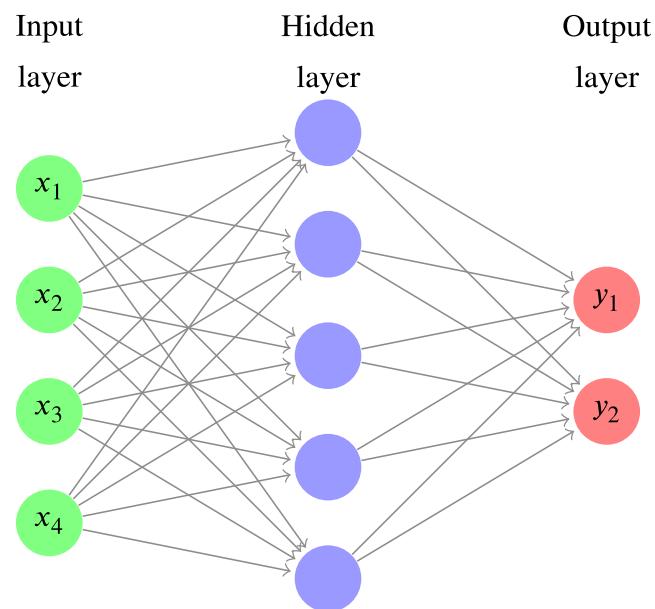


FIGURE 6 Diagram of a single-layer neural network, composed of input, hidden and output layers

classification works, while providing details about the DL models used and the framework within which the model was implemented. It also provides information about the data source, as well as the pre-processing of the data and its labels, while reporting the classification accuracy (CA) and a short comparison with other methods if the reviewed work has provided it. One of the main metrics when comparing different methods for classification is their CA, which is defined as the percentage of correct predictions by the network.

$$CA = (TP + TN) / (TP + TN + FP + FN), \quad (1)$$

where TP (true positive) and TN (true negative) represent the number of correctly classified instances, while FP (false positive) and FN (false negative) represent the number of incorrectly classified instances. For multiclass classification, CA is averaged among all the classes.

Deep learning algorithms are gaining momentum in their growing accuracy in different applications. However, they have inherent limitations, which should be considered before choosing a DL algorithm for a given application. This is because accuracy, for example in a fish classification task, may significantly differ from true accuracy due to the distribution of samples in the training and testing populations. To address this limitation of classification accuracy, the receiver operating characteristics (ROC) (Krupinski, 2017) and area under the curve (AUC) (Janssens & Martens, 2020) are widely used as a standard measure for determining the performance of a model in a binary classification setting. Their definition is very similar to accuracy, but they help one understand the probability that the classifier produces correct outputs with desired levels of true positives and false negatives, using a certain classification threshold.

The works in **Tables 2** and **3** can be divided into two general categories. The first category deals with designing effective CNNs that address the challenge of unconstrained, complex and noisy

underwater scenes, while the second category also tries to address the usual problem of limited fish training data sets.

As mentioned, when processing unconstrained underwater scenes specific attention should be paid to implementing a classification approach that is capable of handling variations in light intensity, fish orientation and background environments, and similarity in shape and patterns among fish of various species. In order to overcome these challenges and to improve classification accuracy, various works have devised different methodologies. In Varalakshmi and Julanta Leela Rachel (2019), the authors used different activation functions to examine the most suitable for fish classification, while in Sarigül and Avci (2017), different number of convolutional layers and different filter sizes were examined. In Salman et al. (2016), the authors used a CNN model in a hierarchical feature combination set-up to learn species-dependent visual features for better accuracy. In another work (Qin et al., 2016), principal component analysis was used in two convolutional layers, followed by binary hashing in the non-linear layer and block-wise histograms in the feature pooling layer. Furthermore, a single-image super-resolution method was used in Sun et al. (2017) to resolve the problem of limited discriminative information of low-resolution images. Moreover, Chen et al. (2018) used two independent classification branches, with the first branch aiming to handle the variation of pose and scale of fish and extract discriminative features, and the second branch making use of context information to accurately infer the type of fish. The reviewed works show that depending on the type of environment and fish species similarities in the data set under consideration, various techniques should be considered and investigated to find the best classification accuracy.

As already mentioned, data gathering in the wild is sometimes very difficult and challenging; thus, to maximize the success rate of training, it is essential to consider gathering field data from the beginning of the project. This ensures that the collected training data set has good sample diversity including samples collected at different environmental conditions such as water turbidity and salinity, and it captures fish species similarities. Diversity and comprehensiveness in the data set is one of the key factors in reaching high classification accuracies when the model is deployed in the real world. Data augmentation is another important method that can help improve the classification accuracy, through increasing the data set size and diversity. An alternative to data augmentation is transfer learning, but the model should be always fine-tuned to the new data set to maximize accuracy. Image pre-processing is another important technique that can help improve classification accuracy, and should be considered when working with new fish data sets.

Data set limitation, that is having limited number of fish images from different species, and/or having few numbers of different fish, is another challenge in underwater fish habitat monitoring in general and in fish classification in specific. This challenge has been addressed in Saleh et al. (2020), Jin and Liang (2017), Rathi et al. (2017) and Tamou et al. (2018) using transfer learning.

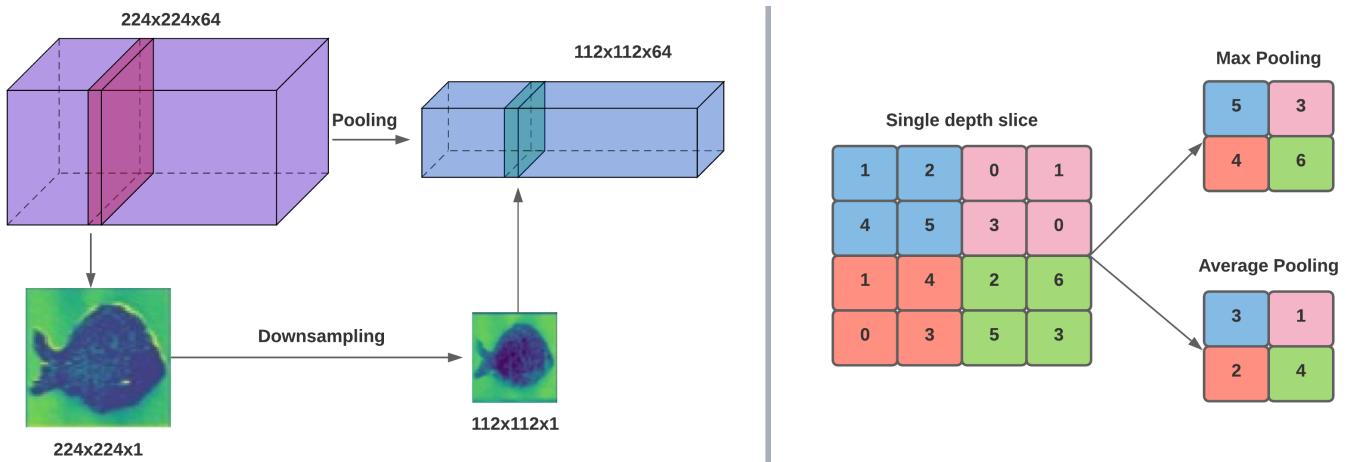


FIGURE 7 Schematic diagram of pooling layer: (Left) single feature map spatially downsampled from a representation block with shape $224 \times 224 \times 1$ to a new representation of shape $112 \times 112 \times 1$. (Right) types of pooling layer (max pooling and average pooling)

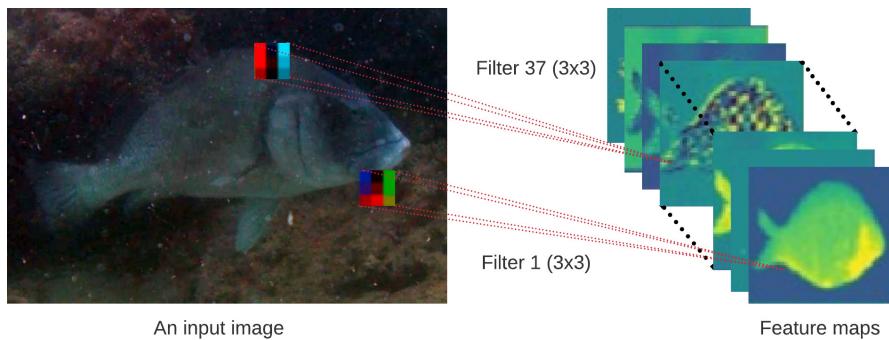


FIGURE 8 Schematic diagram of feature maps of the CNN used in the classification task. The feature map is a two-dimensional representation of an input image. Here, (3×3) is the size of the filter slid over the entire image to generate feature maps

Transfer learning is a ML method that works by transferring information obtained while learning one problem or domain to a different but related problem or domain. Comparing a randomly initialized classifier with another one pre-trained on ImageNet (Russakovsky et al., 2015), Saleh et al., (2020) achieved a fish classification accuracy of 99%, outperforming the randomly initialized classifier, significantly. This finding shows that transfer learning can bring learned information from the ImageNet learning domain to fish classification domain and can be a useful and crucial method for evaluating fish environments. Transfer learning was also used in Konovalov et al. (2019b) where general-domain above-water fish image learning was transferred and used for underwater fish classification. In the same way, to train large-scale models that are able to generate reasonable results, Zhuang et al. (2020) collected 1000 fish categories with 54,459 unconstrained images from various professional fish websites and Google engine.

In addition to transfer learning, some works have developed specific machine-learning techniques suiting their applications. For instance, in a previous study (Siddiqui et al., 2018), a pre-trained CNN was used as a generalized feature extractor to avoid the need for a large amount of training data. The authors showed that by feeding the CNN-extracted features to a support vector machine (SVM) classifier (Pisner & Schnyer, 2019), a CA of 94.3% for fish species classification can be achieved, which significantly

outperforms a stand-alone CNN achieving an accuracy of 53.5%. Also, Deep and Dash (2019) used the same techniques in Siddiqui et al. (2018) to achieve a CA of 98.79%. In addition, Iqbal et al. (2021) developed a new technique for fish classification by modifying AlexNet (Krizhevsky et al., 2012) model with fewer number of layers. Moreover, Konovalov et al. (2019a) presented a labelling efficient method of training a CNN-based fish detector on a small data set by adding 27,000 above-water and underwater fish images.

Convolutional neural networks are sometimes capable of surpassing human performance in identifying fish in underwater images. By training a CNN on 900,000 images, Villon et al., (2018) could achieve a CA of 94.9%, while human CA was only 89.3%. This result was achieved mainly because the CNN was able to successfully distinguish fish that were partially occluded by corals or other fish, while humans could not. Furthermore, the best CNN model developed in Villon et al. (2018) takes 0.06 s on average to identify each fish using typical hardware (Titan X GPU). This demonstrates that DL techniques can conduct accurate fish classification on underwater images cost-effectively and efficiently. This facilitates monitoring underwater fish and can advance marine studies concerned with fish ecology.

If DL methods are going to be deployed widely for different marine applications such as fish classification, there is a need to

implement them efficiently so that they can run on low-power embedded systems, which can run in real time on mobile devices such as underwater drones. To that end, Meng et al., (2018) have developed an underwater drone with a panoramic camera for recognizing fish species in a natural lake to help protect the environment. They have trained an efficient CNN for fish recognition and achieved 87% accuracy while requiring only 6 s to identify 115 images. This promising result shows that DL can be used to classify underwater fish while also satisfying the real-time conditions of mobile monitoring devices. In addition, other efficient hardware design approaches that have proven useful in reducing power consumption and increasing speed in classification task in other domains such as agriculture (Lammie et al., 2019) can be adopted on edge underwater processors.

In DL applications, video storage is currently a bottleneck that may be bypassed with real-time algorithms, because they only need to store some and not all the video frames in memory and process them in situ, as they become available. This eliminates the time it takes for all the frames to be stored and retrieved from memory. This is helpful in situations where large amounts of data have to be processed quickly, for example, in an underwater fish observation camera, where frames are collected continuously and should either be stored locally or transferred to surface, which are both costly and mostly impossible. Using real-time processing algorithms, the frames are processed and only the information obtained, that is the number of fish in a frame, is sent or stored, which is much lighter than the entire frame.

6 | CHALLENGES AND APPROACHES TO ADDRESS THEM

Despite the rapid improvement of DL for marine habitat monitoring through visual analysis, four main challenges still exist. The first challenge is to develop models that can generalize their learning and perform well on new unseen data samples. The second challenge is limited data sets available for general DL tasks, and in particular for marine visual processing tasks. The third challenge is lower image quality in underwater scenarios. The fourth challenge is the gap between DL and ecology.

To address these challenges, various computer algorithms and techniques have been developed. In the following subsections, we explain the challenges in detail and briefly review various approaches to address them. However, we do not intend to include details of these approaches as they are out of the scope of this paper. The interested reader is invited to refer to relevant DL materials and the cited papers.

6.1 | Model generalization

One of the most difficult challenges in DL is to improve deep convolutional networks generalization abilities. This refers to the gap between a model's performance on previously observed data (i.e.

training data) and data it has never seen before (i.e. testing data). A wide gap between the training and validation accuracy is usually a sign of overfitting. Overfitting occurs when the model accurately predicts the training data, mostly because it has memorized the training data instead of learning their features.

One way to monitor overfitting is by plotting the training and validation accuracy at each epoch during training. That way, we will see that whether the gap between the validation and training accuracy/error is widening (over- or under-fitting) or narrowing (learning). A well-known and effective method for improving the generalizability of a DL model is to use regularization (Kukac'ka et al., 2017). Some of the regularization methods applied to fish and marine habitat monitoring domains include transfer learning (Zurowietz & Nattkemper, 2020), batch normalization (Islam et al., 2020), dropout (Iqbal et al., 2021) and using a regularization term (Tarling et al., 2021).

6.2 | Data set limitation

Another challenge of training DL models is the limited data set. DL models require enormous data sets for training. Unfortunately, most data sets are large, expensive and time-consuming to build. For this reason, model training is usually conducted by collecting samples from a small number of data sets, rather than from a large number of data sets.

A data set can be categorized into two parts: labelled data and unlabelled data. The labelled data are the set of data that need the labelling of classes, for example fish species in an image, or absence or presence of fish in an image. The unlabelled data are the set of data that have not been processed. The labelled data form the training set whose size is closely related to the accuracy of the trained model. The larger the training set, the more accurate the trained model. Large training set, however, is expensive to build. They require a large number of resources, such as people-hours, space and money, making it very difficult for many researchers to achieve them, and in turn hinder their research.

Since it is difficult to obtain a large labelled data set, various techniques have been proposed to address this challenge. Some of the techniques applied to the fish and marine habitat monitoring domains include transfer learning (Qiu et al., 2018), data augmentation (Saleh et al., 2020; Sarigül & Avci, 2017), using hybrid features (Blanchet et al., 2016; Cao et al., 2016; Mahmood et al., 2016), weakly supervised learning (Laradji et al., 2021) and active learning (Nilssen et al., 2017).

6.3 | Image quality

Underwater image recognition's average accuracy lags significantly behind that of terrestrial image recognition. This is mostly owing to the low quality of underwater photographs, which frequently exhibit blurring, and colour deterioration, caused by the physical characteristics of the water and the hostile underwater environment.

TABLE 2 Classification

Article	DL model	Framework	Data	Annotation/ pre-processing/ augmentation	Classes and labels	Perf. metric	Matric value	Comparisons with other methods
Recognition of fish categories using deep learning technique (Varalakshmi & Julanta Leela Rachel, 2019)	CNN	Keras, TensorFlow	Authors-created data set containing 560 fish images, 400 training and 160 test images.	Each image is assigned the fish species name as a label	10 classes of 10 different fish species	CA	95%	NA
Comparison of different DL structures for fish classification (Sarıgil & Avci, 2017)	CNN	Torch	The public QUT fish data set contains 3960 images of 468 fish species in different environments.	Each image is assigned the fish species name as a label	468 classes of 468 different fish species	CA	46.02%	NA
Fish species classification in unconstrained underwater Environments based on DL (Salman et al., 2016)	CNN	NA	The images are from the public Fish4Knowledge data set (LifeCLEF 2014, LifeCLEF 2015)	Each image is assigned the fish species name as a label	25 classes of 25 different fish species	CA	96.75%	Comparison with the conventional SVM machine-learning tool that achieved 83.94%
Deepfish: accurate underwater live fish recognition with a DL architecture (Qin et al., 2016)	CNN	MATLAB	The images are from the public Fish4Knowledge data set	Each image is assigned the fish species name as a label	23 classes of 23 different fish species	CA	98.64%	Comparison with conventional machine-learning tools as baseline methods achieving 93.58%
Fish recognition from low-resolution underwater images (Sun et al., 2017)	CNN	NA	93 videos from LifeCLEF 2015 fish data set	Each image was annotated by drawing a bounding box and labelling by species name	15 classes of 15 different fish species	CA	76.57%	Authors used the traditional Gabor features and dense SIFT features that generated CA of 38.28% and 28.63%, respectively.
Automatic fish classification system using DL (Chen et al., 2018)	CNN	NA	Eight target categories: Albacore tuna, Bigeye tuna, Yellowfin tuna, Mahi mahi, Opah, Sharks, Other.	Each image is assigned the fish species name as a label	8 classes of 8 different fish species	CE	0.578, 1.387	Ranked 17th on Kaggle leaderboard on test set at stage 1 and 16th at stage 2.
A realistic fish-habitat dataset to evaluate DL algorithms for underwater visual analysis (Saleh et al., 2020)	ResNet-50	PyTorch	Authors-created database containing 39,766 images from 20 habitats in remote coastal marine environments of tropical Australia	point-level and semantic segmentation labels	20 classes of 20 different fish species	CA	0.99	NA

TABLE 2 (Continued)

Article	DL model	Framework	Data	Annotation/ pre-processing/ augmentation	Classes and labels	Perf. metric	Matrix value	Comparisons with other methods
Deep learning for underwater image recognition in small sample size situations (Jin & Liang, 2017)	CNN	Caffe	The images are from the public Fish4Knowledge data set	Each image is assigned the fish species name as a label	10 classes of 10 different fish species	CA	85.08%	NA
Underwater fish species classification using CNN and DL (Rathi et al., 2017)	CNN	NA	27000 images from the public Fish4Knowledge data set	Each image is assigned the fish species name as a label	23 fish classes	CA	96.29%	NA

Note: The last column presents the work's achieved accuracy.

Most CV applications perform some initial pre-processing of images before feeding them to their image processor. In underwater scenarios, these pre-processing techniques are typically used to enhance the image quality. Pre-processing can also help with the red channel information loss problem, which is required for obtaining relevant colour data. The red channel information loss problem is about losing the actual intensity of the red colour in the scene, for instance, compared with the blue and green colour channels. This is more pronounced in the underwater environment and as the depth increases, which attenuates red channel values more strongly than the other colour channels. We should therefore consider that the red channel value depends not only on the distance from the subject but also on the intensity of the light reflected by the subject, as the reflection of intense light is typically much stronger than that of a light of a very low intensity. Another issue that arises in the detection of a specific target in an underwater image is the fact that multiple pixels can potentially be activated in the image in the form of an object. For example, sunlight shining through a periscope lens can cause spurious activation of a given pixel. There is a need for a reliable method and system for determining whether a given pixel in a remote underwater image is activated by some cause other than the presence of a target in the area of the image.

Pre-processing of underwater photographs has been extensively researched, and several solutions have been devised for correcting typical underwater image artefacts (Carlevaris-Bianco et al., 2010; Kumar & Prabhaka, 2011). However, the image quality produced by these approaches is subjective to the observer, and because acquisition settings vary so widely, these methods may not be applicable to all data sets. According to empirical results (Beijbom et al., 2012; Shihavuddin et al., 2013), the current tendency appears to be to perform picture repair and enhancement processes based on the data set, that is determining the most appropriate pre-processing strategy for a specific data set. This strategy also depends on the purpose (e.g. labelling, classification or both) of the images in the data set.

In addition, basic image enhancement techniques have been shown to be effective in improving image quality. For instance, in Cao et al. (2016) increasing the uniformity of the background was used to boost picture contrast in underwater images for marine animal classification. This is a strong indicator that simple enhancing approaches might result in increased performance. Furthermore, some recent studies have employed DL algorithms to enhance image quality using low-quality images. In He and Li (2019), for example, end-to-end mapping is performed between low-resolution and high-resolution images.

When compared to state-of-the-art handcrafted and traditional image enhancement methods, DL-based algorithms typically perform better in addressing picture quality in terrestrial photographs. However, significant new research is required to customize these DL-based techniques for underwater images and maritime data sets. This poses as a future research opportunity for image quality enhancement in fish monitoring applications. Below, we discuss some more opportunities.

TABLE 3 Classification

Article	DL model	Framework	Data	Annotation/ Pre-processing/ Augmentation	Classes and labels	Perf. metric	Matrix value	Comparisons with other methods
Underwater live fish recognition by deep learning (Tamou et al., 2018)	AlexNet CNN	MATLAB	27000 images from the public Fish4Knowledge data set	Each image is assigned the fish species name as a label	23 classes of 23 different fish species	CA	99.45%	NA
WildFish++: A comprehensive fish benchmark for multimedia research (Zhuang et al., 2020)	CNN	NA	Authors-created data set of 54,459 labelled images from various professional websites and Google engine	Each image is assigned the fish species name as a label	100 classes of 1000 different fish species	CA	74.7%	Comparison with other state-of-the-art approaches
Automatic fish species classification in underwater videos: exploiting pre-trained DNN models to compensate for limited labelled data (Siddiqui et al., 2018)	CNN	MAT-LAB	The data set contains 50–120 10-s video clips of 16 species from Western Australia during from 2011 to 2013.	Each image is assigned the fish species name as a label	16 classes of 16 Different fish species	CA	89.0%	Comparison of their proposed method of CNN + SVM achieving a CA of 89.0% with two previous works: SRC (Hsiao et al., 2014b), 49.1%; and CNN (Salman et al., 2016), 53.5%
Underwater fish species recognition using deep learning techniques (Deep & Dash, 2019)	CNN	Keras, TensorFlow	35,000 images from the public Fish4Knowledge data set	Each image is assigned the fish species name as a label	23 classes of 23 different fish species	CA	98.79%	NA
Automatic Fish Species Classification Using Deep Convolutional Neural Networks (Iqbal et al., 2021)	Modified AlexNet CNN	TensorFlow	The images are from two public data sets: QUT fish data set and LifeCLEF-15	Each image is assigned the fish species name as a label	6 classes of 6 different fish species	CA	90.48%	Comparing their proposed modified AlexNet achieving a CA of 90.48% with original AlexNet CA of 86.65%
Underwater fish detection with weak multi-domain supervision (Kononov et al., 2019a)	CNN	Keras, TensorFlow	Authors-created data set of 40,000 labelled fish images from video sequences	Each image is labelled as fish or no fish	2 classes	CA	99.94%	NA

TABLE 3 (Continued)

Article	DL model	Framework	Data	Annotation/ Pre-processing/ Augmentation	Classes and labels	Perf. metric	Matrix value	Comparisons with other methods
A deep learning method for accurate and fast identification of coral reef fishes in underwater images (Villion et al., 2018)	GoogLeNet CNN	Caffe	Authors-created data set containing 450,000 images from over 50 reef sites around the Mayotte island	Annotation included drawing a rectangle around a single fish and associating the species name as label.	20 classes of 20 different fish species	CA	94.9%	Comparing accuracy to human experts. The rate of correct identification was 94.9%, greater than the rate of correct identification by humans (89.3%).
Underwater-drone with panoramic camera for automatic fish recognition based on deep learning (Meng et al., 2018)	CNN	NA	Authors-created data set of 100 labelled images from Google search engine	Each image is assigned the fish species name as a label	Four classes of four different fish species.	CA	87%	NA

6.4 | Deep learning gap

Deep learning is an emerging field that has a lot to offer in terms of ecology. The first and most obvious ecological applications are fish classification or fish count. However, there is still a gap between the DL-predicted fish counts and, for example, absolute abundance (fish per area or volume unit). The existing DL literature discusses mainly the use of CNNs for the ecological problems of species classification or fish counting. However, the absolute abundance of fish is important for ecological research and species conservation.

Another important problem in ecological research is fish population dynamics. A step in addressing this problem is to analyse long-term data on fish movements and fish densities. However, such long-term data sets are relatively rare and expensive to obtain. Hence, there is a need to obtain as much information as possible from the small amount of data given. This requires novel methods to give an accurate long-term estimate of fish densities or, even better, an estimate of the absolute abundance of fish.

Other exemplar ecological questions that can be addressed using DL include species habitat selection, or the relationship between the physical environment and the life history of species (Shryock et al., 2014; Van Allen et al., 2012; Vincenzi et al., 2019). DL methods can help us with this because they can take advantage of all the available information. The current state of DL research can be improved by considering alternative network architectures, more complex training algorithms and more detailed knowledge of the problem domain. The existing DL literature suggests that we may see many new methods in future. Most of them still do not have sufficient data to prove that they can outperform existing methods. There are, however, examples of successful applications, such as fish classification. For many ecological problems, a DL method can give very accurate predictions of fish densities or absolute abundance. However, it remains unclear whether this accuracy can be obtained only with the appropriate method or whether this is a property of the particular data set on which the method was trained. From this perspective, the development of a general method for predicting fish densities and absolute abundance from very little data is a major problem in ecology.

One potential approach to solving this problem is to take advantage of DL models trained on other data sets, as long as they are related to the fish density/abundance problem. The ecological literature suggests that the relationship between the physical environment and the life history of species (e.g. fish density) is likely to be complex because the physical environment differs from species to species. Therefore, we may be able to find many similar data sets on other related problems (e.g. environmental science or engineering). In addition to developing and testing general methods to estimate the absolute abundance of fish from very little data, there is a need to develop general methods that can take advantage of the ecological knowledge and domain-specific data from a particular problem.

7 | OPPORTUNITIES IN APPLICATION OF DL TO FISH HABITAT MONITORING

New methods and techniques will need to be devised to improve the accuracy of deep learning models for various marine habitat monitoring applications and to bring them closer to their terrestrial counterparts.

7.1 | Spatio-temporal and image data fusion

Most of the current marine habitat monitoring and visual processing tools only use image-based data to train their model to understand the habitats and monitor the environment. In such tools, each frame or image is separately processed and spatio-temporal correlations across neighbouring frames are simply overlooked. Exploiting this extra information and fusing it with the image processing model can be beneficial (Yang et al., 2020). For instance, fusing a master-slave camera set-up with LSTM (Wang et al., 2017b) can help to learn the kinematic model of fish in a 3D fish tracking system. Future works should consider including spatio-temporal information in training their model and understanding the scene. In particular, approaches similar to long short-term memory (LSTM) networks or other RNN models can be used in conjunction with CNNs, to obtain improved classification or prediction outcomes by taking advantage of the time-domain information. For example, an RNN and a CNN model are combined in Måløy et al. (2019) to achieve better performance for salmon feeding action recognition from underwater videos. In Peng et al. (2019), the authors propose a spatio-temporal recurrent network to classify behavioural patterns. Similar schemes have been proposed in Xu et al. (2021). However, their performance and complexity heavily rely on the ability of the RNN to track the temporal relations of the frames and on the effectiveness of the CNN.

For instance, estimating and monitoring fish development based on previous continuous observations, and analysing fish behaviour are some of the applications where time-domain information will be not only useful but also critical. Such models can also be used to build novel video-based protocols for the surveillance of critically endangered reef fish biodiversity.

7.2 | Underwater embedded and edge processing

Deep neural networks have proven to be successful in both industry and research in recent years, particularly for CV tasks. Specifically, large-scale DL models have had a lot of success in real-world scenarios with large-scale data. This is mainly due to their capacity to encode vast amounts of data and handle millions of model parameters that enhance generalization performance when new data are evaluated. However, this high computational complexity and substantial storage requirement makes them difficult to use in real-time applications, especially on devices with restricted resources (e.g. embedded devices and underwater edge processors for online monitoring). One approach to address this is to use compressed networks such

as binarized neural networks, which have shown promise towards reaching low-power and high-speed edge inference engines (Lammie et al., 2019), for near-underwater-sensor processing. This can significantly improve underwater image analysis capabilities, because the collected large-volume images do not need to be transferred to surface for processing, and only the low-volume results can be communicated to shore. This also solves another problem, which is the challenging underwater communication (Jahanbakht et al., 2021).

7.3 | Combining data from multiple platforms

The use of different data collection platforms such as autonomous underwater vehicles (AUVs) or occupied submarines can provide different image data from different perspectives of the same or different underwater habitats, to train more effective DNNs. In addition, using simultaneous data from multiple platforms can give more monitoring information, for instance, of fish distribution patterns, especially in situations where the number of platforms is limited. However, combining data from multiple platforms introduces some challenges such as the lack of ground truth (e.g. the number of fish in the sampled area for all the platforms), and the need to develop techniques that can integrate these data in a robust manner. Future research can work towards addressing these challenges to exploit the significant benefits of multiple platform data combination.

7.4 | Automated fish measurement and monitoring

Deep learning can be used to achieve automated fish measurements, which may be useful in underwater fish monitoring, for instance to survey fish growth (Yang et al., 2020) through monitoring of fish length (Palmer et al., 2022) and abundance (Ditria et al., 2019). Here, abundance means the number of fish in an image or video frame, and not the fish count per area or volume unit. In addition, automated measurements can realize remote fish assessments, for example when the monitoring locations are remote, or the environmental conditions and/or potential hazards do not allow frequent underwater scouting by humans.

Deep learning can also be used for automation of monitoring of other fish biological variables such as their movement dynamics, present species, and their abundance and biomass. On top of these, DL can be used to automate understanding of environmental and habitat features. To achieve these, new data sets should be collected, and new or existing DL techniques should be devised or customized in future research.

8 | CONCLUSION

Deep learning (DL) sits at the forefront of the machine-learning technologies providing the processing power needed to enable underwater video to fulfil its promise as a critical tool for visual sampling of fish. It offers efficient and accurate solutions to the challenges of adverse water conditions, high similarity between fish species, cluttered backgrounds



and occlusions among fish, which have limited the spatio-temporal consistency of underwater video quality. As a result, DL, complemented by many other advances in monitoring hardware and underwater communication technologies, opens the way for underwater video to provide comprehensive fish sampling. This can span from shallow fresh and marine waters to the deep ocean, opening the way for the development of the truly comparative understanding of marine and aquatic fish fauna and ecosystems that has hitherto been impossible. At least as importantly, DL solves the problem of handling the vast quantities of data produced by underwater video in a consistent and cost-effective way, converting a prohibitively expensive activity into a simple issue of computer processing. By enabling the processing of vast quantities of data, DL allows underwater fish video surveys to be conducted with unprecedented levels of spatial and temporal replication enabling the massive knowledge advances that flow from the ability of underwater videos to be deployed contemporaneously across many habitats, and at many spatial scales, or to provide continuous data over time.

Deep learning and associated techniques have the potential for widespread use in marine habitat monitoring for (1) data classification and feature extraction to improve the quality of automatic monitoring tools; or (2) providing a reliable means of surveying fish habitats and understanding their movement dynamics. While this will allow marine ecosystem researchers and practitioners to increase the efficiency of their monitoring efforts, effective development of DL will require concentrated and coordinated data collection, model development and model deployment efforts, as well as transparent and reproducible research data and tools, which help us reach our target sooner.

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CONFLICT OF INTEREST

All authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no data sets were generated or analysed during the current study.

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