



# **Deep Learning for Detecting Amphoras in Ancient Shipwrecks**

by

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Bachelor Thesis in Computer Science

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## Abstract

Amphoras have great archaeological significance and are often found in ancient shipwrecks. The increasingly abundant visual data and the advent of more advanced deep learning algorithms motivated us to automate the detection of underwater amphoras. We trained a convolutional neural network (CNN) based model called Single Shot Detector (SSD) with a 50-layer Residual Network (ResNet-50) backbone on a very small dataset with only 50 images, and we still managed to achieve a 0.238 MS COCO mean average precision ( $mAP_{coco}$ ) and a 0.503 Pascal VOC  $mAP@0.5$ . Underwater amphora detection is a challenging task. We believe future studies can achieve better results by increasing the size and resolution of the dataset, training bleeding-edge object detectors like YOLOv5, and defining 2 separate classes for the head and the body of amphoras. The code and the trained model are available at [https://github.com/tillchen/amphora\\_object\\_detection](https://github.com/tillchen/amphora_object_detection).

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# 1 Introduction

## 1.1 Motivation

### 1.1.1 Amphoras

The name *amphora* is derived from the Greek word *amphoreus*, which means "two-handled" [1, 2, 3]. It is the combination of two linguistic roots: *amphi* (on both sides) and *phoreus* (bearer) [1, 2, 3]. Amphoras (or amphorae) were commercially used from 1500 B.C.E. to 500 C.E. to ship products throughout the Mediterranean by the ancient Greek and Roman empires [2, 4].

Amphoras were designed to hold large quantities of liquid (wine, oil, and water) and dry products (grain, preserved fish, and nuts) [2, 5, 6]. Like many measure units that are named after the packages, amphoras were also a semi-standard unit for liquid [2]. The structurally strong egg-like shape and the high volume-to-weight ratio made amphoras very efficient packages [2, 4].

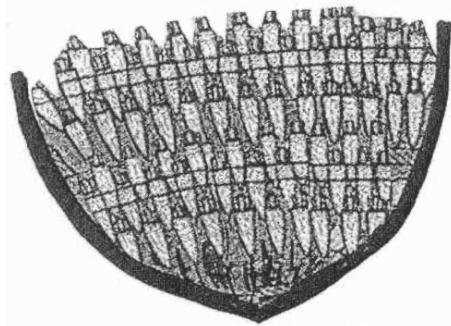


Figure 1: The egg-like shape enabled amphoras to interlock and minimize the waste of space on a ship. Source: [2].

Amphoras' various shapes and stamps - which changed by time, region, producer, contents, and brand identity - were used to identify the package status and the different products inside [2, 4].



Figure 2: Amphoras have various shapes. Source: [4].

Amphoras have great significance in archaeology. They can be used as evidence for

the trade patterns throughout the Mediterranean [2]. As they were usually discarded at the trade destination and have been found in shipwrecks, archaeologists use them to recreate the transit routes [2]. Furthermore, researchers can date ruins and shipwrecks by classifying different amphoras [2, 7].

### 1.1.2 Computer Vision for Underwater Archaeology

Computer vision is the science of perceiving and understanding the world through images and videos [8]. There have been multiple exciting applications of computer vision, including image classification [9], object detection and localization [10, 11], art generation (neural style transfer) [12], image creation with Generative Artificial Networks (GAN) [13], face recognition [14], human pose estimation [15], action and activity recognition [16], and image recommendation system [17].

However, there is still limited research for the usage of computer vision and machine learning in archaeology, especially underwater archaeology, compared to other domains [18, 19]. Computer vision, instead of visual inspection, can be used to automate the detection, assessment, and classification of artifacts [18].

Underwater computer vision has proven to be challenging, largely due to: 1) the distortion and attenuation caused by light propagation in water, 2) the unrestricted natural environment with the abundance of marine life and suspended particles, and 3) underwater objects are often broken [19, 20, 21, 22].

Despite the challenges, computer vision has lower costs [20] compared to sonar imagery [23] and laser scanning [24]. Plus, the increasingly abundant visual data obtained through unmanned underwater vehicles (UUVs), autonomous underwater vehicles (AUVs) [21, 25], and seafloor cabled observatories [19] motivate us to utilize deep learning.

The study of deep-water shipwrecks is in high demand, as more and more threats to these sites are emerging [26]. Some new trawling techniques can destroy the surface of these sites [26]. It is thus crucial to implement efficient, accessible, and accurate techniques like deep learning based computer vision to study deep-water shipwrecks.

## 1.2 Deep Learning

Machine learning is the class of algorithms that allow computers to learn and improve from data instead of being explicitly programmed [27, 28]. And deep learning is the subfield of machine learning that builds artificial neural networks with more than one layer between the input and output layers [28, 29, 30]. Deep learning constructs complex representations by combining simpler ones from the previous layers [31].

### 1.2.1 Artifical Neural Networks (ANNs)

Inspired by the biological neuron, artificial neural networks (ANNs) were first introduced in 1943 using propositional logic [32]. The neuron activates its binary output when the number of active binary inputs reaches the activation threshold, which makes it possible to build networks that can perform any logical proposition [28, 32].

Then Perceptron was introduced in 1957, which is based on a different artificial neuron called threshold logic unit (TLU) [33]. The input values are real numbers. TLU computes the weighted sum of the input and then applies a step function like the Heaviside function

$$heaviside(x) = \begin{cases} 0 & x \leq 0 \\ 1 & x \geq 0 \end{cases} \quad [28, 33].$$

A TLU can perform linear binary classification, whereas a layer of TLUs plus a bias neuron form a Perceptron capable of multi-output classification [28].

The output of a Perceptron is computed as follows, where  $\mathbf{X}$ ,  $\mathbf{W}$ ,  $\mathbf{b}$ , and  $\phi$  are respectively the input matrix, weight matrix, bias vector, and activation function:

$$h_{\mathbf{W}, \mathbf{b}}(\mathbf{X}) = \phi(\mathbf{X}\mathbf{W} + \mathbf{b})$$

Perceptron is trained using a variant of the Herbb's rule [34], which is famously summarized as "neurons wire together if they fire together" [35]. However, the Perceptron can not learn complex patterns due to its linear decision boundary, and it does not output a class probability [28]. To address these limitations, Multilayer Perceptron (MLP) was introduced by stacking multiple Perceptrons.

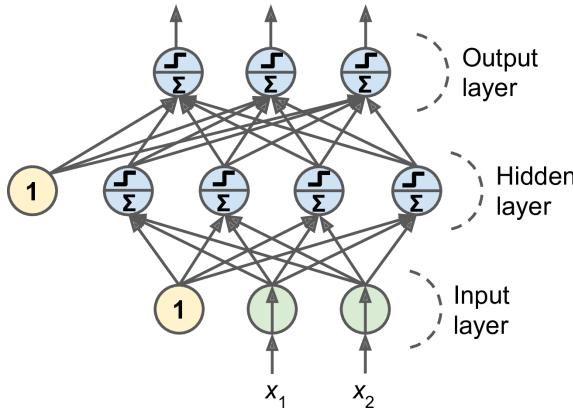


Figure 3: A Multilayer Perceptron with one hidden layer. Source: [28].

Backpropagation [36] is used to train the MLP, which first computes the loss, then measures each connection's loss contribution, and finally reduces the loss by adjusting the weights in the Gradient Descent [37] step. Activation functions like Rectified Linear Unit  $ReLU(x) = \max(0, x)$  are adopted to add nonlinearity, which gives deep neural networks the theoretical ability to approximate any continuous function [28].

### 1.2.2 Convolutional Neural Networks (CNNs)

Convolutional Neural Networks (CNNs) [38] were inspired by the visual cortex, and they have been used in computer vision since the 1980s [28]. We can not simply use a deep neural network with fully connected layers for computer vision, as it breaks down for large images due to the immense number of parameters [28]. CNNs also have successful applications in other domains like recommender systems [39] and natural language processing (NLP) [40].

Hubel et al. [41, 42, 43] found that many biological neurons have small receptive fields, which means they only fire if a finite region of the visual field is stimulated. Some neurons only react to specific patterns, while the others with larger receptive fields react to more complex patterns.

The filters or convolution kernels, which are learned during training, are neurons' weights that can be presented as small images the size of receptive fields [28]. A layer of neurons with the same filter outputs a feature map, which highlights the parts of an image that maximizes the activation of the filter [28].

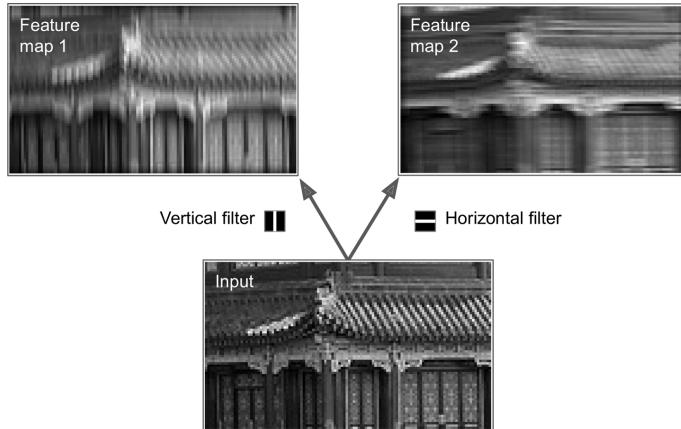


Figure 4: Two feature maps by applying two different filters. Source: [28].

The pooling layers subsample (i.e. shrink) the input image to make the network less computationally intensive [28]. Plus, pooling layers can bring some invariance to small translations, rotations, and scaling [28].

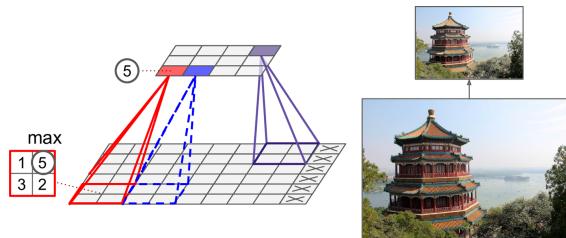


Figure 5: A max pooling layer with  $2 \times 2$  as the kernel size and 2 as the stride. The max value from the receptive field passes to the next layer. Source: [28].

The typical CNN architecture involves the aforementioned convolutional layers, pooling layers, and fully connected layers. Some well-established CNN architectures are LeNet-5 [44], AlexNet [45], GoogLeNet [46], VGGNet [47], ResNet (Residual Network) [48], Xception (Extreme Inception) [49], MobileNet [50, 51], and SENet (Squeeze-and-Excitation Network) [52].

ResNet is the backbone network of the model used in this paper. ResNet's skip connections help speed up the training considerably, since: 1) the network preconditions the problem to be the identity function, which is often close to the target function, and 2) the network can start making progress even if some layers have not started learning yet [28, 48]. Batch normalization [53] is used after each convolution to reduce the vanishing gradient problem [54] and the need for other regularization techniques like dropout [55].

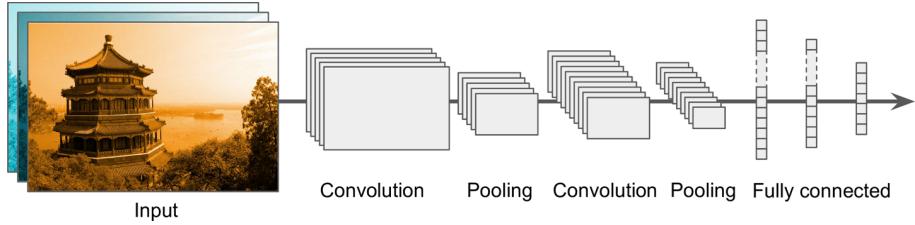


Figure 6: The typical CNN architecture. Source: [28].

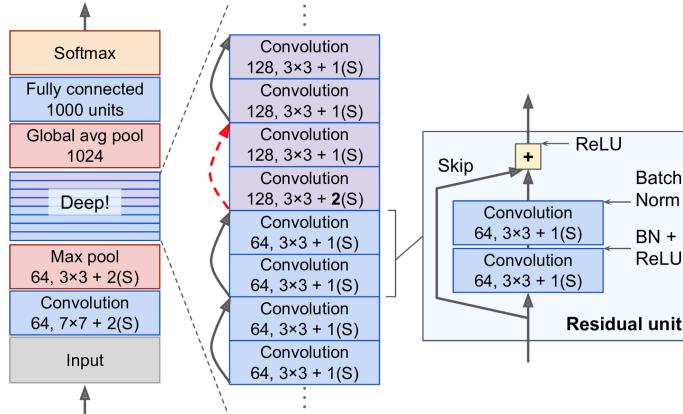


Figure 7: ResNet architecture. Source: [28].

### 1.3 Deep Learning vs. Traditional Computer Vision

The improvements of deep learning algorithms, computing power, image resolution, and the amount of visual data have enabled deep learning to achieve state-of-the-art performance in many computer vision tasks, including image classification, object detection, and semantic segmentation [19, 56, 57].

Traditionally, computer vision requires the manual feature extraction step, which relies on domain knowledge to produce high-quality features [8, 10, 57]. These handcrafted features are further processed by a machine learning classifier like a support vector machine (SVM) [8, 10, 57]. However, manual feature extraction becomes more and more complex as the number of classes grows [57]. Besides, conventional machine learning algorithms' generalization ability saturates quickly as the size of training data expands [19].

Deep learning removes the manual feature extraction step and makes training end-to-end [8, 57]. Thus, deep learning requires less domain knowledge, and it is more flexible as we can re-train the models on custom datasets for specific tasks [57].

However, deep learning's performance does depend on obtaining large datasets with high image resolution [57]. Some popular public datasets like PASCAL Visual Object Classes (VOC) [58], ImageNet [59], and Microsoft Common Objects in Context (COCO) [60] have respectively 11 thousand, 14 million, and 328 thousand images [11]. Having a highly limited dataset for a task may cause deep learning to have poorer results than traditional computer vision.

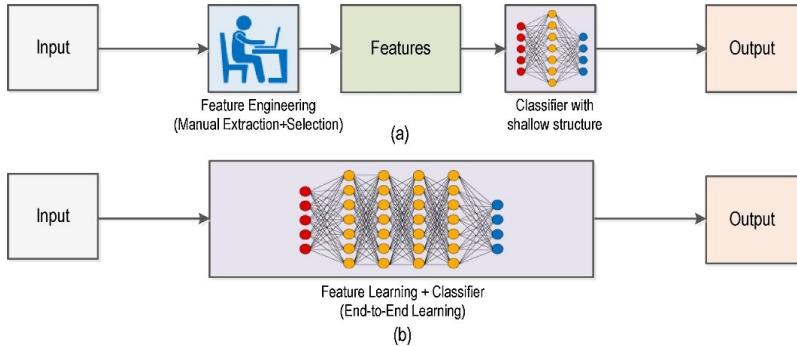


Figure 8: Traditional computer vision (a) vs. deep learning (b). Source: [57].

## 1.4 Object Detection

Object detection is the computer vision task that localizes and classifies objects in an image [8, 10, 11, 28]. Object detection is one of the most challenging tasks in computer vision, as it can be considered as both a regression task for bounding box prediction and a classification task [8, 61, 28]. Plus, the large variations in viewpoints, poses, occlusions, and lighting conditions add extra difficulties to perform perfect object detection [10, 11].

The traditional sliding window approach is to train a CNN to classify and locate a single object, and then slide it across the image [28, 62, 61, 63]. This approach slides the CNN multiple times with various window sizes to detect objects at different scales, which causes it to be quite slow [28].

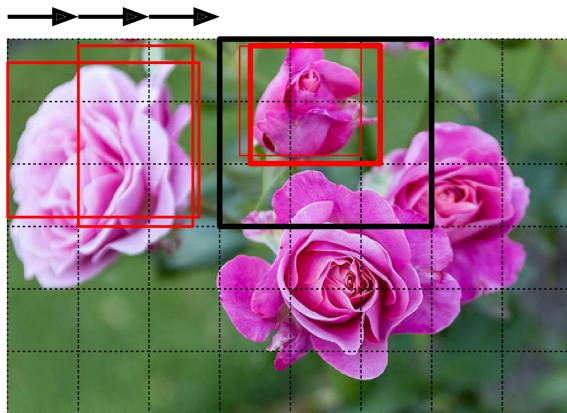


Figure 9: The sliding window approach for object detection. Source: [57].

Luckily, many novel object detectors have been introduced. Here we summarize three influential object detector families: Region-Based Convolutional Neural Networks (R-CNN) [61, 64, 65], Single Shot Detector (SSD) [66], and You Only Look Once (YOLO) [63, 67, 68, 69, 70].

### 1.4.1 General Object Detection Framework Components

Before we dive into specific object detectors, it's worth understanding the four high-level components of general object detection frameworks.

**Region Proposal** Region proposal finds regions of interest (RoIs) for further processing. This is achieved by discarding regions with a low objectness score, which is a score that indicates the probability of the region containing objects [71].

**Backbone Network** A pre-trained CNN is used for feature extraction and predictions. The bounding-box prediction is the tuple  $(x, y, w, h)$ , which are respectively the coordinates of the center, the width, and the height [8, 28].

**Non-Maximum Suppression (NMS)** The backbone network typically produces multiple overlapping bounding boxes for one object, thus NMS finds the box with the maximum class probability and suppresses the rest [8]. The steps include [72]:

1. Sort the boxes based on the probability score.
2. Select the box with the maximum probability score.
3. Compute the overlap - intersection over union (IoU) - of the boxes and discard the ones with an IoU higher than the NMS threshold.
4. Repeat recursively on the remaining boxes.

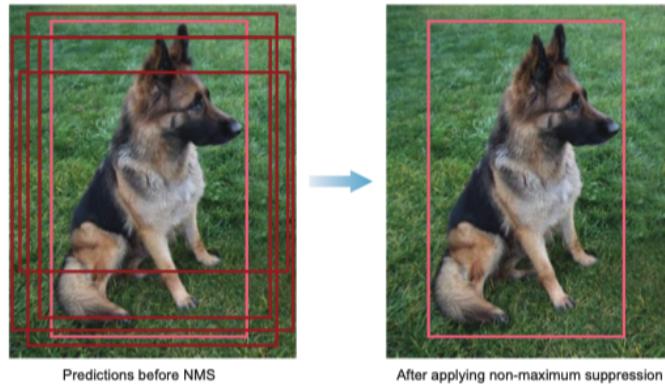


Figure 10: NMS. Source: [8].

**Metrics** The two main metrics for object detection are frames per second (FPS) and mean average precision ( $mAP$ ) [8, 11, 28, 73]. To understand  $mAP$ , we need to understand first the aforementioned intersection over union (IoU) and the precision-recall curve (PR curve). IoU is also known as the Jaccard index, which measures the similarity between two sets [73]. IoU can be mathematically formulated as follows [8, 73]:

$$IoU = \frac{B_{\text{ground truth}} \cap B_{\text{prediction}}}{B_{\text{ground truth}} \cup B_{\text{prediction}}}$$

We say that a prediction is a true positive (TP) if the classification is correct and the IoU is higher than the NMS threshold, otherwise it is a false positive (FP) [8, 11, 73]. A false negative (FN) is a ground truth that does not have a prediction [73]. Precision and recall are defined as follows [29, 74]:

$$Precision = \frac{TP}{TP + FP}$$

$$Recall = \frac{TP}{TP + FN}$$

There is a trade-off between precision and recall [8, 28, 29, 73]. We can obtain the average precision (AP) by drawing the PR curve and computing the area under the curve (AUC) [8, 73]. We then get the  $mAP$  by averaging the AP over all the classes [8, 28, 73]. The traditional Pascal VOC metric uses  $mAP@0.5$  with a 0.5 IoU threshold [11, 58]. The new COCO metric  $mAP_{coco} = mAP@[0.50 : 0.05 : 0.95]$  is averaged over various IoU thresholds from 0.5 to 0.95 in steps of 0.05, which rewards detectors with better localization [11, 75]. Note that AP is sometimes used in the COCO metric to implicitly mean  $mAP$  [75], although we use  $mAP$  consistently in this paper.

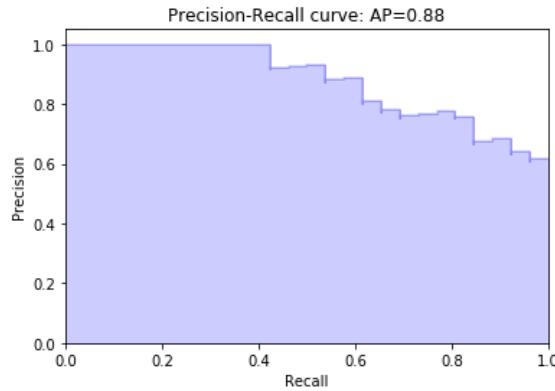


Figure 11: A PR curve with a 0.88 AUC/AP. Source: [73].

#### 1.4.2 Region-Based Convolutional Neural Networks (R-CNN)

The evolution from the original R-CNN [61] to Fast R-CNN [64] and then to Faster R-CNN [65] builds up the R-CNN family.

**R-CNN** R-CNN has four components [8, 61]:

1. Region proposal with a greedy search algorithm called selective search, which finds Rols by combining similar pixels into boxes.
2. A pre-trained CNN as the network backbone.
3. Classification with a linear SVM.
4. Localization with a bounding-box regressor.

R-CNN has the following disadvantages [8, 61, 64]:

- The FPS is very low. The selective search algorithm proposes about 2000 Rols, which is computationally expensive as the CNN has to process each proposal separately.

- The training is multi-stage, inelegant, expensive, and not end-to-end. It involves training three components separately: the CNN, the SVM, and the bounding-box regressor.

**Fast R-CNN** Fast R-CNN made the following changes from R-CNN [8, 64]:

- The backbone CNN comes before region proposal, so that the images only go through the CNN once instead of 2000 Rols going through the CNN separately.
- Classification is performed by the softmax layer of the CNN instead of the SVM. And localization is also an output layer of the CNN.
- A Roi max pooling layer was added after region proposal to reshape the input size for the fully connected layers.

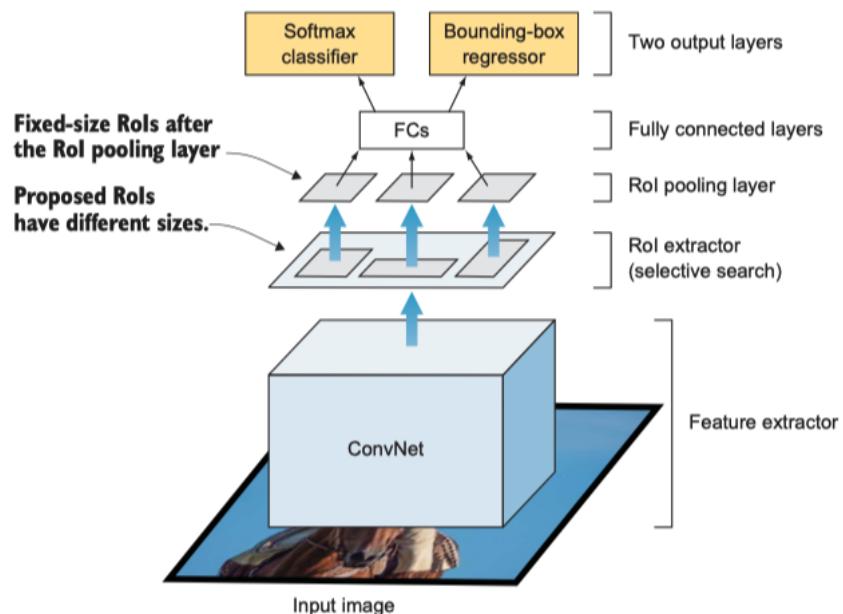


Figure 12: Fast R-CNN. Source: [8].

Fast R-CNN is significantly faster than R-CNN, although the selective search algorithm still exists as the bottleneck [8, 64, 65].

**Faster R-CNN** Faster R-CNN made the following improvements from Fast R-CNN [8, 65]:

- Region Proposal Network (RPN) or attention network replaced selective search, which reduced the number of proposals, speeded up the model, and made training end-to-end. RPN is a Fully Convolutional Network (FCN) [76] that outputs objectness scores and Rols, and it can be used as a standalone network for single-class object detection. RPN adds very little cost as the features are also shared with the detection network.
- Anchors were introduced as reference boxes at different scales and aspect ratios. Thus, the regression layer only needs to output the offsets of the coordinates, width,

and height from the anchors. The anchors are created with the sliding-window approach. By default, 9 anchors (3 scales and 3 aspect ratios) are generated for each window.

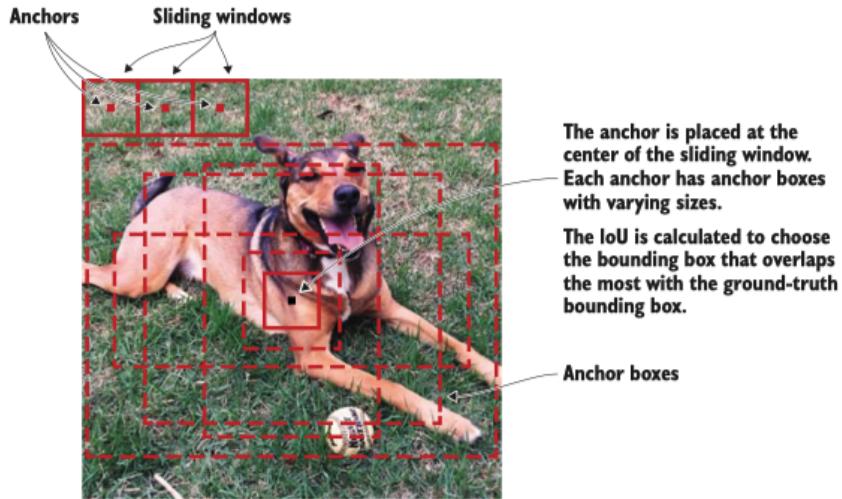


Figure 13: Anchors in Faster R-CNN. Source: [8].

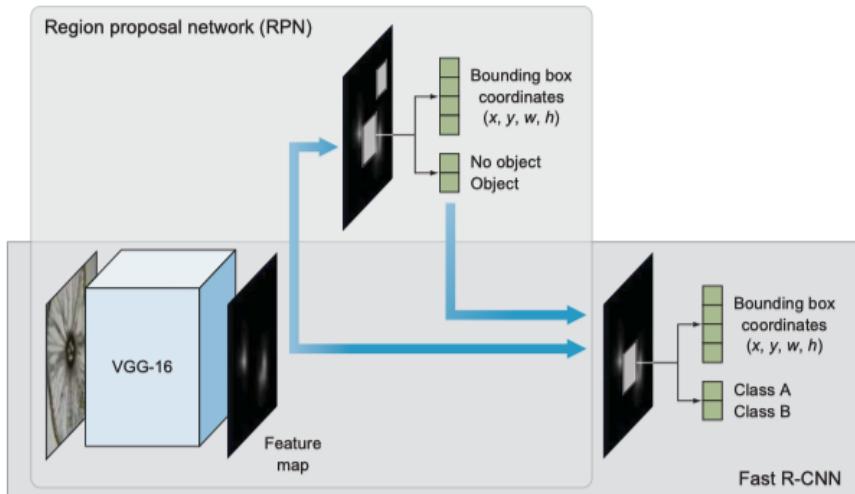


Figure 14: Faster R-CNN. Source: [8].

To summarize, the R-CNN family are two-stage detectors that separate region proposal and detection [8, 11]. They can not achieve real-time detection, and they are very computationally intensive [8, 66, 63]. One-stage detectors like Single Shot Detector (SSD) and You Only Look Once (YOLO) skip the region proposal to achieve real-time detection [8].

#### 1.4.3 Single Shot Detector (SSD)

Single Shot Detector (SSD) makes both the objectness prediction and classification directly in one shot [8, 66]. It has three main components [8, 66]:

- The backbone network. It also uses anchors called priors like in Faster R-CNN. But the network sends the bounding box offsets and the class scores to NMS directly when it finds a box that contains the object features.
- Multi-scale feature layers, which are convolutional layers that decrease in size progressively to detect objects at various scales. The resolutions of feature maps decrease as the CNN reduces the spatial dimension.
- NMS.

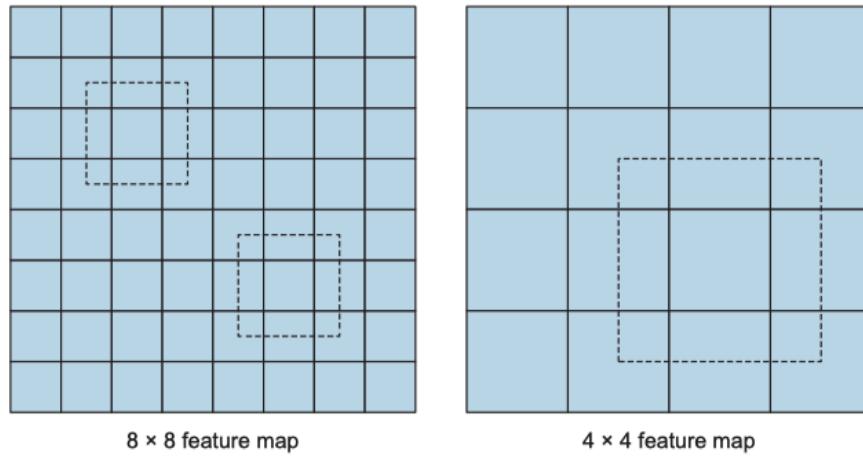


Figure 15: Multi-scale feature maps in SSD. Higher-resolution feature maps (left) detect smaller objects. Lower-resolution feature maps (right) detect bigger objects Source: [8].

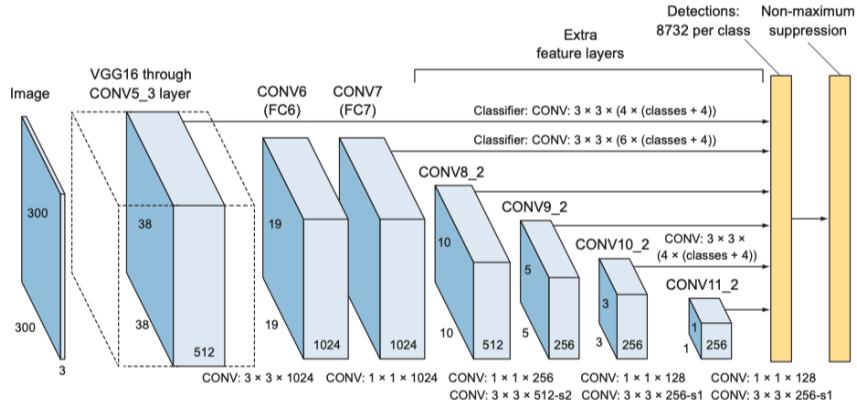


Figure 16: SSD. Source: [8].

#### 1.4.4 You Only Look Once (YOLO)

YOLO is a one-stage real-time detector family similar to SSD. The YOLO family has also been going through a series of improvements since the original YOLO paper was published. YOLOv1 [63] introduced the general architecture; YOLOv2 [67] added anchors similar to Faster R-CNN and SSD; YOLOv3 [68] further refined the architecture.

YOLO divides the image into a grid, and the grid cell detects objects if the object's center is inside the cell [63]. The backbone network is called DarkNet, which is inspired by GoogLeNet [8, 63].

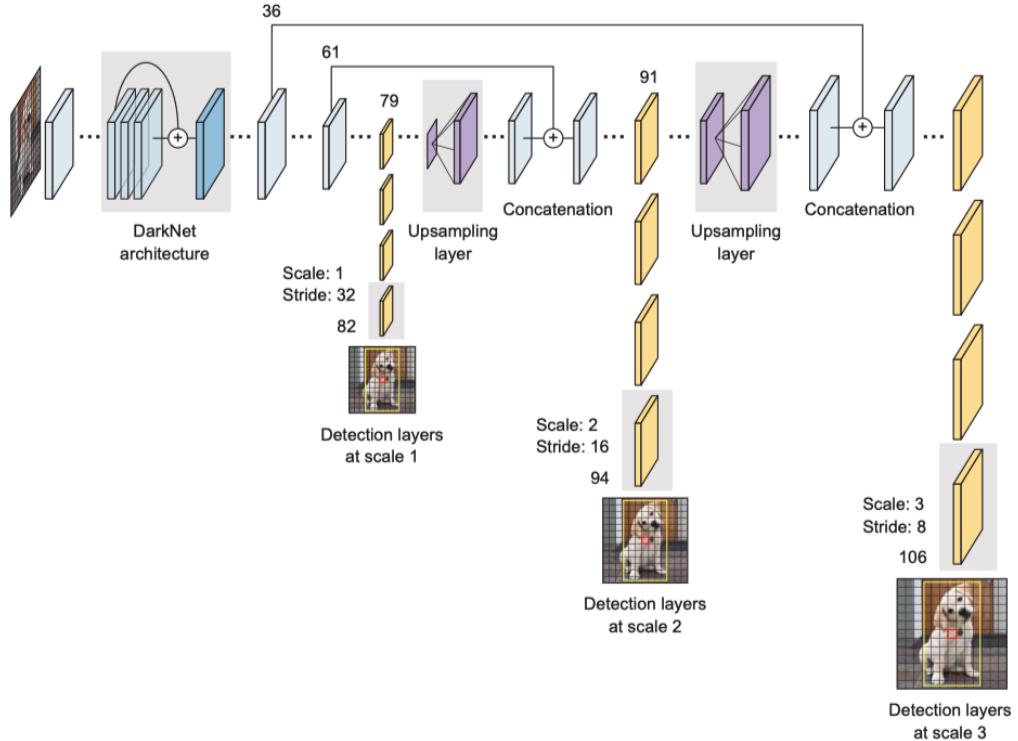


Figure 17: YOLOv3 architecture. YOLO performs detections at 3 different scales. Layer 79 makes a grid of  $13 \times 13$  to detect large objects. Layer 91 makes a grid of  $26 \times 26$  to detect medium objects. And finally layer 106 makes a grid of  $52 \times 52$  to detect small objects. Source: [8].

YOLOv4 [69], a bleeding-edge detector introduced in 2020, utilized numerous new features to improve the performance from YOLOv3, including DropBlock regularization [77], Mish activation [78], Self-Adversarial Training [69], etc.

YOLOv5 [70] is under active development and the authors have yet to publish a paper.

## 2 Related Work

For fish detection, Qin et al. [19, 79], Zhang et al. [80], Villon et al. [81], Xu et al. [82], and Konovalov et al. [83] respectively used Fast R-CNN, a model similar to R-CNN, sliding window with a CNN, YOLOv3, and Xception.

For crab detection, Cao et al. [84] proposed a detector called Faster MSSDLite, which is based on SSD with a MobileNetV2 backbone and Feature Pyramid Network (FPN) [85].

For planktons and corals, we have only found research for classification but not object detection [19, 25].

For amphora detection, Pasquet et al. [22, 62] used sliding window with a CNN on a high-resolution orthophoto (i.e. aerial photo). This is the only study we found on amphora detection with deep learning.

### 3 Data and Methods

#### 3.1 Data

The dataset consists of 50 images (294 objects) in the training set and 7 images (31 objects) in the validation set, which maintains a 90%: 10% ratio for the object count. Two additional images were used as the test set. All the images were obtained through various sources [86, 87, 88, 89, 90, 91, 92, 93, 94, 95] and were labeled with labellImg [96].

#### 3.2 Model

Out of the three families of object detection frameworks we have discussed in section 1.4, SSD was chosen due to the following reasons:

- Faster R-CNN is too computationally intensive and too slow for AUVs and UUVs.
- YOLOv5, the state-of-art model of the YOLO family, is under active development and the authors have yet to publish a paper.

The TensorFlow Object Detection API [97, 98] was used. `ssd_resnet_50_fpn_coco` is the model name in the TensorFlow 1 Detection Model Zoo [99]. The backbone network is ResNet-50 (50-layer ResNet) (see section 1.2.2) instead of VGG-16 in the original SSD paper, as it improves *mAP* significantly [48]. Similar to the approach from Cao et al. [84] for crab detection, Feature Pyramid Network (FPN) was adopted to improve the detection at different scales [85].

#### 3.3 Model Training

We used transfer learning [100] as the model was pre-trained on the COCO dataset, which means the weights and biases are restored instead of being randomly initialized and the model does not have to learn the low-level features from scratch [28]. `num_classes`, `batch_size`, and `num_examples` in `eval_config` were adjusted to 1, 8, and 7 respectively in the configuration file, while the rest of fields were unchanged. The images were reshaped to 640 x 640 with the `fixed_shape_resizer`. The activation function is ReLU6, a modified version of ReLU that caps the maximum value at 6 and thus encourages the model to learn sparse features earlier [101]. We used  $L_2$  regularization [102] to reduce overfitting [103]. Data augmentation [45] - a method to artificially enrich the dataset by randomly flipping horizontally and cropping the images - was also used as a regularization technique. We chose the momentum optimizer [104] as it converges faster than Stochastic Gradient Descent [105] by keeping accelerating to the optimum [28]. Learning rate warmup and learning rate scheduling by cosine decay were also added to speed up the convergence, so that the learning rate starts small, increases gradually, and

then decreases after reaching the maximum [28, 106, 107, 108]. The model was trained on Google Colaboratory [109] with a GPU runtime, and the training took 2 hours and 40 minutes to reach the peak  $mAP$  result at step 8621.

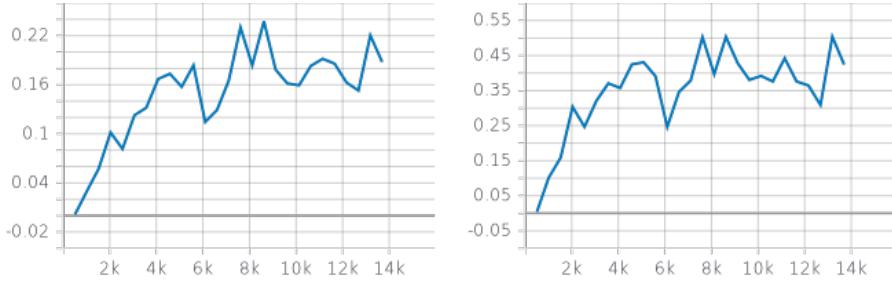


Figure 18:  $mAP_{coco}$  (left) and  $mAP@0.5$  (right).

## 4 Evaluation

The main metric  $mAP_{coco}$  (see section 1.4.1) from our model is 0.238, while the traditional  $mAP@0.5$  is 0.503. The documented  $mAP_{coco}$  in the TensorFlow 1 Detection Model Zoo for `ssd_resnet_50_fpn_coco` is 0.35, which was measured on the COCO validation set. Our model's performance is indeed lower than that in the model zoo. And it is somewhat difficult to perform a direct comparison with the result from Pasquet et al. [62], as they did not compute the  $mAP$  and only mentioned that they detected around 90.3 percent of amphoras. However, we can conclude that our model did not detect more than 90.3 percent based on the visual inspection of the validation images in figure 19.

Nevertheless, our model's performance is still impressive due to the following reasons:

- Our dataset is very small. As we have mentioned before in section 1.3, the COCO dataset has 328 thousand images compared to our 57 images plus 2 test images. For Pasquet et al., they split one 38000 x 15000 orthophoto into 400 x 400 images and used 25% of them for training, which means the training set alone was around 890 images.
- Our dataset is more diverse than that of Pasquet et al. Since our dataset images are obtained through numerous sources instead of from a single orthophoto, they reflect better the various shapes of amphoras (see figure 2). Plus, our dataset has both large and medium instances of amphoras that vary significantly in terms of scale. The diversity of our dataset made it harder to achieve a high  $mAP$ , although it encouraged the model to generalize better.
- Underwater object detection is more challenging than general object detection performed by the COCO dataset. As we have mentioned before in section 1.1.2, the same challenges also apply to amphora detection. In fact, the undetected amphoras in figure 19 are almost all either broken, or partially buried in sand, or blocked by suspended particles. We only defined one class for all amphoras even though some of them are broken, while Pasquet et al. defined 2 separate classes for the head and the body to better detect broken instances.

- Our  $mAP@0.5$  score is comparable with that from Xu et al. [82] for fish detection. They achieved a 0.5392  $mAP@0.5$  using YOLOv3, although they did not compute the  $mAP_{coco}$ .

We also ran the model on 2 test images shown in figure 20. To our surprise, the model managed to detect the amphora in the first image even though it is so broken that only half of it is present. As for the second image, none of the amphoras was detected. The size of the second image is only 709 x 411, while it has hundreds of amphora instances. This means that they are mostly small instances defined by the COCO metric, which our training set does not include. It is a known issue that small objects are significantly harder to detect than medium and large objects, mainly due to the low resolution and thus the lack of features to learn [110, 111, 112]. Plus, the image can be described as a crowded and densely packed scene, which is also notoriously challenging for object detectors since the objects overlap with each other so strongly that it is even impossible for human experts to differentiate the instances [62, 113, 114, 115]. We tried to split the image and add parts of it to the training set. However, the inter-occlusion of the instances caused many labeling errors, and the resolution of each instance was so low that the training could not converge to a solution.

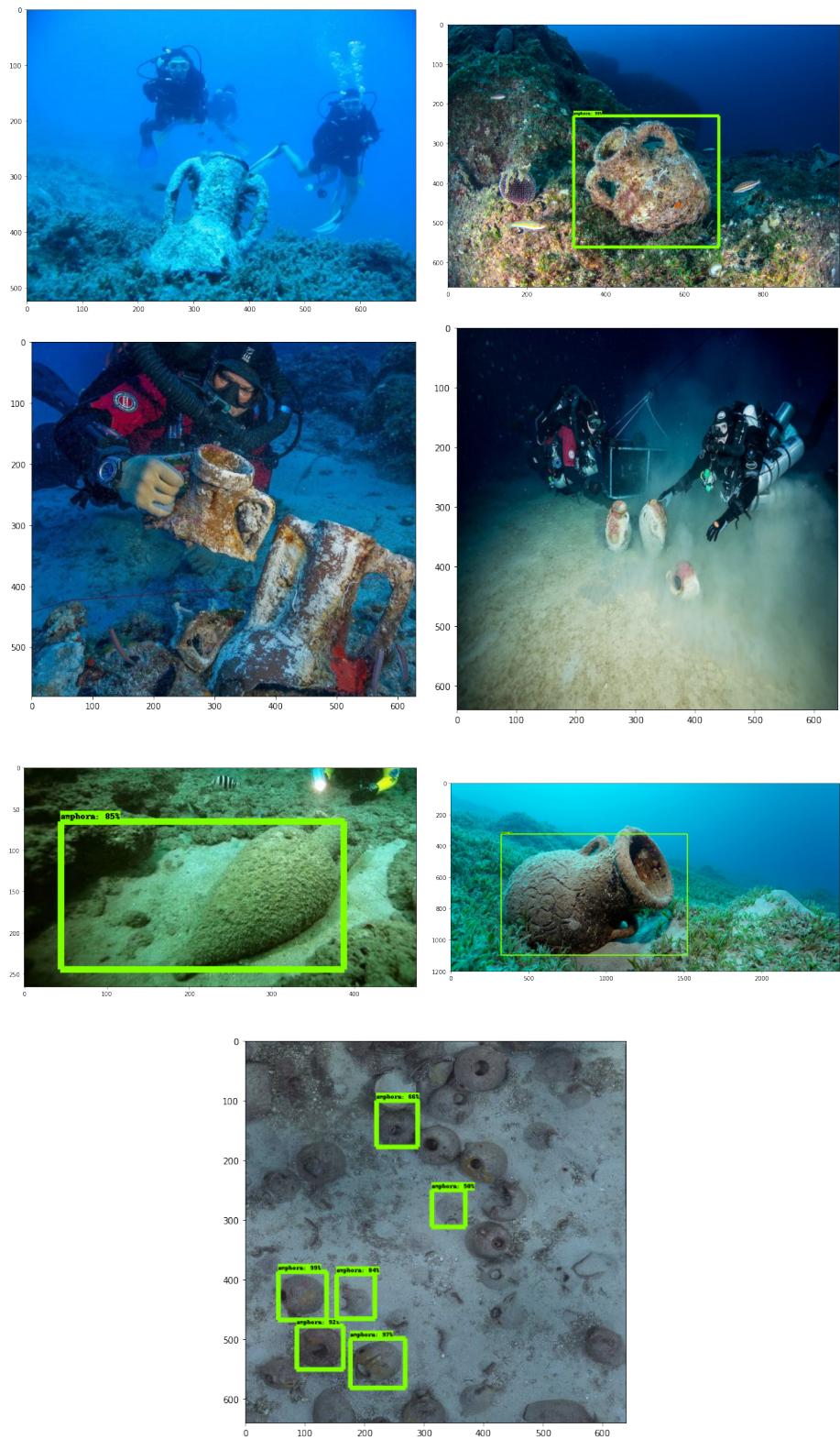


Figure 19: The validation images. Source: [87, 88, 89, 90, 91, 92, 93].

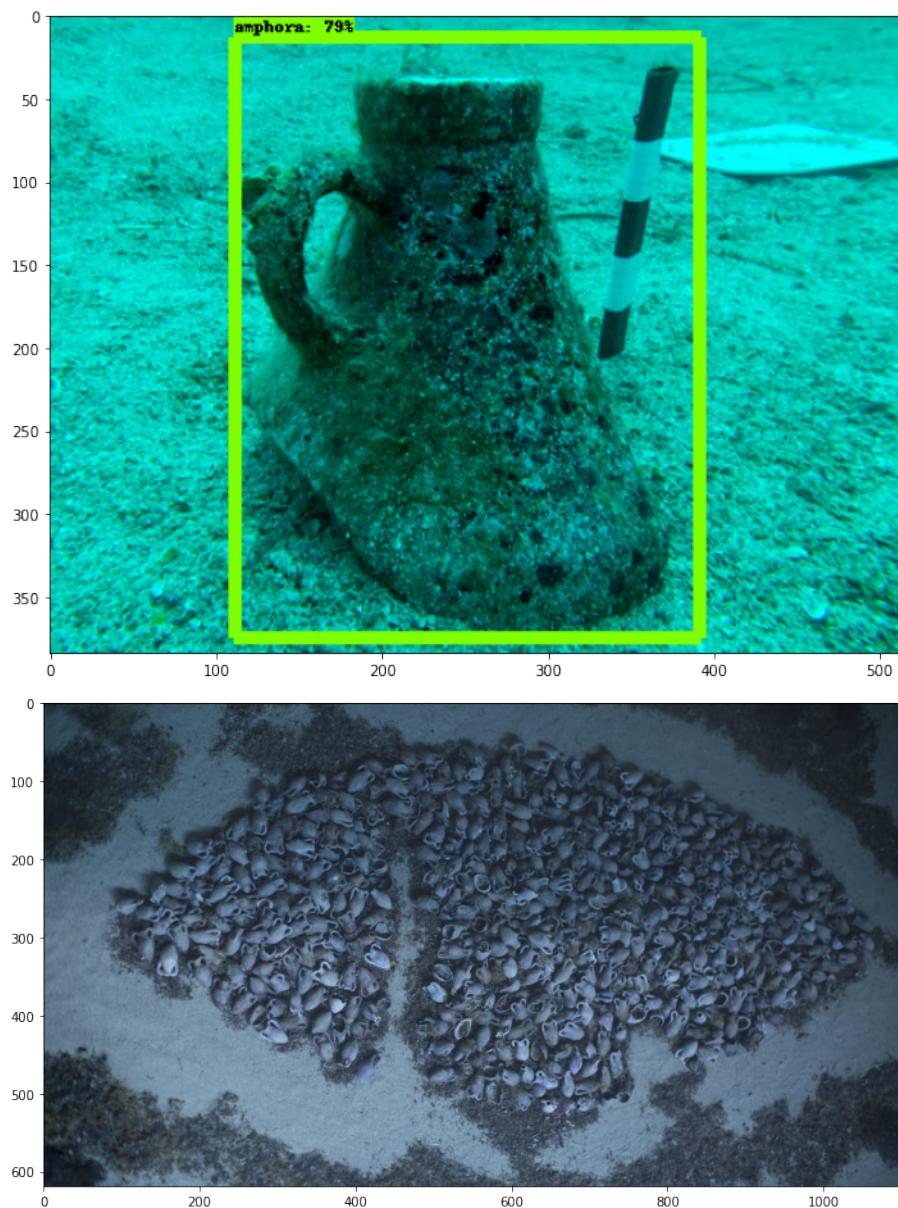


Figure 20: The test images. Source: [94, 95].

## 5 Conclusion and Future Work

In this paper, we reviewed the relevance of amphoras, computer vision’s potential in underwater archaeology, deep learning, and three major object detector families. We then trained an SSD model with a ResNet-50 backbone on a very small and low-resolution dataset, and we still managed to achieve a  $0.238 mAP_{coco}$  and a  $0.5392 mAP@0.5$ . Detecting underwater amphoras is a challenging task, as the object detectors have to overcome the same difficulties posed by general underwater object detection (see section 1.1.2), the considerable variations of the amphoras’ shapes (see figure 2), and the crowdedness of the scenes in some shipwrecks (see figure 20).

We hope this paper can serve as a proof of concept for future studies since there are many aspects to improve upon:

- The small number and the low resolution of the images in our dataset are the bottlenecks towards higher performance. There are indeed very limited publicly available high-resolution images for underwater amphoras [62]. Future studies may focus on obtaining more amphora images through AUVs and UUVs to improve  $mAP$ . Higher resolution images like orthophotos can especially address the issue of detecting small objects [110] and also the issue of detecting overlapping objects by reducing labeling errors. Plus, more data augmentation techniques like randomly change to grayscale and randomly adjust brightness, contrast, and hue can be easily added in the `data_augmentation_options` from the TensorFlow Object Detection API to potentially further enrich the dataset.
- Many bleeding-edge object detectors with better performance are emerging. The SSD model in this study has a  $0.35 mAP_{coco}$  and a 76 ms detection speed on the COCO validation set. YOLOv5 can achieve a  $0.367 mAP_{coco}$  with a mere 2 ms detection speed or a  $0.504 mAP_{coco}$  with a 6.1 ms detection speed for  $640 \times 640$  images, and a  $0.55 mAP_{coco}$  with a 70.8 ms detection speed for  $1280 \times 1280$  images. It will be worth experimenting with YOLOv5 after its authors publish a paper and its active development stabilizes. Some other models in the TensorFlow 2 Detection Model Zoo [116] are also interesting to look into. Note that we used the SSD model in the TensorFlow 1 Detection Model Zoo, as the TensorFlow 2 version requires two scripts to be running to train and evaluate at the same time. It is unfortunately not possible to do so on Google Colaboratory. But one with access to GPUs can easily train an EfficientDet [117] D1  $640 \times 640$  model with a  $0.384 mAP_{coco}$  and a 54 ms detection speed or an EfficientDet D7  $1536 \times 1536$  model with a  $0.512 mAP_{coco}$  and a 325 ms detection speed from the TensorFlow 2 Detection Model Zoo. CenterNet [118], a novel keypoint-based detector that models an object as a single center point and regresses to the object size without NMS (see section 1.4.1), is also available in the TensorFlow 2 Detection Model Zoo. CenterNet can achieve a  $0.417 mAP_{coco}$  with a 6 ms detection speed or a  $0.614 mAP_{coco}$  with a 76 ms detection speed for  $512 \times 512$  images, and a  $0.645 mAP_{coco}$  with a 211 ms detection speed for  $1024 \times 1024$  images.
- Following the approach from Pasquet et al. [62], we can try to define 2 separate classes for the head and the body to better detect broken instances.

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