Automated Detection in Archaeological Geophysical and Remote Sensing Surveys

Détection Automatique dans des relevés géophysique archéologique et télédetection

Leiden University - ESIEA

Research Internship Thesis

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Chapter 1

Foreword

This internship was not as traditional as it could have been: both because of the COVID-19 Situation, which profoundly modified the course of my work, but also because it was at its heart a research position, and not a more traditional developper/manager type of work. While this type of work is not typically assumed by engineers in their final year of study, this experience has proven to me to be unvaluable, as it has allowed me to delve deep into research I have been doing in my free time; and gave me the means and the time to create what was only a dream for me a few years ago: a dedicated object detection model optimized for Archaelogical Remote Sensing Surveys.

As such, this document is also not traditional, and is not be a simple insternship report. It is much more detailed in the work undertaken, the previous state of the art, be it in automated detection in archaeology or in satellite imagery. This project is a continuation of work I have started almost 3 years ago, and was my first opportunity to dedicate an entire section of my life working full time towards it, which is invaluable. While I believe this project is a success, because it achieved its stated goal, there is much work left to be done. Digital Archaeology is flourishing, and there is vast amounts of data, be it digital like geophysical surveys or manuscript like digging reports, that are still untouched. I truly believe that this treasure trove, combined with advanced machine learning techniques might gives novel way to understand our past. By doing so, we might be better prepared for the challenges that are coming to us.

I can only give my deepest and most sincere thanks to the Leiden University and both Professor Lambers and Mr. Verschoof-van der Vaart MA for their help. This institution accepted my offer and gave me an opportunity to push myself, which I will stay forever grateful for.

Chapter 2

Executive Summary

The work undertaken during those 6 months is a continuation of my previous studies in automated detection of Archaelogical targets in Geophysical Surveys.

Here, we use state of the art Deep Learning techniques on LiDAR surveys to detect 3 classes of targets: barrows, celtic fields and charcoal kilns, whose description and definition can be found in Section 6.2. The dataset used are LiDAR surveys that have been done in a large region of the Netherlands, and which has already been used in a number of automated detection tasks. The goal here is to evaluate the performance of a modified YOLO[1] in this particular kind of object detection task. We will use techniques taken from detection using satellite imagery, as they often deal with issues similar to detection in large LiDAR surveys.

Automated object detection is a highly studied subdomain of Deep Learning, which has made very important advances in the recent year and performance of the models has skyrocketed, along with their speed. Object detection, and more generally Computer Vision is in very high demand, but most research is done on what we call "natural images", i.e. photographs, and not much is done using geophysical surveys. There is a need for high performance and fast object detection systems using different sensors in multiple fields.

Le travail entrepris durant ces 6 mois est dans la continuité de mes précédentes recherche dans la détection automatique de cibles Archéologique dans des relevés géophysique.

Ici, nous utilisons des techniques de pointe de Deep Learning dans des relevés LiDAR pour détecter 3 classes de cibles: des tumulus, des champs Celtiques et des charbonnières, dont la description et la définition peut être trouvé en Section 6.2. Le dataset utilisé ici est un ensemble de relevés LiDAR ayant été faite dans une grande région des Pays-Bas, et qui a déjà été utilisés dans un certain nombre de projet de détection automatique d'objet archéologique. Le but ici est d'évaluer la performance d'un modèle YOLOv4[1] optimisé pour ce genre de tâche. Nous allons également faire usage de techniques empruntés a la détection dans des images satellite, qui partagent certaines caractéristiques et problématiques.

La détection automatique d'objet est un sous domaine très étudié du Deep Learning et de la vision automatique et qui a connus de très grandes avancées dans les années précédentes. La performance, à la fois en terme de précision mais aussi de vitesse d'exécution a bondi en avant. La détection d'objet, et plus généralement la Vision Automatique est très demandé actuellement, mais la majeure partie des études et modèle se font sur ce

que nous appelons des "images naturelles", i.e. des photographies, et peu en comparaison sur des relevés géophysique. Il y a un besoin dans plusieurs domaines pour des détecteurs d'objet rapide et précis étant capable d'analyser des images fondées sur d'autre signaux que le spectre visible.

Chapter 3

Introduction

This document is served as the final assignment of my graduate engineering degree which concludes my 5 years as an ESIEA Student. This document details my work during my 6 months stay as an intern and research student at Leiden University.

This internship was done at the department of Digital Archaeology, which aims to apply information technology to Archaeology. Leiden University is one of the top institution in the world, and this department is to my knowledge the best in the subfield of automated detection. This work was done under the supervision of Mr. Verschoof-van der Vaart, a PhD candidate whose work has heavily influenced mine. Mr. Verschoof-van der Vaart also studies detection methods. In his 2019 article, Mr. Verschoof-van der Vaart introduces a new kind of dataset based on LiDAR surveys in a central region of the Netherlands, which was used here. He also gave me some very interesting techniques and metrics, and pushed me to think more deeply about the work I was undertaking.

In short, the aim of this project is to create a dedicated object detection framework for use in Archaeological detection in LiDAR surveys. We use novel methods coming from satellite imagery detection, along with the state of the art in detection techniques to accomplish this task. As such, this project is significantly oriented towards research and development. A fairly comprehensive State of the Art has been redacted, along with a complete document detailing the architecture of the network, the type of tricks and tools used, along with training and testing methodology. Finally some discussion on our results, along with hints on the direction of further research are given.

While this work could seem somehow academic and as such "hors sol", some very interesting insights can be glanced from working with Archaeology and Archaeologist. In its essence, Archaeology deals with the incomplete, the unknowable and the fuzziness of reality; things that are also main concerns with Engineering. This is a common theme that we will find throughout this document: given imperfect tools and measures of reality, how can we develop an understanding and give some forms of guarantees on the performance and accuracy of our methods ? **Understanding how Archaeologists deal with this uncertainty and the practical aspects of their subject can give us keys in doing a better work in our own field.** As such, I feel that there is a close relation between Engineering and Archaeology, and that more cross field projects need to be done to more firmly tie those two domains together.

Part I

Context

Chapter 4

Organisation & Managerial Conditions

This internship was particular in two ways: first the university of Leiden was not accostumed to the type of work I was proposing. Internship of this type were unheard of, and I was also providing them with a research subject. I worked under the supervision of M. Verschoof-van der Vaart, a PhD candidate in the department of Digital Archaeology of Leiden University. M. Verschoof-van der Vaart is also working on automated detection in LiDAR.

Then the COVID-19 situation profoundly modified planning. Initially, I was planned to stay at Leiden in the Netherlands, and work physically within the University, in a lab made for Master students. The COVID-19 forced the university to close down shortly before my departure, and then France entered a two month quarantine. This modified the way I was going to work.

Under those unique circumstances, I was allowed a rare freedom, and much trust. I was lucky enough that I could conduct my work remotely, since most of it was writing documents, studying and reading papers, training and evaluating networks.

I spent the entire internship working from home. I would interact regularly with Leiden University to give updates or give reports. I used the computing server of my old computer club, the DTRE to train the networks and run experiments.

However this situation also came with negative consequences. Since I was not physically present at the University, frequent, non formal contact was not possible. I also had issues gaining access to the computing facilities of the University, which slowed my work by forcing me to use a less performant computing server. Due to this, I had to severely restrict the reach of this research project. I was planning to give a serious look at the improvements and other study paths presented in Section 17, but due to a lack of time and computing capabilities, I could not.

I first proposed a study schedule to my advisor, reproduced as a GANTT in Figure 4.1, splitting my 6 months supposed stay into different sections. The first section of the project was a thorough state of the art review of satellite detection techniques, with a write up on each article, along with a detailed planning and recommendation on the architecture and training of the model, which a synthetic version is presented in Section 9 and Section 11. Then came the actual training of the model, and continuous improvements. Finally, a significant amount of time was reserved for the redaction of this present document.

	30/03 10/03	13/04 24/04	27/04 08/05	11/05 22/05	25/05 05/06	08/06 19/06	22/06 03/07	06/07 17/07	20/07 31/07	03/08 14/08	17/08 28/08	31/08 11/09
State of the Art												
Environement Setup												
First Network Architecture												
Trainings												
Architecture V1												
Refinements & Trainings												
Architecture V2												
Article & Final Thesis Writing												

Figure 4.1: Initial GANTT for the study project

Splitting my time between coding tools, training and evaluating networks and redacting documents was a challenging task. Since I was in charge of my planning, and how my day was going to be spent, I needed to make sure that all my tasks were done before I could move on to the next phase. While the independance I was given meant I had entire freedom on how I would accomplish my tasks and when, it also meant I had to work on my organisational skills, and make sure I did not do superfluous work.

Luckily, training networks to completion took a fairly long time. This meant that I could use this time to advance myself on other tasks, such as redacting reports, or programmation. This multitasking was key in the completion of this project in due time. On a typical day I would first check on the results of a training launched the previous day. I would then report those results on a file, along with some identifying informations, such as the day or the name of the network configuration file. I would then start another training, and use the time left to write my thesis, or compute some metrics.

Chapter 5

Sustainability & Social Responsability

The University of Leiden holds the fifth place in the SustainaBul, a ranking of the most sustainable higher educations institutions. This ranking is done by the national student network in the Netherlands, the *Studenten Voor Morgen*. Industrial Ecology and biodiversity, among other sustainable themes are an important part of the University research and teachings.

Leiden University also holds the 7th place in UI Green Metric, a sustainability ranking created by the University of Indonesia. This rankings looks into a given University take on the challenges of energy, recycling, transportation, water or climate change. The University of Leiden quickly rose among this ranking, coming from the 49th place only two years ago. This rise in ranking comes from the multiple actions undertaken by the University to create a more sustainable and carbon neutral environment. For example, many extra solar panels were installed on the University buildings, and the waste generated is now recycled in the entire University. Working with other universities through their national network has also helped Leiden to gather and share much more information to the organisers of the UI Green Metric. Effort is still ongoing to enhance the sustainability score by investing more funds in the areas of Education, Research and into greener infrastructure. The National goal is to make all of Netherlands Universities enter the ranking top 50.

Leiden University publish its policies and efforts towards making the institution more sustainable each year with an annual sustainability report. Much progress has been made in the last year. The entire vehicle fleet of the University is now electric and its restaurants and cafés have almost entirely eliminated beef products. Much effort have been directed into reducing the institution CO2 footprint, being more economical with ressources and reducing energy consumption. The University also compensates for its CO2 emissions by financially supporting sustainable projects who aims at reducing the CO2 of the world via green certificates. The University of Leiden has decreased its carbon footprint by 51% compared to 2016. The Leiden University Green Office (LUGO) is a student lead system of checks and balance that aims at keeping the University true to its commitment to sustainability.

Part II

Preliminaries

Chapter 6

Elementary concepts

The aim of this short section is to present the various domains of studies seen in this work and explain concepts that are necessary for comprehension. This is by no means a complete overview of the concepts but merely a basic introduction into the basic objects studied in this document.

6.1 LiDAR

LiDAR is a method for accurately measuring distances and stands for "*light detection and ranging*". LiDAR is used to make high resolution depth maps, and has seen uses in geography, seismology, autonomous vehicles[2]... LiDAR is able to map out large regions of terrain and produces very high resolution data, while being relatively cheap. LiDAR accurately captures the distance between the sensor and an object, similar in how a sonar works: LiDAR works by emitting short laser pulses and measuring the time of flight between its emission and the time at which it hits an object.

In Archaeology, LiDAR is used to create DEM, that are then integrated into a GIS for analysis. A GIS is a specialised type of software designed to capture and analyze geopgraphic data. By carefully choosing the wavelength used, LiDAR is able to see through vegetation and show structure that would be otherwise hidden. This type of sensing data allows us to see *microrelief*: very small variation in the terrain elevation. Buried objects are now visible, and possibly detectable.

6.2 Archaeological Structures

This works centers around 3 types of Archaeological Structures. As the dataset is based on the work of Verschoof[3], we will use the same classes of objects. Moreover, as the author of this document is not a trained Archaeologist, it would be foolish to try to identify new types of objects to detect.

We will describe those three type of objects:

Figure 6.1: Example of a series of Charcoal Kilns. Each kilns is about 5-10 meters in diameters. Veluwe Region, Netherlands.

Charcoal kilns are circular structures used for production of charcoal by heating wood at a specific temperature and then covering it with soil. Charcoal kilns are an ancient method of charcoal production and can be found all around Europe, mostly around forests. Charcoals kilns are around 5-10 meters in diameters, and are characterised by a faint dark circular outline on a LiDAR survey[4]. They are often found in groups, as can be seen in Figure 6.1

Figure 6.2: Example of a group of Celtic fields, easily recognized by the streaks, and standard size. Each cell is about 30×30 meters. Veluwe Regions, Netherlands.

The second class are Celtic fields, which are traces of ancient agricultural field system. Those fields are found in North-West Europe, but are not necessarily related to the Celtic Culture. They are divided into rectangular cells of regular size, and were believed to be used by a single individual or family[5]. Figure 6.2 shows an example of such fields. In our classification system, **one cell is considered a Celtic field object, not the entire field**. This allows for easier identification, since if one cell is most likely regularly rectangular, the entire field often is not.

Figure 6.3: Two examples of barrows: the "blobs" in the center of the image. Each barrow is about 10 meters in diameter. Veluwe Region, Netherlands.

Finally, the last type of object we aim to detect and classify are barrows. Barrow are mounds of raised earth or stone, over a burial placed in the middle. Barrows are funerary monuments, and are fairly common in Europe. Most dates from around 2200 BC to 1100 BC. Barrows have standard size of about 10 meters in diameters, although more prestigious dignitaries were buried in bigger barrows[6]. Figure 6.3 shows 2 barrows. It should be noted that barrows are fairly common, and can easily be spotted all around North-Western Europe.

6.3 Deep Learning

Deep Learning is a ensemble of techniques which are based on Artificial Neural Networks, with multiple layers stacked upon each other. Those layers will progressively extract higher level features from the input.

One of the most successful innovations of Deep Learning would be Convolutional Neural Networks, or CNN, first introduced by Yann LeCun[7]. Convolution Neurons applies the convolution operation on its input. The convoluted matrix is learned through training.

While the first application of CNNs was in the 90's, they found a renewed interest during the mid 2010's, where the use of GPUs allowed for a massive increase in computation speed which rendered the use of deeper and more powerful networks possible. One of the first of such networks was AlexNet[8] which was trained on a commercial GPUs and outperformed competitors by more than 10 points of mAP. Other quickly followed suit, with deeper and more performant nets being developed each year, like GoogleNet[9], VGG[10] and resNet[11] which introduced the idea of feature fusion via residual units.

Today, deep convolutional networks with residual units are a staple in computer vision, but are also used in audio analysis[12][13][14][15][16] among various other fields with great success.

The work here centers around the task of object detection. This task is actually two fold: given an input image, localise an object then give a classification of this object. A good object detector must be able to do both, but they are evaluated differently.

A Deep Learning model is trained on a dataset. Deep Learning requires very large amounts of data to correctly train as they are very prone to overfit. In statistics, a model is said to overfit when it "describes features that arises from noise or variance in the data, rather than the underlying distribution from which the data is drawn"[17]. In other words, this means that the model has "memorised" the data, and will perform badly on data which it has never seen before. In Figure 6.4, we see a classification task where a curve has to be drawn to differentiate two class and the green line is overfitted to the data, while the black line is a more reasonable fit.

Overfitting is an issue that affects all Deep Learning models, but a lot of effort has been done to address this, either by creating a more diverse and robust dataset with data augmentation, or by modifying the network itself via regularisation and normalisation.

Figure 6.4: Example of overfitting on a classification task. The black line represents a good fit to the data, with an acceptable error rate or, misclassified data points. The green represents overfit: while the error rate is lower than the black line, the fit is too complicated, and will badly generalize on unseen data. Doc. Wikipedia

There are two main parts of training a model on a particular dataset. First the dataset is divided in two sub dataset. One is used for training, and the other for evaluation. For simplicity, we will use an example of classification of an input image. During training, the model will produce a inference based on the input data *i.e.* a label. We will compare the inferred label to the ground truth using a particular metric, like Categorical Cross-Entropy or MSE and obtain a distance between the two labels. This distance is known as the loss. We will try to reduce the loss by optimising the weights of the model using gradient descent, as shown on Figure 6.5.

Given a multi variable differentiable function $F(x)$ that is defined in the neighborhood

of a point $a \in \mathbb{R}^n$, the gradient descent is defined as follows:

$$a_{n+1} = a_n - \gamma \nabla F(a_n) \tag{6.1}$$

With a small $\gamma \in \mathbb{R}^+$, we have $F(a_{n+1}) \leq F(a_n)$, meaning that $\gamma \nabla F(a)$ is subtracted from a, moving toward a minimum. The parameter γ is called the learning rate. A large learning rate will mean that the descent might converge faster, but might "overshoot" and miss the minimum, while a small learning rate means a more precise convergence, but will dramatically increase the number of steps necessary. On Figure 6.5, the learning represent the length of each arrow during the descent. It should be noted that nowadays, gradient descent is rarely used with modern networks, as most uses other optimizers, such as ADAM[18] or ADAGRAD[19], which are based on the gradient descent, but also uses adaptive trainings steps.

Figure 6.5: Gradient Descent on a loss function with one parameter. Since the loss function of neural network is not convex, there are possibly multiple minimum, which the gradient descent algorithm can get "stuck" into. As the dimensionality of the problem increase, the complexity of the dynamics of the gradient descent increase.

Since the gradient gives the direction of steepest incline of a differentiable function $F(x)$, this means that the function $F(x)$ declines the fastest in the direction of negative gradient. In Deep Learning backpropagation is used, an recursive and efficient process that is able to compute the gradient with respect to the weights of the network.

Chapter 7

Metrics

One of the hardest part of creating and training ML models is accurately evaluating their performance. How can you known if your model is giving out accurate predictions ? What is accuracy, and how can we precisely define it ? Understanding the types of errors a detection model can make is a crucial part in enhancing their performance. In this section, we will present metrics used in detection and classification tasks that can help us to evaluate and understand how and where a given model succeed and fail.

7.1 Type of Errors

In a classification task, where a model is asked to classify an item into a fixed number of categories based on input characteristics, a model will predict the class of a given item. For example if an input image contains a cat or a dog. In doing so, the model can make mistakes. When predicting a particular class, there are 2 type of predictions that can be made: positive or negative, and those predictions can be true or false. When a network correctly predicts that an image contains a cat, it is a true positive. When it predicts that there is no dog when there is one, this is a false negative.

All in all, there are 4 categories of predictions: True Positive (TP), False Positive (FP), True Negative (TN) and False Negative (TN).

7.2 Precision and Recall

Precision is defined as "the fraction of detections reported by model that were correct" and recall is "the fraction of detections reported by the model which were correct"[20, p.411]. We can see those concepts visualised in Figure 7.1. In that Figure, the precision would be equal to the number True Positives in green divided by number of selected elements *i.e.* the green and red sets combined. The recall would be equal to the number of true positives over the total number of relevant elements or the dark gray set and the green set combined.

Precision and recall allows us to quantify with more accuracy the quality of a model than just the number of errors that it makes. For example, in the case of a model trying to detect a rare event like a disease that would infect only a small fraction of the population,

Figure 7.1: Precision and recall on a classification task. Figure adapted from Wikipedia[21]

say one in a million, **a detector that would always infer that a person is not sick would be able to attain a** 99.9999% **accuracy.** However, while this detector would achieve a very high precision, it would have a very bad recall, which would indicate that it is not a very good model after all.

7.3 Intersection over Union (IoU)

The intersection over union, or Jaccard Index quantifies the accuracy of the bounding box prediction. IoU measure the quality of a bounding box : if the predicted bounding box overlaps significantly with the ground truth bounding box, then it should have a low score, and inversely if the prediction does not overlap with the ground truth. The IoU is given by the following equation:

$$IoU = \frac{\text{area}(BBox_{truth} \cap BBox_{pred})}{\text{area}(BBox_{truth} \cup BBox_{pred})} \tag{7.1}$$

Generally a detection is considered correct if the IoU ≥ 0.5; this threshold is also used when computing the mAP. It should also be noted that the IoU is not the only way to measure how good a bounding box is. Improvements on this metric has been done that

Figure 7.2: Intersection over Union
Source: https://www.pyimagesearch.com/2016/11/07/intersection-over-union-iou-for-object-detection/

gives out a better measure on the quality of the box, such as the GIoU[22], dIoU[23] and cIoU[23]. Those metrics are used in our model, and are presented in Section 14.3.1.

7.4 F1-Score, Average Precision and Mean Average Precision (mAP)

The F1-Score is a measure of test accuracy. It is the harmonic mean of precision and recall :

$$2 \cdot \frac{precision \cdot recall}{precision + recall} \tag{7.2}$$

The Average Precision (AP) is a popular metric used to measure the accuracy of object detector. In this section, we will use the example of a model asked to detect a single class of object, like a dog. In total, there are 5 dogs in the dataset.

To compute the AP, one first draws a list of all predictions made by the model, and rank it according to the predicted confidence level. As we go down the list, the recall value will increase, as it is the proportion of TP over all possible positives. Precision will have a "zig-zag" pattern, where it will go up with TP but down with FP. The AP is defined as the area under this curve, or:

$$AP = \int_0^1 p(r)dr \tag{7.3}$$

Where $p(r)$ is the precision of the model according to a given recall value. Since precision and recall are always between 0 and 1, AP will also be between 0 and 1.

The COCO mAP, or mAP@50 is simply the AP average over all classes for IoU that are over 0.5. Sometimes, different values of the mAP are given for different values of the IoU required to have a successful detection.

The mean average precision is the metric used by the COCO dataset[24]. As said above, when the IoU between the prediction and the ground truth is over 0.5, the prediction is considered a valid detection.

7.5 Confusion Matrices

		Predictions	
		P	N
Truth	P	TP	FN
	N	FP	TN

Table 7.1: Abstract representation of a confusion matrix. If the prediction is the same as the ground truth, then the prediction is a True Positive/Negative (TP/TN). If it is not, it is a False Positive/Negative (FP/FN)

This metric is a very popular way of seeing how a model fails to classify objects, in particular how it confuses classes. A confusion matrix is a $N \times N$ matrix, with N being the number of classes. Each row represents the instance in a predicted class, while each column represents the predicted instance.[25]. A perfect model would give a diagonal matrix, where each prediction match with the label.

		Predictions		
		Cat	Lion	Dog
Truth	Cat	12	6	1
	Lion	7	8	0
	Dog	0	1	14

Table 7.2: Example of a confusion matrix. Here, we can easily see that the model often confuses Lion and Cat, but the Dog class is not being confused much for any other class.

Table 7.2 shows an example of a confusion matrix for a model predicted 3 classes. In the case of an object detector, where the model outputs bounding box which can be anywhere in an input image, a prediction is considered only when the IoU of the box and the ground truth is over 0.5. Predictions matrices are also usually normalised.

7.6 Matthews Correlation Coefficient

The MCC is a metric often used in bioinformatics to measure the quality of binary class predictions, and takes into account true and false positive. The MCC has been introduced by Matthews in 1975, and is a correlation coefficient between prediction and ground truth.[26] The MCC is regarded as a more balanced metric than the F1-Score[27][28] and has seen some recent use in archaeological object detection. The MCC can be used with classes of very different size, and returns a value between -1 and 1. A score of -1 means complete disagrement between predictions and truth, 0 indicates that the predictions are not better than a random choice of class, and 1 indicates that a perfect prediction.

The MCC is regarded as one of the best way to describe a confusion matrix using a single number, and is defined as follow:

$$MCC = \frac{TP \times TN - FP \times FN}{\sqrt{(TP + FP)(TP + FN)(TN + FP)(TN + FN)}} \tag{7.4}$$

In the case of multi class prediction, the formula is slightly more complicated, and is defined in terms of a $K \times K$ confusion matrix, and C classes[29]:

$$MCC = \frac{\sum_k \sum_l \sum_m C_{kk} C_{lm} - C_{kl} C_{mk}}{\sqrt{\sum_k (\sum_l C_{kl})(\sum_{k'|k \neq k'} \sum_{l'} C_{k'l'})} \sqrt{\sum_k (\sum_l C_{lk})(\sum_{k'|k \neq k'} \sum_{l'} C_{l'k'})}} \tag{7.5}$$

7.7 Evaluating a model

Computing those metrics and analyzing them allows a researcher to better understand the behavior of its model, and preventing degenerate behavior. It should however be noted that those metrics do not always give out accurate or useful information. In that case, only knowledge and experience of the usual issues can help.

For example, it can happen that a model will always infer one class other another, for any kind of object and still obtain good accuracy[1]. It can also be the case that a metric is very sensible at a some scale of errors but not at others: the L2 distance for example grows quadratically and outputs small distances when the L1 distance is below 1, but very high values that might be hard to optimize for when the L1 distance is over 1.

The only way to diagnose those issues will be to manually inspect the prediction of the model, and carefully choosing the metrics used.

[1]This often happens in the case of an unbalanced dataset, where one class appear more often than any other.

Chapter 8

Challenges

8.1 Differences between natural images and remote sensing surveys

Traditional work in object detection focusses on what we will call "natural images", which are photographs of scenes seen in normal settings. For examples, people sitting at a table, or children in front of horses. They are similar to images we would see with our own eyes. This means that, if there is an object in a photograph, there is a high probability that this object also exist and is the same category in the real scene that has been photographed. In other words, there is a good correspondence between the real object, its classification, and the kind of signal it emits in the visual field. A photograph of a camel will contain a camel, and we are able to very confidently classify the image as containing a camel, even though we are only classifying a *visual representation*, not the object itself.

In remote sensing surveys, or more generally with any kind of image that is not made of purely visible light, the difference between the representation and the real object is more pronounced, and while it might be easy to detect and classify objects in the representation, to guarantee that those detected objects always match up with a real object is much more tricky. How can we say that the white mass seen in an X-Ray scanner that we detect and classify as a tumor is not only indeed a tumor in its representation, but also match up with a real tumor in a patient? The problem is even more prevalent with remote sensing surveys, with noise and geological details adding yet another layer of complexity.

8.2 Occlusion and Vegetation

Occlusion is a common issue in object detection, as more often than not object are not perfectly visible and are obscured by others. This issue is even more prevalent in detection of Archaeological structures.

In the classes of objects that we aim to detect, most of them are quite sizeable and during construction of newer buildings or roads, those are often seen as obstacles to be removed, and part of them might be constructed upon. This hinders the visibility of those objects, and can pose a problem in detection.

(a) A natural image, taken from the COCO[24] dataset

(b) An example from the LiDAR dataset. On the bottom right, we can see an example of a barrow. However, this barrow is very similar to the roundabout seen slightly above.

Figure 8.1: A natural image *versus* a LiDAR image

Vegetation can also cause issues in the case of remote sensing surveys and wooded area can be prohibitively hard to analyze due to the occlusion created by trees[**kenzlerLambers2015**]. With LiDAR it can be possible to remove some of the occlusion caused by vegetation by carefully analyzing the return signal from the laser, but this might not be applicable with other type of remote sensing data.

8.3 Issues with detection in remote sensing surveys

Whereas in natural images might be around a thousand pixels in width, remote sensing surveys cover hundreds of kilometer square of area, and are often tens of thousands of pixels wide. Moreover, the size of the object to detect is tiny in comparison to the size of the image, which is not usually the case in natural images. Traditional object detection techniques take advantage of this by heavily downscaling the image through the layers of the network, greatly reducing the computational cost. This is not possible to do with remote sensing surveys: a barrow, which might be a few meters wide in reality will be only a few pixels wide, and by downscaling we might lose all informations concerning those small objects. Those issues are similar with detection in satellite imagery, described in Van Etten[30], which might indicates that ideas used to mitigate them might also be applicable in our case.

When working with remote sensing surveys, one must always keep in mind those issues. In our case, the only reliable way of classifying archaeological objects is by prospecting and physical inspection, something that **cannot be done using only remote sensing surveys**. However, this create another issue, one of scale. The dataset comprised of 16 LiDAR images. Each image has a very large resolution, 13140×10290, and cover about 30km^2 of terrain. In its entirety, the dataset contains the position of about 3000 objects

located around about $\sim 480\text{km}^2$ of terrain. It would be impossible for me to verify the correctness of every object in the dataset, because a definitive confirmation would imply a physical verification on site.

In short, even if the network architecture is fit for the task and trained properly, an already hard task, and even if the annotations in the dataset are entirely correct something that is even harder to do, we will still have an uncertainty as to whether the detected objects are not only actually real, but of the correct class.

Tying this in with the ideas developed above: doing detections in remote sensing surveys, be it of Archaeological objects or otherwise, we should have some skepticism in the detections. Both because geophysical representations of objects are not always trustworthy, and because our detection system, as good as it can be, might always make mistakes.

8.4 Dataset

In of itself, it is quite challenging to obtain large segments of LiDAR surveys, or for that matter any kind of remote sensing surveys that is annotated. Deep Learning techniques usually requires vast amount of data to train properly. However, here data can be prohibitively expensive to produce: a geophysical survey of an area is itself a challenge, with funding to secure and planning to be done. Moreover, annotating those dataset especially with Archaeological targets require experts and is very time consuming. Those two characteristics can render the annotation of such a dataset very complicated.[31]

In Archaeology, the practice of Open Data, the act of freely sharing the data produced, is not yet widely adopted for a multitude of reasons. One of them is the possibility of looting. Since those surveys can show very clearly the presence of a potential archaeological object who might contain valuables such as gold, sharing this data to the world might make the act of looting easier[32].

Chapter 9

State of the Art in Detection in Satellite Imagery

A detailled SotA have already been done, and is available as its own document. For the sake of brievity, we will not include its entirety in this section, but we will only highlight the major contribution of each paper.

9.1 You Only Look Twice[30]

You Only Look Twice is a model developped by Adam Van Etten, and is focussing on rapid multi scale detection for satellite imagery. This approach uses a modified YOLO[33] framework. A new backbone architecture is used, with finer grained features and a denser final grid, to better detect the very small objects found in satellite imagery. This approach also uses an ensemble method, where multiple networks are run simultaneously at different scales. Finally, the problem of large input image size is mitigated by partitioning the images using a sliding window.

This network was trained on small snippets or segments of large images from 3 differents sources to detect 5 classes of objects: cars, airplanes, boats,building footprints and airports.

9.1.1 Network Architecture

The YOLO network has been modified to better detect heavily packed objects, often found in satellite imagery. The YOLT network takes as input a 416×416 pixel image, which it downscales 16 times. The network outputs a 26×26 prediction grid, which is much finer than the 7×7 prediction grid offered by a "regular" YOLO network. **This finer prediction grid is what allows the network to detect densely packed objects.**

A passthrough layer is also used to pass coarse features from the earlier and high resolution layers to the final low resolution layers. This passthrough layer is similar to the identity layer used in ResNet[11] and was first used in YOLOv9000[34].

Each layer uses Batch Normalization[35] and uses the leaky-ReLU activation[36], except for the last layer, which uses a linear activation. This final layer provides the predictions

for the bounding boxes and class.

9.1.2 Scale Mitigation

The author uses two different detectors on the input images running simultaneously. One is trained to detect small scale objects, like vehicles and building, while the other is trained to detect airports and large structures. The size on the input images of these detector is different, as one takes in 200 meters segments, while the other uses 2000 meters segments.

As there is about 100 times less 2000 meters segment in the original images as there is 200 meters segments, the large scale network runs much less often than the small scale network. This limits the reduction of inference speed that running two detectors would do.

9.1.3 Training

The author uses training data from three sources: DigitalGlobe satellites, Planet satellites and aerial platforms. The author also uses some data augmentation techniques, with random rescaling and rotations to get more examples, as the dataset for some classes such as airports or airplanes is small.

9.1.4 Results

It should be noted that the author initial tried to train only one detector and obtained very poor results, due to the large scale difference between some of the objects. The results presented here are the one using the two detector approach.

Table 9.1 shows the F1 Score for each class. It should be noted that while the absolute value of the F1 Score for the building class is lower in comparison the other classes, the best contestant in the SpaceNet Challenge 2, where the contestants where asked to detect building outlines using the same dataset as the one used here obtained a F1-Score of 0.69. This puts this detector in the Top-3.

Object Class	F1 Score
Car	0.90 ± 0.09
Airplane	0.87 ± 0.08
Boat	0.82 ± 0.07
Building	0.61 ± 0.15
Airport	0.91 ± 0.14

Table 9.1: YOLT Detection performance on all classes

The network is also very fast, being able to analyze $32km^2/min$ for the small scale network and $6000km^2/min$ for the large scale network.

9.2 A Simple and Efficient Network for Small Target Detection[37]

In this article by Ju et al; the authors try to address the issue of low small target detection performance in classical detection networks. The authors put forth 3 modifications to improve detection performance: first, a "dilated module" that helps to expand the recepetive field of convolutional layers without loss of resolution. Secondly, feature fusion is applied on the feature maps of different layers of the network . Finally, a passthrough layer, similar to the one described in You Only Look Twice[30], described in section 9.1 and in ResNet[11] is applied to get the finer-grained information from the earlier layers and the more semantic information coming out of the deeper layers.

The performance of the network is evaluated on the VEDAI[38] dataset along with the DOTA[39] dataset, and obtains state of the art results, with FPS performance comparable to a tiny YOLOv3 network[33] but with average precision comparable to a "full size" YOLOv3 network.

9.2.1 Proposed Modules

Dilated Modules

(a) 1-Dilated Convolution (b) 2-Dilated Convolution (c) 4-Dilated Convolution

Figure 9.1: Dilated Convolution Example

Dilated convolution are used to expand the receptive field of the convolution operation without increasing the size of kernel or without reducing the size of the feature maps and losing information about small targets. Figure 9.1 shows the dilatation of a convolution kernel and the impact on the receptive field. Dilated Convolution has been introduced by Yu and Koltum in "Multi-scale Context Aggregation by Dilated Convolutions"[40].

Dilated modules are used to help to locate the small targets accurately and aggregate multi-scale contextual information. Dilated convolution is used as a basic element to build a dilated module. The module reuse features from earlier and deeper layer by concatenation. A 1×1 convolution is used to reduce the dimension of the module.

Passthrough module

In a detection network, earlier layer contains more fine grained information which can be useful to detect and accurately determine the location of small objects. Usually this

information is "lost" in the deeper layers. A passthrough layer with a stride of 2 is used to utilize those earlier features. The passthrough layer transform the feature map from a $2N \times 2N \times C$ to $N \times N \times 4C$. This passthrough layer is used to construct the passthrough module. This module merges features from earlier layers with the ones in the deeper layers. Again, a 1×1 convolution is used to reduce the dimension of the module.

Feature Fusion

Here, concatenation is used to merge features from earlier layers with ones coming from deeper layers. There are two different kind of fusion used in this paper.

The first is concatenating the feature maps between different dilated modules. Since the dilated modules don't change the dimension of the feature maps, the merging can be directly done by concatenation.

The second kind is the passthrough layer. Since the feature maps undergoes downsampling, their dimensions changes. The paper propose to unify their dimension by using another passthrough layer and upsampling.

9.2.2 General Architecture

The proposed architecture is inspired by the tiny YOLOv3, but uses deeper layers along with dilated modules and feature fusion. 1×1 convolution are used to reduce the dimensions, which helps increase the speed and efficiency of the network.

Figure 9.2: General Architecture

Since the goal of the network is to detect small targets, large downsampling as the one used in YOLOv3 are not adequate. However, the number of downsampling layers affects the size of the receptive field, which in turns determines the amount of contextual information of small targets. Two dilated modules are used to expand the receptive field. The feature maps are downsampled twice and used as fine grained information and combine with feature maps that are downsampled thrice using a passthrough modules.

The final layer provides the results of the prediction, which contains the location of the bounding box, and the class of the targets. The size of the last layer is $N = N_{boxes} \times (N_{classes} + 4 + 1)$ with 4 being the number of offsets for the bounding boxes, and 1 for the "objectness" prediction.

9.2.3 Results

The models were trained and tested on the VEDAI[38] and DOTA datasets[39]. The authors notes that the targets in VEDAI are smaller than the ones in the DOTA datasets, but the quantity of targets in DOTA are higher than of VEDAI.

To obtain a good comparison between existing architectures and the proposed model, the author ran 4 experiments on both datasets, using YoloV2, Tiny YOLOv3, YOLOv3 and their own model. The same size of input (512×512) was used on each model.

We should note that while YOLOv3 tends to obtain better scores in AP, the computing cost associated with running this algorithm in much higher, as it requires ten times more BFLOPs than the proposed model (see Table 9.2). This complexity is reflected in the number of Frames Per Seconds that is able to be computed. In short, it seems that the proposed method is able to obtain results similar, if slightly inferior than YOLOv3 but is much faster and has much less parameters than both YOLOv3 and tiny YOLOv3.

Object Detection Algorithm	YOLOv2	Tiny YOLOv3	YOLOv3	Proposed Model
Input	512×512	512×512	512×512	512×512
Model Size	202.3M	34.7M	236.3M	2.8M
FPS (Higher is better)	58.3	**76.4**	14.7	75.4
BFLOPS (Lower is better)	44.417	**8.243**	101.784	9.692
AP (Higher is better)	54.33	58.17	**85.37**	80.16

Table 9.2: Comparative results of FPS, BFLOPs and Model Size with all tested algorithms. BFLOPS refer to the number of billions of floating points operations needed to calculate the prediction.

In short, this model combine the precision of YOLOv3 with the fast and efficient computation of the tiny model.

9.3 Object Detection in Remote Sensing Images Based on Improved Bounding Box Regression and Multi-Level Features Fusion[41]

This article by Qian et al. aims to solve two issues prevalent in anchor-based detection methods: first the loss of low level information when using only the highest level feature maps for the feature extraction of region proposal. Secondly, existing metrics, such as IoU, are not able to measure the distance between two non overlapping bounding boxes. During training, the bounding box loss is not able to directly optimize this metric.

The authors implements a new metric, the GIoU, which is able to measure the distance between non-overlapping bounding boxes, along with a bounding box loss system that is able to directly optimize the new metric. A new MLFF is proposed, and incorporated into an existing network.

This allows the authors to reach state of the art performance on the NWPU VHR-10 dataset[42].

9.3.1 Architecture

General Network Architecture

The network can use an arbitrary size image as an input. This image is fed into a FPN, which acts as the backbone of the network. This FPN outputs multi-scale feature maps at different levels. Those multi-scale feature maps are used by the MLFF, which pools features using RoIAlign[11] across multiple levels and concatenates them along the channel dimension. The fused features are utilized for bounding box regression and classification. A novel GIoU loss is proposed, instead of the smooth L1 loss.

Figure 9.3: Architecture of the proposed framework. The left part shows the feature pyramid network. Multilevel features fusion is shown in the middle, and classification and bounding box regression based on the IGIoU loss is shown in the rightmost part.

MLFF

A novel MLFF module is proposed. The feature maps of all levels are used by a MLFF module for feature extraction. Each proposal generated by the FPN are mapped to the feature maps of all levels. The size and location of the proposed region in the feature maps can be calculated based on the size ration between the proposal and the feature maps.

Four regions of each proposal are transformed into four groups of 7×7 feature maps, denoted F_2, F_3, F_4 and F_5 in figure 9.3 using RoiAlign[11]. The features are then concatenated along the channel dimension into a fused feature map called F.

Finally, a convolutional layer with a 7×7 kernel is used on F to obtain F_{C1} which is then passed to a fully connected layer.

9.3.2 Generalized Intersection over Union

A novel metric, the Generalized IoU (GIoU) is proposed to enhance the evaluation of proximity between two bounding boxes. The traditional IoU is insensitive to the scales of bounding boxes, and can be calculated using formula 9.1. Let B_{GT} be the ground truth bounding box and B_{PT} be the predicted bounding box.

$$IoU = \frac{area(B_{GT} \cap B_{PT})}{area(B_{GT} \cup B_{PT})} \tag{9.1}$$

The IoU is essentially the fraction of the intersection of the area of the predicted bounding box and the ground truth over the union of both bounding box. The IoU is not capable of measuring the distance when two bounding boxes are not overlapping. The introduced metric, address this issue.

The formula for the IoU is as follows:

$$GIoU = IoU + \frac{area(B_{GT} \cup B_{PT})}{area(B_{EC})} - 1 \tag{9.2}$$

Where B_{EC} represents the smallest enclosing box of B_{GT} and B_{PT}. The IoU is inversely proportional to he distance between B_{GT} and B_{PT} where they are overlapping, but stays at 0 when they were not overlapping. The GIoU is proportional to the distance of the two bounding boxes, and decreases with the distance between B_{GT} and B_{PT}, whether or not the bounding boxes were overlapping.

9.3.3 Bounding Box Regression based on Improved GIoU Loss (IGIoU)

The bounding box regression loss used in traditional object detection methods is usually adopted to smooth the L1 or L2 loss. However, those two loss functions do not directly optimize the IoU metric. The smooth L1 or L2 loss are used to optimize the four parameters of the predicted bounding box, and the IoU is used to give more importance to the overlapping degree between the two bounding boxes.

Integrating the value of the GIoU into the loss can be done using formula 9.3 from Rezatofighi et al. [22].

$$L_{GIoU} = 1 - GIoU \tag{9.3}$$

This loss has a constant gradient during the training process, which restricts the effect of bounding box regression. The authors note that strength of the training should be enhanced when the predicted bounding box is far away from the ground truth, *i.e.* the absolute value of the gradient should be higher when the GIoU is small. Moreover, the value of the bounding box regression loss should decrease with the GIoU.

The improved GIoU Loss (IGIoU) is used to address those issues, and is given in the following formula:

$$L_{IGIoU} = 2 \times log_2 - 2 \times log(1 + GIoU) \tag{9.4}$$

9.3.4 Results

To validate the IGIoU loss and the MLFF module, quantitative comparisons were made between the proposed methods and five others methods on the NWPU VHR-10 dataset[42]. Those results are listed in table 9.3

The proposed method is also evaluated against four state of the art methods on the NWPU VHR-10 datasets, and are listed in table 9.3.

Method	GIoU			IoU		
	mAP (%)	AP50(%)	AP75(%)	mAP(%)	AP50(%)	AP75(%)
Faster R-CNN	53.5	86.8	61.0	54.6	87.1	62.6
Mask R-CNN	54.7	88.8	62.6	55.8	89.4	64.2
FPN	55.3	88.8	64.0	56.5	89.3	65.9
PANet	56.3	**90.5**	63.9	57.8	**91.8**	65.8
Proposed Method	**58.0**	**90.5**	**67.5**	**59.2**	91.4	**69.6**

Table 9.3: Comparison of the ODRSI against four existing detection framework on the NWPU VHR-10

The method obtains state of the art results and better precision scores than all of the other tested methods, except in one case.

9.4 A Single Shot Framework with Multi-Scale Feature Fusion for Geospatial Object Detection[43]

This paper presents by Zhuang *et al.*[**zhuangAl**] a novel architecture along with a new loss system, allowing for more precise bounding boxes along detected objects. The new architectures incorporates ideas similar to YOLT[30] where multiple detectors are trained and ran at different scales. This time the different scales detection is directly incorporated into the architecture itself: the feature maps from different layers are concatenated together. This approach allows the model to fully use the low level feature map with high resolution along with the high level feature maps incorporating more semantic information.

The model is trained and tested on two different datasets: the RSD-GOD dataset, a new dataset comprising of 5 different categories and 18K annotated images introduced by this paper, and the NWPU VHR-10[42] dataset.

9.4.1 Architecture

Base Feature Extractor

The proposed network is heavily based on the Darknet-53 architecture and reuses most of it features. 53 Convolutional layers are used, without pooling layers. The network reduce the features dimension by 2 by applying a stride. The Network also uses residual blocks containing 1×1 and 3×3 convolutional filters and 23 residual blocks. Batch normalisation[35] instead of dropout is used to control overfitting and convergence during training. The network uses leaky ReLU activations on all convolutional layers.

Figure 9.4: Architecture of the Darknet 53, used as a base network for feature extraction

Multi-scale feature fusion detector

To allow the detector to fully exploit both low level high resolution with fine detail feature maps and high level semantic features, multi-scale feature are used.

Three convolutional layers at different scales of the base feature extractor are used to make predictions. The first-scale predictions are made using an added convolutional layer on top of the last convolutional layer of the base feature detector. Following the article definitions, we will call this convolutional prediction layer `conv_6`. Two feature

Figure 9.5: General architecture of the multi-scale feature fusion detector. The model uses Darknet-53 as the base feature extractor. Three predictions are generated at three different scales.

fusion modules are used to combine shallow feature. The first fusion module takes the prediction of the `conv_6` layer, upsamples it and concatenate it to the feature maps yielded by the `conv_4` layer. This gives out the second scale predictions. Finally, the second fusion modules takes the feature maps of the `conv_3` layer and concatenate it to the output of the first fusion modules, after up-sampling. This yield the third and final prediction.

Multi-scale feature fusion module

Three multi-scale feature fusion module are used to create 3 different scale prediction.

In a multi-scale feature fusion module, the dimension of the input feature maps are first reduced through the use of 1×1 convolutional kernel. High level feature maps are up-sampled after the 1×1 convolution to be same size as the lower level feature maps. Then, the high level feature maps are concatenated with the lower level feature maps. Alternate 1×1 and 3×3 convolutional layer are then used to progressively reduce the dimensions of the feature maps and make predictions. Figure 9.6 show details of the feature fusion module.

Figure 9.6: Multi-scale feature fusion module. The Feature maps from different layers are merged through up-sampling and concatenation. Each convolutional layer is batch-normalized, uses leaky ReLU activations, and have a stride of 1.

Anchors and predictions

Since the model is unstable during early training iterations, anchors are used, similar to the ones used in Faster R-CNN [44]. The designed network outputs three kind of feature maps with different size : 13×13, 26×26, 52×52. B anchors are generated and the corresponding B bounding boxes are predicted for each grid cell. During the training, the network outputs 5 coordinate values t_x, t_y, t_w, t_h, t_o; the final location of the predicted bounding box is obtained through the anchor size and the network outputs.

The location of the center of the bounding boxes (b_x, b_y) is relative to the grid cell offset (c_x, c_y) and the sigmoid activation function value of the location coordinates (t_x, t_y). Here (c_x, c_y) denotes the offsets from the top left corner of the original image to the current grid cell. The width and height of anchors are denoted as (p_w, p_h). p_o denotes the confidence score of object probability. The σ denotes the sigmoid function. Applying the sigmoid function on the predicted t_x, t_y, t_o normalize their value and stabilize the model during training.

We compute b_x, b_y, b_w, b_h and p_o using the following formulas:

$$b_x = \sigma(t_x) + c_x \tag{9.5}$$

$$b_y = \sigma(t_y) + c_y \tag{9.6}$$

$$b_w = p_w e^{t_w} \tag{9.7}$$

$$b_h = p_h e^{t_h} \tag{9.8}$$

Figure 9.7: The model generates 4 coordinates: t_x, t_y, t_w and t_h. The center location of the final bounding box (b_x, b_y) is relative to the grid cell offsets (c_x, c_y) and the sigmoid activation function value of location coordinates (t_x, t_y). (c_x, c_y) denotes the offsets from the top left corner of the original image to the current grid cell

$$p_o = \sigma(t_o) \tag{9.9}$$

For each predictions module, 3 anchor priors with different scales are used ($B = 3$). K-means clustering have been applied on the annotated bounding boxes in the training data in order to obtain suitable priors.

The network outputs four coordinates, one object confidence information and C class probabilities for each bounding box. The dimension of the network output tensor is then $S \times S \times N$, where S is the grid size, and $N = (5 + C) \times B$

Loss Function

The training objective loss is defined as the sum of a localization loss (L_{loc}), a confidence loss (L_{conf}) and a classification loss (L_{cla}).

The localization and confidence are computed using the squared error loss (see equations 9.11 and 9.12). The class loss is computed using the categorical crossentropy loss and is given in equation 9.13.

$$L_{overall} = L_{loc} + L_{conf} + L_{cla} \tag{9.10}$$

$$L_{loc} = \lambda_{coord} \sum_{i=0}^{S^2} \sum_{j=0}^{B} [(x_i \hat{x}_i)^2 + (y_i - \hat{y}_i)^2 + (w_i - \hat{w}_i)^2 + (h_i - \hat{h}_i)^2] \tag{9.11}$$

$$L_{conf} = \lambda_{obj} \sum_{i=0}^{S^2} \sum_{j=0}^{B} P^{obj}(c_i - \hat{c}_i)^2 + \lambda_{noobj} \sum_{i=0}^{S^2} \sum_{j=0}^{B} (1 - P^{obj})(c_i - \hat{c}_i)^2 \tag{9.12}$$

$$L_{cla} = -\lambda_{cla} \sum_{i=0}^{S^2} P^{obj} log(\hat{p}_i) \tag{9.13}$$

Here, $\lambda_{coord}, \lambda_{noobj}$ and λ_{cla} represents scaling factors for the weight localization loss, the confidence loss and classification loss. P^{obj} is probability that there is an object in the box. Predicted bounding boxes without objects are more penalized.

The authors used the following values of λ: $\lambda_{coord} = 1, \lambda_{obj} = 5, \lambda_{noobj} = 1, \lambda_{cla} = 1$

Soft Non-Maximum Suppression

The proposed detection method generates a large number of cluttered bounding boxes. In traditional one stage detection pipelines, Non Maximum Suppression (NMS) is used to remove repetitive bounding boxes. NMS ranks location candidates according to their classification, and removes overlapping bounding boxes with the lowest scores.

Here, this method might cause the framework to miss part of neighboring detections, whose classification scores are lower. Instead of removing the location candidates, the Soft Non Maximal Suppression assign a new classification score to the bounding boxes, following equation 9.14

$$s_i = \begin{cases} s_i & iou(b_i, b_M) < T; i \neq M \\ s_i * f(iou(b_i, b_M)) & iou(b_i, b_M) \geq T; i \neq M \end{cases} \tag{9.14}$$

Where b_i denotes the ith bounding box in the location candidates and b_M is the bounding box with the maximum score. If the IoU between b_i and b_M is larger than a specified threshold T, a decayed score will be given to b_i using the Gaussian penalty function:

$$f(iou(b_i, b_M) = exp[\frac{-(iou(b_i, b_M))^2}{\rho}] \tag{9.15}$$

9.4.2 Results

The authors tested their method on the RSD-GOD dataset and compared it to other detection framework: Faster R-CNN[44], SSD[45], YOLOv2[34]. The authors also tested their method with and without the Soft-NMS.

Faster R-CNN obtains the best precision score for the airport class. However, the proposed methods with the soft-NMS obtain the best score for all other classes.

The detector was also trained and tested on the NWPU VHR-10[42] dataset, along with a collection of part detectors (COPD)[46], rotation-invariant CNN (RICNN)[47] and a R-P-Faster R-CNN[48] and the detectors used for the evaluation of RSD-GOD. COPD and RICNN are rotation-invariant frameworks with SVM classifier for geospatial object detection. COPD uses hand-crafted features while RICNN applies learned features from the CNN.

Using lessons taken from those paper, we can hope to create a network that is fit for detection in LiDAR surveys. However, we should emphasize that there are notable differences between satellite imagery and LiDAR surveys. LiDAR surveys suffer more from the problem of occlusion, where objects are partially obscured, which renders detection and classification harder. As stated in Section 8, geomagnetic surveys in general are harder to analyze, and object within can be harder to detect because they don't emit the same kind of response as with visible light.

The main lessons we need to take from the satellite imagery detection methods are their way of addressing the issue of scale. Surveys are often very high resolution, cover large swaths of terrain, but the object we want to detect are often very small both in absolute size and relative size to the image[1], and those issues arise both in satellite imagery and Geophysics. Most of the improvements here can be categorised into 3 main categories: an increase in raw compute performance, an increase in bounding box accuracy and improvements in earlier layer feature reuse.

[1] A barrow, a type of object in our dataset is around 50×50 pixels and the raw input image is 13140×10290. A barrow is therefore about 2×10^{-4} of the original image.

Chapter 10

State of the Art in Detection in Archaeological Remote Sensing

10.1 Automatic Detection in Magnetostatic Surveys using Convolutional Neural Networks

I started work in the field of automated detection in geophysical surveys in 2017, where I first developed, with the help of my colleague Fabien GOGLIO, a simple CNN that could categorise low resolution images of magnetostatic surveys.

The aim of this project was to be able to detect two type of classes of features: "Anomalies" and "Object"

- The Anomaly Class, contemporary ferromagnetic objects : small, localized, point-like disturbance, possessing both a global maxima situated at the center and global minima around the center, in the shape of a halo. They are usually cause by a metallic artefact.
- The Object Class, anthropogenic activity : a linear shape which is not localized at a particular point, and can form more complex geometric shape, such as rectangles. Objects can also be found in non linear forms. They possess smoother gradients variations, and are in general bigger than anomalies. Their intensity is often not consistent, creating blobs.

10.1.1 Dataset

Those surveys were centered mainly on the archaeological dig of Marsal, France, along with various other small scales surveys done around the UK. The project proved to be a success, with high precision being achieved rapidly. However, this was just a proof of concept; showcasing that this kind of techniques could work for this type of data which is very challenging for traditional computer vision.

From those surveys, a 2 new datasets were created, one for classification using CNNs, and another for use with the YOLO model.

The first dataset was constructed by first manually selecting zones containing at least

(a) Anomaly (b) Object

Figure 10.1: Examples of Anomaly and Object class. Detail from a survey done in Bergères Les Vertues, Eastern France

one example of a class, and then segmenting those zones into 128×128 tiles, with an overlap of 48 pixels. Some typical data augmentation was added to make the dataset more robust, like random flipping and rotations.

The second dataset used larger regions of about 1000×1000 pixels, which were annotated using LabelImg[49]. The full sized images were not used as it would result in a massive loss of detail when YOLO would downscale it.

10.1.2 Models

The first model used a low input resolution 128×128 pixel square segmented from the image itself to predict whether the image contained an "anomaly' or an archaeological feature. The model was a simple CNN with a 8 layers of 2D convolution, with 2 layers of Fully Connected to output a 2×1 vector.

The second model used YOLOv3-tiny[33], a novel technique at the time to detect the same classes of objects. The YOLO architecture was not modified, but it was noticed that the tiny version of the YOLO architecture, designed to run on low power computers performed better than the large version.

10.1.3 Results

The CNN performance was very good, with over 90% accuracy on the validation dataset.

Results for the YOLO model were encouraging, with class prediction precision at around 95% and an average IoU havering around 55%. However, the reduced size of the dataset massively impacted the F1-Score, coming out at only 0.16.

10.2 Learning To Look At LiDAR

This paper, authored by Verschoof-van der Vaart and Lambers[3], proposes the use of Deep Learning models for automated object detection using Faster-RCNN[44] on LiDAR surveys. It presents a novel dataset based on LiDAR surveys of a large and archaeologically rich region of the Netherlands, along with a framework for detection of 3 classes of objects based on Faster-RCNN.

10.2.1 Dataset and WODAN

The dataset used is novel, and part of the research effort was to create a workflow that would enable precise annotation of it. LiDAR surveys were taken from a large central area in the Netherlands, know as the *Utrechtse Heuvelug* and the *Veluwe* This area is largely forested and is about $\sim 2350\text{km}^2$ in size.

The dataset was mostly constructed by hand, with human verifications of each image. Using LabelImg[49], the authors annotated each TIF images. In total, the dataset is comprised of 420 images, split into three sub dataset: 365 images were used for training, 41 for validation and 73 for testing. Some data augmentations in the form of horizontal and vertical flips, along with 90 degrees rotations.

10.2.2 Model

The model used here is an altered version of Faster-RCNN with a validation step added after every two epochs to check for possible overfit. The model was trained over 12-18 epochs because of the small dataset, using pretrained weights.

Experiments were done using two different backbone: ResNet50[11] and VGG16[10]. Those experiments aimed to measure the impact a change in the stride of the RPN and the anchors size had on performance.

10.2.3 Results

Experiment	Epochs	Anchorsboxes	Recall	Precision	F1	MaF1
1	12	16, 64, 512	0.76/0.19	0.57/0.71	0.65/0.30	0.43
2	15	16, 64, 128	0.78/0.48	0.36/0.47	0.49/0.47	0.47
3	15	16, 64, 256	0.69/0.97	0.77/0.26	0.73/0.41	0.45
4	15	16, 64, 384	0.71/0.92	0.90/0.26	0.79/0.41	0.46
5	15	16, 64, 512	0.62/0.82	0.55/0.58	0.59/0.68	0.66
6	18	16, 64, 512	0.81/0.20	0.68/0.50	0.74/0.29	0.44

Table 10.1: Results of the experiments. Values before slash are for barrows, after slash are for Celtic Fields.

The results of the different experiments are reproduced in Table 10.1. Those experiments were done using the VGG16 backbone. The average of precision of Celtic Field detections

is 0.46, and recall is 0.60. Barrows fare better with average precision at 0.64 and recall at 0.73.

During all experiments, Faster R-CNN failed to detect charcoal kilns, probably due to the low quantity of examples in the dataset.

10.3 Integrating Remote Sensing, Machine Learning, and Citizen Science in Dutch Archaeological Prospection

This article by Lambers, Verschoof-van der Vaart and Bourgeois[50] presents novel methods for multi class object detection in LiDAR using Deep Learning combined with a citizen science project.

10.3.1 Dataset and Citizen Science

The dataset is comprised of more than 430 km^2 of interpolated LiDAR data gathered from the *Veluwe* region. The image in the dataset have previously been used in another paper by Verschoof-van der Vaart and Lambers [3] and are described in section 10.2. This paper presents a novel workflow to annotate the dataset, which is based on Citizen Science.

This workflow stems from the issue of the lack of a large dataset labelled with Archaeological objects, and the presence of unknown Archaeological objects that have to be validated. Since such a dataset didn't exist at the time of creation of WODAN, it had to be created.

Citizen Science is the use of volunteers and non professional scientists. Those citizen researchers helps with a scientific inquiry. In this project, a workflow based on Citizen Science generates datasets used for machine learning models and to validate new potential archaeological objects. Figure 10.2 shows the workflow used.

Figure 10.2: Proposed workflow. The color indicates the different interest groups

10.3.2 Validation

After the data collection and automated object detection , the new potential archaeological objects are validated in three steps, following the Dutch research strategy: desktop survey, initial field survey and minimally invasive survey. Theses steps conducted by different groups of citizen researchers in collaboration with academic researchers.

The desktop survey serves as a first validation steps, where the results of the prior steps, especially automated object detection will be verified for quality. The results are compared with digital informations sources, like aerial photographs and other remotely sensed data. This first steps allows for the detection of false positives and might lead to new archaeological insights.

The initial field survey serves as the first real verification step in the field, where newly discovered potential archaeological objects will be investigated. A predefined sets of characteristics such as dimensions, height, position etc. This validation steps also serves to detect false positives and might lead to the recognition of important parameters of archaeological objects.

The final verification steps involve direct investigation potential archaeological object with minimally invasive techniques, like hand corings or test trench.

The validations steps serves to determine true and false positives in detection, parameters of the archaeological objects and identification of new data sources. These results are then used to update the data collection and automated object detection.

10.3.3 Implementation

The LiDAR data is being analyzed using the Zooniverse, a website offering citizen science projects. In this project, baptised Heritage Quest, participants are asked to annotate every potential barrow, Celtic field or charcoal kiln in a given LiDAR image. The user can switch between two LiDAR representation, either shaded relief or Simple Local Relief Model. Each LiDAR image will be classified by at least 8 different users, to minimize the inter-analyst variability.

10.4 Combining Deep Learning and Location-Based Ranking for Large-Scale Archaeological Prospection of LiDAR Data from The Netherlands

This paper presents a more advanced version of WODAN, named simply WODAN2.0, a workflow using Deep Learning for automated detection of archaeological objects in LiDAR data. WODAN2.0 adds a step of Location Based Ranking to reduce the false positive rate based on location in the detection workflow.

10.4.1 Dataset

The dataset used used here is based on the same LiDAR survey as Section 10.2, or WODAN1.0. 16 Tiles of LiDAR data were used, each measuring 10000×12500 pixels or 5km $\times$ 6.25km. Those tiles were then cut into subtiles measuring 600×600 with 30 pixels overlap on all sides. Subtiles containing archaeological objects were selected and labeled with LabelImg. The final dataset contained 1024 subtiles for the training subset and 88 subtiles for the validation subset.

WODAN1.0 only included distinct examples of archaeological objects, WODAN2.0 also includes less clearly visible examples of object.

Negative Examples, or subtiles without any examples were also added as an experiment. Negative Examples can help the model learn background texture features, and potentially reduce the number of false positives.

10.4.2 Model and Training

The model used here is a modified FasterRCNN[44].

10.4.3 Location Based Ranking

To make WODAN2.0 more robust and precise over different types of terrain, domain information needed to be introduced to the classification to reduce the number of false positives. LBR was introduced as a step in the detection workflow. LBR is based on the assumption that the location of archaeological objects is not entirely random but based on certain characteristics of past and present environment.

LBR consists of determining, ranking and mapping the principal landscape characteristics, like subsoil and land-use that have had an impact on the preservation of archaeological objects. LBR produces a ranked map on which the location of detection can be compared and assigned to different ranks. Detections in high ranking zones are more likely to be archaeological objects, while detections in low ranking zones are more likely to be false positives.

10.4.4 Results

Table 10.2 shows the results of WODAN1.0 and WODAN2.0 against Heritage Quest, the Citizen Science project aiming at annotating the LiDAR surveys and presented in section ??. While WODAN obtain better performance on certain metrics, it is still inferior to human detection.

Method	Kilns			Celtic Fields			Charcoal Kilns		
	Recall	Precision	F1	Recall	Precision	F1	Recall	Precision	F1
WODAN1.0 (NR)	**62.3**	55.2	58.5	**82.3**	57.66	57.8	-	-	-
WODAN1.0 (R)	53.3	9.0	15.3	43.0	20.5	27.7	-	-	-
WODAN2.0 (NR)	57.1	73.3	**70.1**	74.6	66.0	70.0	-	-	-
WODAN2.0 (R)	44.5	56.5	49.8	40.4	52.1	45.5	34.6	12.2	18
WODAN2.0+NEG (R)	47.4	46.4	46.9	38.5	45.4	41.7	19.2	10.2	13
Heritage Quest (R)	45.3	**80.5**	57.9	75.7	85.0	**80.1**	**38.5**	**55.6**	**45**

Table 10.2: Performance of WODAN1.0, WODAN2.0 and Heritage Quest on individual class. Non Random (NR) and Random (R) dataset are shown, NEG indicates the use of negative examples. Bold indicates best result.

Chapter 11

The YOLO Framework

The first version of the YOLO detection framework was published in 2015[51]. It was, and still is, an hallmark in object detection; combining an mAP comparable with other detection method at the time, but with a very impressive inference time. YOLO was one of the first detection method being able to infer in real time. YOLO is considered a "one stage" detector, meaning that the object localisation and classification is a part of the same method. It passes the image only one time through its CNN, and directly outputs predictions; e.g it looks only once at the input. This dramatically increase the speed of the model. Since then, improvements[34][33] have been made to the model but the general principles behind YOLO stays the same. For a review of the latest version, YOLOv4[1], please refer to Section 11.3.7.

In this section we will give a short explanation of the workings behind this framework.

11.1 General Principle

The main idea behind YOLO is to take the task of object classification and localisation as a regression task. The bounding boxes and class prediction are outputted directly as a tensor, without using a RPN. This idea makes the network perform extremely fast.

YOLO can take as input image of various size, but it will first downscale them to a fixed resolution, which is an hyperparameter. The input image is then divided into an $S \times S$ grid. Each grid cell predicts B bounding boxes and confidence scores for these boxes. Each bounding box is comprised of 5 predictions : x, y, width, height and confidence. The (x, y) are the position of the center of the bounding box relative to the grid cell. The confidence prediction represents the IoU between the predicted bounding box and the ground truth. Each grid cell also predict C conditional class probabilities: $P(\text{Class}_i|\text{Object})$, which are conditioned on the grid cell containing an object.

S, B and C are also hyperparameters, with C being the number of classes.

11.2 Network design and Architecture

The backbone behind YOLO is called Darknet53 containing 53 layers. YOLOv3[33] introduced the idea of prediction at different scale. In the YOLOv3 network, 3 prediction

Figure 11.1: YOLO Model. First the image is divided into a $S \times S$, and for each grid cell predicts B bounding boxes, confidence, and C class scores, which are encoded into an $S \times S \times (B * 5 + C)$ tensor

are made at different scales, a technique known as multi-scale prediction which is improved in several papers of detection in satellite imagery, Multi-scale prediction allows the network to find small objects that are often missed otherwise. Figure 11.2 shows the architecture of the model.

Figure 11.2: Architecture of the backbone of the YOLO Framework

11.3 YOLOv4

This sections describes the latest iteration of the YOLO detection pipeline. While this network is not specifically designed for detection in remote sensing, it consistently obtains extremely great scores in all datasets. Understanding how this version is able to improve both speed and precsion can help us designing a better network. The article details and experiments with a large number of features, be it training wise or architecture wise to help configure a better YOLO model. In short, this article presents the **best practices in CNN design**. First the authors describes two different approaches: the "**Bag of Freebies**" (BoF), where researchers develop better training method to make the detector more accurate without increasing the inference cost. We will summarize those in Section 11.3.2. Another approaches is the one using special modules, that increases the inference cost by a small fractions, but gives out great improvement to the accuracy. This is what the authors calls the "**Bag of Special**" (BoS), which are described in Section 11.3.3.

11.3.1 General Architecture of a Object Detector

The authors describes the composition of a modern detector. Those detectors are usually comprised of two parts. First a backbone, usually trained on ImageNet[52] which creates the feature maps from the input image, and secondly a head, which infer bounding boxes and classes. The backbone we are usually interested in, meaning the ones running on GPUs and not CPUs are VGG[10], resNet[11], resNeXt[53] or DenseNet[54]. We have already seen a few of those backbones in previously reviewed articles, especially resNet.

Figure 11.3: General Architecture of an Object Detector

The head part is divided in two categories: one-stage object detectors such as YOLO[34, 33], SSD[45] or RetinaNet[55]. Examples of two stages detectors are the R-CNNs[56], like Fast R-CNN [57], Faster R-CNN[44] or R-FCN[58].

Modern object detectors usually have a layer collecting feature maps from different stages, such as feature fusion modules. The author call this layer the 'neck'. Networks using this type of mechanisms include Feature Pyramid Network (FPN)[59], Path Aggregation Network (PAN)[60], BiPFN[61] and NAS-FPN[62]

To summarize, an object detector is made up of the following parts:

- **Backbones**: VGG[10], ResNet-50[11], EfficientNet[63], CSPResNeXt50[53], CSP-Darknet53[64].

- **Neck**:
  - **Additional Blocks**: SPP[65], ASPP[66], RFB[67], SAM[68]
  - **Path-aggregation blocks**: FPN[59],NAS-FPN[62] PAN[60], BiFPN[61], ASFF[69], SFAM[70]
- **Heads**:
  - **Dense Prediction (One-Stage)**
    * Anchor-based: RPN[44], SSD[45], YOLO[33], RetinaNet[55]
    * Anchor-free: CornerNet[71], CenterNet[72], MatrixNet[73], FCOS[74]
  - **Sparse Prediction (Two-stage)**
    * Anchor-based: Faster R-CNN[44], R-FCN[58], Mask R-CNN[75]
    * Anchor Free : RepPoints[76]

11.3.2 Bag of Freebies

This section presents training techniques to improve detection rates without increasing the inference costs. Most of those techniques that falls under this definition are data augmentation methods. Data augmentation aims to increase the variability of the training images, so that the model will be more robust. Commonly used techniques are photometric distortions, where the brightness, contrast, hue and saturation of an image is adjusted, or geometric distortion, with random rescaling, cropping, flipping and rotating.

Those techniques are pixel-wise adjustments, meaning that the original pixel information in the adjusted area is retained. Novel data augmentation techniques have an emphasis put in object occlusion issues. Random Erase[77] or CutOut[78] randomly selects a rectangle region in an image and fills with random values. Hide and seek[79] and grid mask[80] randomly selects multiple rectangle regions in an image and replaces them to all zeros. Similar techniques are applied to feature maps, for example, DropOut[81], DropConnect[82] and DropBlock[83].

Other methods uses multiple image together. MixUP[84] uses two images to multiply and superimpose them with different coefficient ratios, and adjusts the labels with these ratios. CutMix[85] crops an image and cover another images with this cropped region, adjusting the labels according to the size of the covered area.

Even StyleTransfer GANs[86] have been used for data augmentation, reducing the texture bias learned by CNN.

Other data augmentation techniques have been focussed in reducing the amount of bias present in the semantic distribution of the dataset. For example, there might be a problem of data imbalance between different classes, which can be solved by hard negative example mining[87] or online hard example mining[88] in two-stage object detectors. However these example mining methods are not applicable in one-stage object detectors. For those detectors, focal loss[89] have been proposed to deal with the problem of data imbalance.

Another issue is that it is difficult to express the relationship of the degree of association between different categories with the one-hot representation, often used when executing labeling. Label smoothing[90] convert hard label into soft label, which can make

(a) Classic image data augmentation: crop, rotation, flip, hue, saturation, brightness

(b) MixUp

(c) CutMix

Figure 11.4: Some data augmentation techniques

the model more robust. Knowledge distillation have also been used to design a label refinement network.[91].

Finally, the objective function for the bounding box have also been the focus of improvements. Usually, Mean Square Error (MSE) have been used to perform regression on the center point coordinates, height and width of the Bounding Box. However, to directly estimate the coordinates of the bounding box is to treat those points as independent variables, which **does not consider the integrity of the object itself**. The IoU loss[92] puts the coverage of the predicted bounding box area and the ground truth area into consideration. GIoU loss[22] is an improvement on this loss, and also include the shape and orientation of the object in addition to the coverage area[1]. Finally, DIoU loss[23] also considers the distance of the center of an object and CIoU[23] considers the overlapping area, the distance between center points and the aspect ratio.

11.3.3 Bag Of Specials

Other methods that improve the detection rate at the expense of a small increase in inference cost are what the authors refers to as "Bag of Specials" (BoS). Those methods are generally plugin modules that enhance certain attributes of the model. For example, they can enlarge the receptive field, introduce an attention mechanism or strengthen the feature integration capability.

Common modules uses to improve the receptive field are SPP[65], ASPP[66] and RFB[67]. The SPP originates from Spatial Pyramid Matching (SPM) [93]. SPM method is to split the feature maps into several $d \times d$ blocks of equal size, where d can be $1, 2, 3, ...$ This forms spatial pyramids, where we can then extract bag-of-words features. SPP integrate SPM into a CNN, and uses the max-pooling operation instead of bag-of-word. However, this SPP module output one dimensional feature vectors, which makes it inapplicable for Fully Convolutionnal Network (FCN). In YOLOv3[33], the SPP module is improved by concatenating the max-pooling outputs with kernel size $k \times k$ with $k = \{1, 5, 9, 13\}$ and

[1] An improvement to this has been done for automated detection in satellite imagery by Qian and Al and is covered in section 9.3

stride of 1. This modules improves the YOLOv3 AP_{50} by 2.7% on the MS COCO[24] datasets for only 0.5% extra computation.

Attention is also used to improve the capabilities of detection networks. Attention modules are divided in two categories: channel-wise attention, with the Squeeze-and-Excitation (SE)[94] and point-wise attention with Spatial Attention Module (SAM) [68]. SE modules can improve the accuracy of ResNet by 1% in the ImageNet[52] dataset, however this comes at in increase of inference time of 10% on a GPU. In comparison, SAM only demands 0.1% extra calculation but improve the ResNet50 top-1 accuracy by 0.5%. This module does not affect the inference speed.

Feature integration modules allows the model to take into account features computed from earlier layers. Early examples are skip connections[95] or hyper-column[96] integrate low-level physical and geometric features to high-level semantic feature. Now, lightweights modules that integrates different feature pyramids are used, like SFAM[70], ASFF[69] and BiFPN[61]. The idea behind SFAM is to use SE modules to execute channel-wise re-weighting on multi-scale concatenated feature maps. ASFF uses softmax as point-wise level re-weighting and adds feature maps of different scales. In BiFPN multi-input weighted residual connections is used to execute scale-wise level re-weighting, and then add feature maps of different scales.

A good activation function is crucial to correctly train a network, and much work has been put into trying to design a better one. In 2010, ReLU[97] was proposed as a solution to vanishing gradient problem. Offshoots, such as LeakyRelu[36], PReLU[98], ReLU6[99], Scale Exponential Linear Unit (SELU) [100], Swish [101], hard-Swish[102] and Mish[103] have been proposed. LReLU and PReLU serves to solve the problem that the gradient of ReLU is zero when the output is less than 0. ReLU6 and hard-swish are specially designed for quantization networks. The SELU activation function tries to self-normalize a neural network. Swish and Mish are continuously differentiable.

Post-processing with NMS is usually done with detection network to remove superfluous bounding boxes and only retain the ones with the highest response. However NMS does not consider contextual information, so Girshick *et al.*[104] added classification confidence scores in R-CNN as a reference. Soft NMS[105] considers the problem that occlusion of an object may cause the degradation of confidence score in greedy NMS with IoU score. DIoU NMS[23] adds the information of the center point distance to bounding box.

11.3.4 Additional Improvements

The main goal of this architecture is to make the detector suitable for training on a single consumer-grade GPU so additional design improvements were made. First, new methods of data augmentation are used: Mosaic and Self-Adversarial Training. Optimal hyper-parameters were chosen using genetic algorithms. Finally, modifications were made to existing methods to make them more efficient for training and detection, namely SAM, PAN and Cross mini-Batch normalization.

Figure 11.5: The Mosaic data augmentation technique

Mosaic is a new data augmentation method that mixes 4 training images so that 4 different context are mixed, and is shown in Figure 11.5. This allows detection of objects outside their normal context. Batch normalisation calculates activation statistics from 4 different images on each layer, which significantly reduces the need for a large mini-batch size.

Self-Adversarial Training operates in 2 forward-backward stages. In the 1st stage, the neural network alters the original image instead of the network weights. **This way, the network executes an adversarial attack on itself, altering the original image and making it look like there is no object to detect**. In the 2nd stage, the network is trained to detect an object on this modified image in the normal way.

Figure 11.6: Cross Mini Batch Normalization

Cross mini Batch Normalisation is used. It is a modified Cross Batch Normalization (CmBN). CmBN collects statistics only between mini-batches within a single batch.

SAM is modified from spatial-wise attention to point-wise attention (figure 13.9), and the shortcut connection in PAN are replaced to concatenation, as can be seen in figure 13.7

(a) SAM (b) Modified SAM

Figure 11.7: SAM and its YOLO modification

(a) PAN (b) Modified PAN

Figure 11.8: PAN and its YOLO modification

11.3.5 YOLOv4 Architecture

YOLOv4 basic architecture is as follows:

- **Backbone**CSPDarknet53[64]
- **Neck**: SPP, PAN
- **Head**: YOLOv4

For the backbone, YOLOv4 uses the following "Bag of Freebies": CutMix and Mosaic Data Augmentation, DropBlock regularization and Class label smoothing. The bag of Specials are Mish Activation, Cross-stage partial connections (CSP) and multi-input weighted residual connections (MiWRC).

For the detector, YOLOv4 uses these "Bag of Freebies": CIoU-loss, CmBn, DropBlock Regularization, Mosaic Data augmentation, Self-Adversarial Training, elimination of grid sensitivity, usage of multiple anchors for a single ground truth, a cosine annealing scheduler [106], optimal hyper-parameters and random training shapes. These Bag of Specials are used: Mish Activation, SPP-block, SAM-block, PAN Path-aggragation block, DIoU-NMS.

11.3.6 Results

Influence of features on Classifier training

The authors studies the influence of different data augmentation techniques, such as bilateral blurring, MixUp, CutMix and Mosaic, along with the influence of different activations like Leaky-ReLU, Swish and Mish.

Table 11.1 shows the results of those tests for the CSPResNext-50 backbone, and Table 11.2 for the CSPDarknet-53 backbone. The classifier accuracy is improved by introducing the CutMix and Mosaic data augmentation, Class label smoothing and the Mish activation.

MixUp	CutMix	Mosaic	Bluring	Label Smoothing	Swish	Mish	Top-1	Top-5
							77.9%	94.0%
✓							77.2%	**94.0%**
	✓						**78.0%**	**94.3%**
		✓					**78.1%**	**94.5%**
			✓				77.5%	93.8%
				✓			**78.1%**	**94.4%**
					✓		64.5%	86.0%
						✓	**78.9%**	**94.5%**
	✓	✓		✓			**78.5%**	**94.8%**
	✓	✓		✓		✓	**79.8%**	**95.2%**

Table 11.1: Impact of Bag of Freebies and different activation on the CSPResNext-50 Classifier. Baseline is shown on the first row. Results which are better than the baseline are shown in bold

MixUp	CutMix	Mosaic	Bluring	Label Smoothing	Swish	Mish	Top-1	Top-5
							77.2%	93.6%
	✓	✓		✓			**77.8%**	**94.4%**
	✓	✓		✓			**78.7%**	**94.8%**

Table 11.2: Impact of Bag of Freebies and Mish on the CSPDarknet-53 Classifier. Baseline is shown on the first row. Results which are better than the baseline are shown in bold

Influence of features on the Detector training

In order to better understand the impact of different Bag-of-Freebies on the detector training accuracy, the authors studies different features that increase the detector accuracy without affecting the FPS.

- **S** - Elimination of grid sensitivity. In YOLOv3, the equation $b_x = \sigma(t_x) + c_x, b_y = \sigma(t_y) + c_y$, with c_x, c_y being whole numbers is used to evaluate the object coordinates. Very high absolute values of t_x are needed for the b_x value to approach c_x or $c_x + 1$. This problem is solved by multiplying the sigmoid by a factor exceeding 1.0, eliminating the effect of grid on which the object is undetectable.

S	**M**	**IT**	**GA**	**LS**	**CBN**	**CA**	**DM**	**OA**	**Loss**	**AP**	AP_50	AP_75
									MSE	38.0%	60.0%	40.8%
✓									MSE	37.7%	59.9%	40.5%
	✓								MSE	**39.1%**	**61.8%**	**42.0%**
		✓							MSE	36.9%	59.7%	39.4%
			✓						MSE	**38.9%**	**61.7%**	**41.9%**
				✓					MSE	33.0%	55.4%	35.4%
					✓				MSE	**38.4%**	**60.7%**	**41.3%**
						✓			MSE	**38.7%**	**60.7%**	**41.9%**
							✓		MSE	35.3%	57.2%	38.0%
✓									GIoU	**39.4%**	59.4%	**42.5%**
✓									DIoU	**39.1%**	64.0%	**44.8%**
✓									CIoU	**39.6%**	59.2%	**42.6%**
✓	✓	✓	✓						CIoU	**41.5%**	**64.0%**	**44.8%**
	✓		✓					✓	CIoU	36.1%	56.5%	38.4%
✓	✓	✓	✓					✓	MSE	**40.3%**	**64.0%**	**43.1%**
✓	✓	✓	✓					✓	GIoU	**42.4%**	**64.4%**	**45.9%**
✓	✓	✓	✓					✓	CIoU	**42.4%**	**64.4%**	**45.9%**

Table 11.3: Ablation Studies of Bag-of-Freebies using CSPResNeXt50-PANet-SPP with 512×512 input. Baseline is shown on the first row. Results better than baseline are shown in bold.

- **M**: Mosaic data augmentation - using the 4-image mosaic during training instead of a single image
- **IT**: IoU thresholding - Using multiple anchors for a single ground truth with $IoU(truth, anchor) > IoU_{threshold}$
- **GA**: Genetic Algorithms - Using genetic algorithms to select the optimal hyperparameters during network training
- **LS**: Class label smoothing - using class label smoothing for sigmoid activation
- **CBN**: CmBN - using Cross mini-Batch Normalization for collecting statistics inside the entire batch instead of inside a single mini-batch
- **CA**: Cosine annealing scheduler - altering the learning rate following a cosine
- **DM**: Dynamic mini-batch size - automatic increase of mini-batch size during small resolution training by using random training shape
- **OA**: Optimized Anchors - using the optimized anchors for training with 512×512 network resolution
- **GIoU, CIoU, DIoU, MSE**: Using different loss algorithms for bounded box regression

An ablation studies using those bag of freebies is shown in table 11.3

11.3.7 Influence of different backbones and pre-trained weights on the detector

The authors conducted another study, where they measured the performance of different backbones with the same training parameters, which is reproduced on table 11.4. It is apparent that **the model with the best classification accuracy is not always the best in terms of detector accuracy**. CSPResNeXt-50 models trained with different features obtain better classification accuracy, CSPDarknet53 obtains a higher accuracy in the object detection task.

Using BoF and Mish activations for the CSPResNeXt50 classifier increases its classification accuracy but further application of the pre trained weights reduces the detector accuracy. This is not true for CSPDarknet53: with the applications of BoF and Mish increasing both the detector and classifier accuracy. Considering those results, it would seem that **CSPDarknet53 is more suitable for the detector.**

Model (with optimal settings)	**Input Size**	**AP**	AP_50	AP_75
CSPResNeXt50-PANet-SPP	512×512	42.4	64.4	45.9
CSPResNeXt50-PANet-SPP (BoF-backbone)	512×512	42.3	64.3	45.7
CSPResNeXt50-PANet-SPP (BoF-backbone + Mish)	512×512	42.3	64.2	45.8
CSPDarknet53-PANet-SPP (BoF-backbone)	512×512	42.4	64.5	46.0
CSPDarknet53-PANet-SPP (BoF-backbone + Mish)	512×512	43.0	64.9	46.5

Table 11.4: Comparison study of different classifier pre trained weights for detector trainings.

Influence of mini-batch size on detector training

Finally, the author studied the impact of the mini-batch size on training, which have been reproduced in table 11.5

Model	**Input Size**	**AP**	AP_50	AP_75
CSPResNeXt50-PANet-SPP (without BoF/BoS, mini-batch 4)	608×608	37.1	59.2	39.9
CSPResNeXt50-PANet-SPP (with BoF/BoS, mini-batch 8)	608×608	38.4	60.6	41.6
CSPDarknet53-PANet-SPP (without BoF/BoS, mini-batch 4)	512×512	41.6	64.1	45.0
CSPDarknet53-PANet-SPP (with BoF/BoS, mini-batch 8)	512×512	41.7	64.2	45.2

Table 11.5: Comparison study of different mini-batch size for detector training.

It seems that that after adding BoF and BoS training strategies, **the mini-batch size has almost no impact on the detector performance**. This would allow the use of consumer grade GPU to be used to train those detectors, as they would not require as much VRAM for the training.

Part III

Implementation and Results

Chapter 12

Dataset

12.1 Dataset creation

The original dataset from Verschoof-van der Waart[3] was constructed using LiDAR surveys from a small region of the Netherlands. The data I was given was constructed in the form of a GIS project, with the position of the different objects being encoded in .shp files.

A dataset for the training of a Mask-RCNN[75] model was also present. It was made from more of a dozen of very high resolution and details TIF files, cropped to various pixels format, and annotated using the COCO[24] format.

I wanted to create a new dataset that was of a higher resolution, but if each object was annotated and given a position in a given reference system, it was not indicated in which image the object was located. To create a new dataset, I first needed to associate each object with a LiDAR survey image.

12.1.1 Cropping Images

In order to do this, we first converted the .shp files, which are GIS specific to CSV using the `ogr2ogr` script. In our case the .shp files contained the position of the bounding boxes of the different objects in the same reference as the image. Each class of objects had its own .shp file. To find out in which image each object where, we needed to also find the coordinates of the images. Luckily, those were encoded in the TIF files themselves. Using `gdalinfo`, we are able to retrieve the position of the image. Finally, we check if all of the vertex of the bounding box of an object are inside of the position of an image to associate it. Using this newly acquired information, we build a new database containing the position of the bounding box, the type of object and in which image this object is in.

We are now in possession of all the necessary information to create a new dataset. This dataset will be created by cropping 1000×1000 images from the original LiDAR images, which will be centered around an object. This is done for every object in the dataset (around 2K). Luckily, those objects are often cluttered together, meaning that we will often see multiple examples of one class in one image. To create a cropped image, we first need to transform the coordinates of the object, which are from a world reference into a image reference, i.e. between 0 and the length/width of the image. This is done using

Figure 12.1: Functional Diagram of the createAnnotation script. For each objects in the CSV, it cycles for each of the .tif files, extract information concerning its position using the `gdalinfo` program, then if all of the vertex of the bounding box are inside of the image, it adds it to the row of the object, and append it to a new CSV

simple scaling and translating formula, given in Equation 12.1. This gives us values that are equivalent to pixels in the image rather than a position in the GIS world.

$$f[x] = \frac{x - x_{min}}{x_{max} - x_{min}} * (y_{max} - y_{max}) + y_{min}, \tag{12.1}$$

Where x_{min}, y_{min} are the minimum value of the original range and the destination range respectively, and where x_{min}, y_{min} are the maximum value of the original range and the destination range respectively

We center the 1000×1000 image around those newly transformed values, adding a random jitter value, taken uniformly between $(-100; 100)$. This guarantees us that the image won't be perfectly centered around an object, creating a more difficult image to analyze. Finally, we need to find which objects are in the cropped image. To do so, we iterate through every object in the database, and if they are in the same image, and if all of their vertex are in the cropped section, we add it to the annotation of the image.

12.1.2 Annotations

Using the scripts, we create a dataset using the already annotated GIS project. This dataset contains about 7500 examples, split into a 80/20 train/test dataset. The anno-

tation is done using the COCO format[24], where each image is accompanied with a .txt file containing the position of each bounding box, along with its class. The bounding box is position is encoded as $(x, y, width, height)$, where x, y is the position of the top left corner of the bounding box. Those coordinates are also relative to the image, meaning that $(x, y) \in [0, 1] \times [0, 1]$. To obtain those bounding box, we again took their position from the .shp file and converted their position from a world reference to a image reference using the same formula as above. We then normalised to obtain values between 0 and 1.

Chapter 13

Architecture

The decision was made to try and adapt the YOLOv4[1] architecture, based on a CSV-Darknet53 backbone, to archaeological object detection by applying modifications inspired from the State of the Art object detection methods in satellite imagery detection. Those modifications mostly concerned feature fusion, and receptive field improvements by way of dilated convolution.

13.1 Feature Fusion

Feature Fusion is a technique used in most CNNs. The main issue with Deep Networks is that, as the input is convoluted as goes further into the network, the feature maps contains more and more semantic and less geometric information. In other words, deeper feature maps incorporates information as to *what is it* and less about *where is it/what does it looks like*. Moreover, since the feature maps gradually become smaller and smaller, by way of max-pooling, stride of convolution or otherwise, this means that the receptive field or *what the layer is actually sensing* becomes coarser and coarser. Small objects can be missed, since they disappear during the downscaling.

Feature Fusion aims at mitigating this loss by adding information coming from earlier feature maps. Traditional networks usually uses "Skip Connections" to achieve this. ResNet[11] simply uses vector addition to add the weight matrices in its Residual Modules. DenseNet[54] concatenates the weight matrices from earlier layer to later ones along the channel dimensions.

13.2 Backbone and activation

The backbone is CSPDarknet53[64], most notably used in YOLOv4[1]. This backbone obtained better result than the CSPResNeXt-50[53] in the YOLO paper, which is why it is used. Inspiration could also be taken from Zhuang *et al.*[43], with passthrough and concatenation from earlier layers.

Layer	Filters size	Repeat	Output size
Image			416 × 416
Conv	32 3 × 3/1	1	416 × 416
Conv	64 3 × 3/2	1	208 × 208
Conv Conv Residual	32 1 × 1/1 64 3 × 3/1	Conv Conv Residual × 1	208 × 208 208 × 208 208 × 208
Conv	128 3 × 3/2	1	104 × 104
Conv Conv Residual	64 1 × 1/1 128 3 × 3/1	Conv Conv Residual × 2	104 × 104 104 × 104 104 × 104
Conv	256 3 × 3/2	1	52 × 52
Conv Conv Residual	128 1 × 1/1 256 3 × 3/1	Conv Conv Residual × 8	52 × 52 52 × 52 52 × 52
Conv	512 3 × 3/2	1	26 × 26
Conv Conv Residual	256 1 × 1/1 512 3 × 3/1	Conv Conv Residual × 8	26 × 26 26 × 26 26 × 26
Conv	1024 3 × 3/2	1	13 × 13
Conv Conv Residual	512 1 × 1/1 1024 3 × 3/1	Conv Conv Residual × 4	13 × 13 13 × 13 13 × 13

Figure 13.1: Architecture of the Darknet 53 backbone

13.3 Activation Functions

The performance of different activation functions will be tested. Mish[103](Figure 13.4) and Swish (Figure 13.3) or even Scaled Exponential Linear Unit (SELU) (Figure 13.2) are good candidates.

13.3.1 Scaled Exponential Linear Unit

SELU is one of the first activation developed to address the issue of normalisation in FNN: as those networks become deeper and deeper, they become more and more sensitive to gradient issues. Usually, Batch Normalisation is used to mitigate this, but this makes FNN sensitive to normalisation during training. **SELUs has been developed to incorporate normalisation inside the activation function.**

SELU is defined by the following equation:

$$\sigma[x] = \lambda \begin{cases} x \\ \alpha * exp[x] - \lambda \end{cases} \tag{13.1}$$

With α and λ being fixed parameters who are derived from the inputs. In the Figure 13.2,

the values used are for standard scaled inputs with a 0 mean and a 1 standard deviation: $\alpha = 1.6732$ and $\lambda = 1.0507$.

Figure 13.2: Scaled Exponential Linear Unit (SELU) Activation Function

13.3.2 Swish

Swish[101] is a part of a recent push in research toward a better activation function to replace ReLU. While ReLU offers very good performance, it is not smooth due to the non differentiable point at $x = 0$, and is always zero for all $x < 0$ which can imper learning. Swish has been developped by Google Brain to address those issues, and can be defined as follow:

$$\sigma[x, \beta] = x \cdot (1 + exp[-\beta x])^{-1} \tag{13.2}$$

Where $(1 + exp[-\beta x])^{-1}$ is the sigmoid function and where β is either a constant or a training hyperparameter. If $\beta = 1$, then Swish is equivalent to the weighed Sigmoid-Weighted Linear Unit (SiL). If $\beta = 0$, then Swish becomes the scaled linear function $f[x] = 0.5 \cdot x$. As $\beta \leftarrow \infty$, Swish approaches a $0 - 1$ function, like the ReLU. In other words, Swish can be interpreted as **a non linear interpolation between the linear function and the ReLU function, which degree of interpolation can be controlled by the model if β is set as a trainable parameter**

Figure 13.3: The Swish activation function, with different values of β

13.3.3 Mish

Mish is a novel activation function which has been proposed by Misra[103] to act as a replacement for the immensely popular ReLU function. Mish is built as a successor for ReLU and is inspired by the Swish function, described above. Mish is very simple, and defined as below:

$$\sigma[x] = x \cdot \tanh[1 + exp[x]] \tag{13.3}$$

Similar to Swish, Mish is unbounded above, preventing saturation, but bounded below, creating a self-regularisation. Mish has an order of continuity C^{∞}, a preferable property over ReLU having a C^0, which can cause problem in gradient-based optimisation. Finally, Mish is non monotonic, which causes small negative inputs to be preserved as negative outputs. Mish obtains improve performance by up to 1.6% on dataset such as the MNIST[107] or CIFAR-10[108]

Figure 13.4: The mish activation function

13.4 Dual Scale Detectors

An idea introduced in YOLT[30] is to use two different detectors running simultaneously: one trained on small scale images to detect small objects, the other trained on larger images to detect bigger objects. The small scale network would be fed small chips of images, while the large scale network would be fed downscaled large swathes of terrain. This meant that the large scale network would run much less often than the small scale network, and mitigate the loss of performance of running two network at the same time.

An ensemble method similar to this could be used, where two networks try to find objects at different scales.

13.5 Multi-scale Feature Fusion

To be able to detect the small objects often seen in LiDAR data, some kind of MLFF module needs to be used. There are a few existing modules and techniques that can boost

the detection rates of a model by aggregating low level feature maps from earlier layers with ones from higher layers.

The MLFF module from Zhuang *et al.*[43] takes 3 feature maps from different layers, upscales and concatenates them, then applies a series of convolution operations to obtain 3 predictions at different scale. This is very similar to the MLFF used in YOLOv3[33], where 3 predictions are made at different scale level and which reuses feature maps from deeper layers to build the predictions.

Figure 13.5: Feature Fusion implementation of Zhuang *et al.*. We are only interested in the bottom part of the figure, with feature maps from different levels being concatenated.

The MLFF module from Qian *et al.*[41] shown in Figure 13.6 takes each proposal generated by a RPN, and maps its position to all level of feature map generated by the FPN. From there it obtains N regions of the feature maps (N being the number of levels), which it transforms into 7×7 feature maps through the RoiAlign[75] operation. Finally, it concatenates these 4 regions along the channel dimensions, and applies two convolution operations along with a Fully Connected Layer for bounding box regression and classification.

Figure 13.6: Architecture of the model from Qian et al. We are interested in the module shown in (b), where particular regions of different feature maps are concatenated together

The PAN is a sort of multi layer feature fusion module. Following the same principle as the MLFF from Qian *et al.*, PAN takes the features maps generated by a FPN. It first downscales the lower level layer (denoted P_i with a 3×3 convolution operation with a stride of 2. It then adds element wise this downscaled layer with the layer P_{i+1}. This is done iteratively until the up most layer is attained. **In the YOLOv4 paper, instead of adding the layers, a concatenation is done**.

(a) PAN (b) Modified PAN

Figure 13.7: PAN and its YOLO modification

13.6 Receptive Field Improvements

To improve the size of the receptive field, the modified SPP module from YOLOv3[33] would be used. Experimentations could be done using dilated convolutions, as seen in Yu *et al.*[40] and Ju *et al.*. Dilated convolution improve the receptive field by increasing the kernel size without increasing the number of parameters in the kernel. This can help reducing the number of parameters, improving performance of the network in terms of FPS, or more appropriately in terms of square kilometers per seconds. We can replace some of the classical convolution blocks from the CSPDarknet53 backbone with dilated convolution modules, as can be seen in Figure 13.8.

Figure 13.8: General Architecture of the Darknet Backbone with a dilated convolution module replacing a convolution block

13.7 Attention Modules

Attention modules are used to improve the accuracy of detections network by increasing the importance of particular regions or channels. The SAM[68] would be used, as it increases the accuracy without significantly impacting inference speed. Testing would have to be done to evaluate whether the SAM improvement done by Bochkovsky *et al.* in the YOLOv4 paper[1] gives out a performance increase.

(a) SAM (b) Modified SAM

Figure 13.9: SAM and its YOLO modification

13.8 Post-processing

NMS needs to be used to remove the superfluous bounding boxes generated by the network. Soft Non maximum suppression, as introduced by Qian *et al.* [41] would be used to achieve such a task, while trying to not miss the smaller objects.

13.9 List of all the possible testing arrangements

We will need to test a multiple of different modifications on the base CSPDarknet-53 and test out if those modifications results in performances improvements.

- Double YOLOv4 trained on large and small scale (similar to YOLT[30])
- CSPDarknet with one or two dilated convolution modules
- MLFF module from Zhuang *et al.*: see Figure 13.5
- MLFF module from Qian *et al.*: see Figure 13.6
- Modified PAN module: see Figure 13.7
- Modified SAM Module: see Figure 13.9

- Different activations: ReLU, Leaky ReLU, SELU, Mish or Swish
- Different activations: Different IoUs: GIoU, cIoU, dIoU
- Various input resolutions

Now State of the Art methods uses more dedicated techniques to fuses information from different depths. Usually multiple predictions are done at different depths levels, and incorporates information from all layers. YOLOv3[33] also uses multi-scale predictions to improve performance. **Leveraging the power of those techniques is key in enhancing the performance on deep learning models in high resolution - small scale object detection.**

13.10 YOLOv4

The latest version of the YOLO architecture is used as a base to modify. YOLO is a state of the art detector, obtaining extremely good results on a variety of datasets, and with the benefits of still being extremely fast: it is capable of running on real time will requiring only a modest amount of processing power. YOLOv4 is the latest iteration of this architecture, incorporating the latest and best modifications and improvement on the always growing class of object detectors. For a review on those improvements, please refer to section 11.3.7.

Chapter 14

Data augmentation techniques and training regimes

This section will present techniques that improve the accuracy of the detector but are not part of the architecture in itself. Those techniques applies during training but not during inference, so they do not increase the inference computing cost.

14.1 Data Augmentations

Deep Learning is known for requiring vast amount of data in order to train it properly and avoid overfit[109]. However, most domains which requires Deep Learning do not possess the amount of data that is required and this issue is particularly true here: see section 8.4.

Data Augmentation is a solution to this issue and tries to enhance both the size and quality of the dataset so that a more robust model can be trained. It makes the examples "harder", by adding variability to the dataset. This is done by modifying the image in various way, with color modification or geometric transformations. We will describe here the augmentations that are used in our model.

14.1.1 Image Modification

An issue seen in LiDAR is the fact that object are often occluded, fragmented and do not appear with the same clarity as examples seen in satellite imagery. This means that we need to construct and train a network that is robust to changes in context and occlusion. Fortunately, research has been focussed in constructing better data augmentation techniques that attempt to solve those issues. Those techniques "mixes" different images from the dataset, covering parts of one another to make it harder for the network to correctly infer. CutMix[85] is one of those techniques. Mosaic, introduced by Bochkovsky, Wang and Liao in the YOLOv4 paper[1] creates a new images out of 4, by creating a "mosaic" of sort, where the 4 images can take varying portions of the new image.

14.1.2 Regularization and Normalization

Regularization reduce the complexity of a network and prevents overfitting. This is usually done by "dropping" random connections in a network, and training without those connections, a technique known as DropOut[81]. DropBlock[83] relies on a similar method, but is more suitable for convolutional networks. DropBlock works by first choosing random seed points in a mask, and dropping a continuous region around those points. This is more effective than removing purely random activation as close activations contain closely related information.

(a) Base image (b) Random Drop in activations (c) DropBlock

Figure 14.1: Regularisation by dropping: random drops *v.s.* DropBlock
The blue regions represents neurons that contains semantic information on the base image. (b) shows the effect of removing activations at random, which is not effective as neurons close to each other contains closely related semantic information. (c) shows the DropBlock method, which have a better chance of entirely removing important semantic information on the base image, such as the head or the feet of the dog, forcing the remaining neurons to learn useful features

Label smoothing [90] convert hard labels, like one hot labeling into soft labels. This works by introducing a noise distribution in the labeling of the data, and converting the original label in relation to this noise distribution. **However, this label smoothing requires a rewriting of the loss system.**

14.2 Self Adversarial Training

In the YOLOv4[1] paper, the author mention the use of **self adversarial training**. In this training regime, the network first tries to alter the original image instead of its weights. This is an adversarial attack on itself, modifying the original image to fool itself into a wrong inference. Then, the network is trained to detect an object on this modified image in the normal way.

14.2.1 Modifications on the original dataset

In total, 4 different datasets where used. Those dataset kept the general philosophy, explained in section 12, where an object is selected to be the center of cropped image, with randomised jitter added.

- **Version 1**: The first version of this dataset used 1000×1000 pixels images, where object seen in another example could be reused
- **Version 2**: The second version also used 1000×1000 pixels images, but object seen in another example could not be reused. The aim of this modification was to improve the variability of images. This greatly reduced the raw number of images in the dataset, from about 3000 to slightly more than a thousand, which in turn gave way to a loss in performance.
- **Version 3**: The third version used 500×500 pixels images, where object seen in another example could be reused. Smaller images meant that inference could be done without downscaling.
- **Version 4**: The final version used 1000×1000 pixels images, where object seen in another example could be reused. In addition to the images centered a particular object, a further 1000 images centered around random coordinates in random base images were added. This meant that the dataset now had images that could contain no objects. This gave the best results.

14.3 Loss Systems

There are multiple ways of measuring the quality of the bounding box that is produced by the model, the most used is of course the IoU or Jaccard Index. However, the IoU is more akin to a measure of *how good* a bounding box is : an excellent bounding box will have an IoU close to 1. However, the IoU does not indicate *how bad* a bounding box is: if there is no intersection between the bounding box and the ground truth, the IoU will of course be 0. But this means that bad bounding box that is close to the ground truth will have the same score as a *very bad* bounding box that is far away from the ground truth. Recent work have been done to address this issue, and is presented here.

14.3.1 GIoU, DIoU and CIoU

Generalized Intersection over Union Loss: an improvement on the traditional Intersection over Union performance metric would be used to more accurately measure the accuracy of the bounding boxes. The GIoU is defined as follows:

$$GIoU = 1 - IoU + \frac{area(B_{GT} \cup B_{PT})}{area(B_{EC})} \tag{14.1}$$

With IoU being defined in Equation 14.2

$$IoU = \frac{area(B_{GT} \cap B_{PT})}{area(B_{GT} \cup B_{PT})} \tag{14.2}$$

In those equations, B_{GT} represents the bounding box ground truth, B_{PT} represents the predicted bounding box and B_{EC} represents the smallest enclosing box of B_{GT} and B_{PT}.

(a) Two intersecting bounding boxes

(b) Two non-overlapping bounding boxes

Figure 14.2: Illustration showing the two cases of bounding box position: intersecting and non-overlapping. The rectangle enclosed by a green solid line denotes the ground truth B_{GT}; the predicted box B_{PT} is denoted by a red solid line, and the smallest enclosing box B_{EC} is denoted by a blue dashed line.

The GIoU loss is a better measure of the quality of the predicted bounding box. Qian *et al.* also presents a new loss system that has a stronger gradient when the predicted bounding box is farther away to the truth. This loss system is shown in Equation 14.3

$$\mathcal{L}_{GIoU} = 2 \times log_2 - 2 \times log(1 + GIoU) \tag{14.3}$$

In Zheng *et al.*[23] the general IoU loss is defined as follows:

$$\mathcal{L} = 1 - IoU + \mathcal{R}(B_{GT}, B_{PT}) \tag{14.4}$$

Where $\mathcal{R}(B_{GT}, B_{PT})$ is a penalty term for the predicted box and ground truth. The authors then design a specialised penalty based on this formula.

The Distance IoU Loss is defined as follows:

$$\mathcal{L} = 1 - IoU + \frac{\rho^2(B_{GT}, B_{PT})}{c^2} \tag{14.5}$$

Here, b_{GT}, b_{PT} represents the center point of the ground truth bounding box and predicted box respectively, $\rho(\cdot)$ is the Euclidean distance and c is the diagonal length of the smallest enclosing box covering the two boxes *i.e.* B_{EC}.

The Complete IoU Loss incorporate the dIoU and add another term which forces aspect ratio consistency. The cIoU is defined as follows:

$$\mathcal{L} = 1 - IoU + \frac{\rho^2(B_{GT}, B_{PT})}{c^2} + \alpha v \tag{14.6}$$

Where α is a positive trade-off parameters. v measures the consistency of aspect ratios and is defined as follows.

$$v = \frac{4}{\pi}(\arctan[\frac{w_{GT}}{h_{GT}}] - \arctan[\frac{w_{PT}}{h_{PT}}])^2 \tag{14.7}$$

Finally the trade-off parameter α is defined as follows:

$$\alpha = \frac{v}{1 - IoU + v} \tag{14.8}$$

The cIoU loss and the dIoU both obtain AP improvements up to 3.14% on a FasterR-CNN[44] model trained on the COCO[24] dataset, up to 2.92% on a SSD[45] model also trained on COCO.

14.3.2 Loss flooding

In a recent paper by Ishida *et al.*[110], a new kind of regularization is presented, where **the model is prevented from reaching a zero training loss, even though it has zero training error**. This technique, called *flooding* intentionally prevents further reduction of he training loss when it reaches a certain low value: the *flooding level*. This approach makes the loss move around the flooding level by doing gradient descent if the loss is above the flooding level, but gradient ascent if it is below. This technique allows the network to obtain better generalization results and is very easily implementable.

(a) Without Flooding (b) With Flooding (c) CIFAR-10 without flooding (d) CIFAR-10 with flooding

Figure 14.3: Subfigure (a) shows the different regime during which a network first learns, then overfit. During [A], the network learns correctly, and both the training loss and the test loss decreases. During [B] the training loss continues to decreases, but the test loss increases; this is overfitting. In [C] the training loss is nearly zero. The authors show a way to avoid [C] by flooding the bottom area, forcing the loss to stay around a constant, which leads to a decreasing test loss. This is seen in (b) and (c) on the CIFAR-10 dataset

By letting the loss constant, the model hopefully drift towards a subspace where the loss landscape is flat, leading to better generalization. The authors tested this approach with various datasets, namely MNIST[107], Fashion-MNIST[111], CIFAR-10[108] and often obtained better results and in nearly every datasets, suggesting this approach is effective. Considering the ease of implementation, the lack of performance degradation and the possible improvements on performance, this technique could be very worthwhile.

14.4 Training methodology

First, a non modified YOLOv4 model, using the original architecture has been trained on the dataset, and will serve as a baseline, along with the Fast RCNN model trained by Verschoof-van der Vaart and Lambers[3]. This will allow us to effectively quantify the improvements or deteriorations in performance between the model themselves.

We trained each model on the same dataset, for 10000 epochs. Most trainings were done using already pretrained weights used for detections on the COCO dataset, but

some trainings were done using a completely untrained model. For every model, the best version of the weights were selected, based on the mAP. Some models were also trained with defaults anchors, and with anchors computed specifically for the dataset, to see the impact of this modification.

Chapter 15

Results

During training, the network was evaluated on multiple metrics: the IoU[1], the F1-Score and the mAP. For each training, the weights with the best mAP were kept.

15.1 Performance statistics

15.1.1 Model modifications

Off all the modifications made on the network, by it on the architecture itself or with the training procedure, the most performance boost over a "vanilla" or unmodified YOLOv4 was the use of the CV2 library during training, which allowed the use of the Mosaic data augmentation. Increasing the input size also gave way to improvements in the accuracy for class prediction, but with a lower IoU. It should be noted that using CV2 during training has a significant negative impact on training time lasting up to 25% longer[2].

The best performing model uses CV2 augmentations during training, along with the GIoU loss and the DNMS. This model is trained on the last version of the dataset, which uses 500×500 pixels images with reuses of objects. The CV2 augmentations gives the model a better robustness against occlusion, a recurring issue in the dataset. The larger input size give a better class accuracy. The dataset used was the V4, or the 1000×1000 pixels images, with random coordinates.

Table 15.1 shows the results of training for a vanilla YOLOv4, i.e. a non modified architecture *versus* the best performing model with GIoU and Distance NMS. CV2 data augmentations were also used.

Table 15.2 shows statistics for all classes. F1-Score for the YOLO models are good. The best model obtains a very high map@50 at over 86% and a good average IOU nearing 60%.

Another question that needed to be answered was the impact of the anchors on the performance of the models. Here, 4 models were trained on the version 4 of the dataset: a simple "vanilla" YOLO model with and without optimised anchors and the best performing model with and without optimised anchors. Table 15.3. Here, we can see that while

[1] In this section, the term IoU will be used to describe all types of IoU losses

[2] from ~ 25 hours to more than ~ 30 hours

	Kilns	Barrows	Celtic Field
Faster R-CNN (Verschoof-van der Vaart 2019) [3]	—	55%	58%
Faster R-CNN (Verschoof-van der Vaart 2020) [**wouter2020**]	12%	73%	66%
Vanilla YOLOv4	63.04%	77.04%	85.73%
YOLOv4 + CV2 + GIOU + DNMS	**82.37%**	**80.50%**	**95.92%**

Table 15.1: Per class precision of 3 chosen models. The best performing YOLO significantly outperforms the vanilla model and the Faster-RCNN. Precision values for Faster RCNN were chosen using the best performing model based on the maF1 Score.

	Precision	Recall	F1-Score	Av. IOU	map@50	M
Faster R-CNN (Verschoof-van der Vaart 2019)[3]	—	—	0.63	—	—	
Faster R-CNN (Verschoof-van der Vaart 2020)[**wouter2020**]	—	—	0.37	—	—	
Vanilla YOLOv4	0.58	0.84	0.69	45.75	75.27	0.
YOLOv4 + CV2 + GIOU + DNMS	**0.64**	**0.93**	**0.76**	**57.48%**	**86.27%**	**0.**

Table 15.2: General Statistic based on all classes. Again, the best model significantly outperforms the vanilla model.

the average IoU is slightly improved by the optimised anchors, other metrics are similar or inferior to the model without optimised anchors.

Figure 15.1: Evolution of loss and map@50 during training epochs of the best performing model

Figure 15.1 shows the loss and mAP of the best performing model throughout loss. The loss converge to a stable value, while mAP rises. It also seems that the dreaded overfitting do not seems to happen, as the value of map does not diminishes at the end of training.

	Precision	Recall	F1-Score	Average IOU	map@50
Vanilla YOLOv4 (not anchors optimised)	0.58	0.84	0.69	45.75	75.27
YOLOv4 + CV2 + GIOU + DNMS (not anchor optimised)	**0.64**	**0.93**	**0.76**	**57.48**	**86.27**
Vanilla YOLOv4 (anchors optimised)	0.58	0.84	0.69	45.75	75.27
YOLOv4 + CV2 + GIOU + DNMS (anchor optimised)	**0.64**	0.91	**0.76**	**58.13**	85.72

Table 15.3: General Statistic based on all classes, with base anchors *versus* optimised anchors . Interestingly, the optimised anchors model slightly outperforms the base anchors model with the average IOU, but only by less than a percent, while being inferior or similar in other metrics.

		Predictions		
		Kiln	Celtic Field	Barrow
Truth	Kiln	0.93	0.01	0.05
	Celtic Field	0.01	0.95	0.06
	Barrow	0.02	0.19	0.73

Table 15.4: Confusion Matrix of the best performing model.

A confusion matrix has been computed for the best performing model, and is reproduced in Table15.4, which indicates us which class are confused. Interestingly, while most classes are predicted accurately, the most confusion between classes happen between barrows and Celtic fields.

15.1.2 Impact of anchors on performance

While training, I also wanted to see the impact that a modifications of the anchors of the network had on performance. Computing anchors tailored for the dataset can be done the following command:

```
./darknet detector calc_anchors data/obj.data -num_of_clusters 9\\
-width <width> -height <height>
```

With `<width>` and `<height>` being the width and height of the images.

Replacing the anchors in the configuration file is done by modifying 3 lines in the YOLO modules called `anchors`.

While class prediction performance is not vastly affected by a change in anchors, the average IoU is. This make senses, as the anchors are used by the model to correctly place bounding boxes. Bad anchors will produce bad bounding boxes, which will in turn reduce the IoU of the prediction *versus* the ground truth.

15.2 Detection on sample images

Thanks to darknet, it is fairly easy to use the model to perform inference on one or multiple images. To infer on a single TIF image, one must first create tiles or segments of the image. If not done, darknet would simply downsample the image to a fixed size, losing massive amounts of details. The user can use the script `cutDataset.py`, which will segment every image in the dataset into 1000×1000 tiles. Inference is then done on those tiles, and results are saved in a text file.

15.3 Integration into a GIS

The end result of this project was to create a detection model that worked on LiDAR surveys e.g. images. However, analysis of those results isn't done on the raw images, but on GIS, such as QGIS[112]. Developing some way to integrate the detection results into this kind of software was a priority. Thankfully, QGIS allows for the import of CSV database as shape files. This meant that the detection results could simply be integrated into a database, where each line contained the position of the bounding box in the WKT format along with the confidence and the class.

This operation is done in a few steps. First the user crops the raw LiDAR images into 1000×1000 chunks. This prevents the catastrophic loss of details that would happen with a downscale. Then inference is done on those images. **A "side effect" of using YOLO is the inference speed: on a few benchmark test, the model was able to infer on the entire dataset, i.e. about 3500 tiles or $\sim 500km^2$ in about 8 minutes.** The detection results, with a confidence percentage, class and location of the bounding box of the detection are saved in a text file.

The `detectionsToCSV` script allows the user to take those detections results and create 3 databases of objects, one for each class. The scripts works by first finding the main image in which the cropped image was taken from. Then it uses the `gdalinfo` command line utility to get the coordinates of the main image, and from that compute the coordinates of the bounding box in the world, which are then formatted into WKT and written into the corresponding database. Some post-processing is done on the results: **YOLO seems to sometimes outputs very erroneous detections, in particular for Celtic Fields. Those detections have high confidence scores but are with a very low width and a high height**. A simple fix is to discard boxes where the ratio between width and height is over a threshold.

As we cannot dare to write about object detection without showing examples of such detections, we shall show a few examples of successful detections on the base TIF images.

Figure 15.2: Functional graph of the detection program. First the full size TIF are cropped into reasonable size images, and a list of those images is also generated. Then the darknet detector uses the trained weights and the configuration file to perform inference on those images. The detection results are stored in a text file. This text file is then read to extract the detection attributes, transform their coordinates from local to world and write the results to CSV databases.

(a) Detected charcoal kilns

(b) Detected barrows along a road in the Veluwe Region, Netherlands.

Figure 15.3: Example of successful detections on visualized LiDAR data. The red squares represents detected barrows, green are detected charcoal kilns and blue are detected Celtic fields. Screencaptures from QGIS

(a) Rows of charcoal kilns in the Veluwe Park.

(b) Celtic fields and barrows in a large region of the Veluwe Park, Netherlands.

Figure 15.4: Examples of successful detections of the 3 classes of objects.

Chapter 16

Discussion

As can be seen in the section above, the model performs fairly well on all metrics: see Table 15.1. The IoU is good, meaning that once an object is detected, the bounding box around that object is accurate. Class Accuracy is adequate, with the best performance being with the Celtic Fields, which are very characteristic and easily recognizable. Performance could be improved for the "Barrows" class, since it has the lowest accuracy of all the classes, and the most confused class.

Figure 16.1: Confusion between a roundabounts and a barrow. Details from a survey done in the region of the Veluwe, Central Netherlands.

Some errors do still occurs, especially with **roundabouts being confused for barrows, an issue already noticed in Verschoof-van Der Waart and Lambers[3]**. While this might be an problem with the training of the network, it might also indicate that the LiDAR survey do not hold enough informations to discriminate between those two type of objects, as discussed in Section 8.1.

This ties again with the fact that we are not training a model that is detecting archaeological objects, but simply objects. The model is incapable of infering the archaeological origin of the object based purely on appearance, as is exemplified with the roundabounts

being mischaracterised as barrows. Creating a model capable of such a feat is much harder than simply training an object detector. Some kind of reasoning needs to be done to understand the archaeological properties of objects, or at least extracting more general and global information than can be done using local convolutions. This could be done using domain knowledge to post process the detection results and eliminate false positive. This has been done in a recent article by Verschoof-van der Vaart[**lamberVerschoof**], with location based ranking of barrows being used, with good success.

Part IV

Conclusions

Chapter 17

Further Improvements

17.1 Multi data inference

One promising path is the use of multiple type of data to train and infer. For example, one could use LiDAR surveys combined with spatial photography to produce stronger and more robust model. In our case, we are lucky enough to have vast swath of terrain already surveyed by LiDAR, and high resolution geospatial photography is fairly easy to obtain. Combining those two types of data could help the network become more robust as it would have access to more information.

Combining those two type of data might require the use of a modified file format, able to use 4 channels: 1 for the LiDAR grayscale survey, and 3 for the RGB values of the satellite photography. Modifications to the detection network might also have to be done to be able to use such a file format.

17.2 Semantic Segmentation

Figure 17.1: Example of semantic segmentation on a street scene.

Segmentation of object at the pixel level, instead of using bounding boxes could be done. While bounding boxes are enough for precise location of objects, it might not be enough to compute some attributes of those objects, like their size or orientation. Bounding boxes also poses an issue with objects that are not aligned in the same way. While some techniques allows for rotation of bounding boxes, such as this paper by Lou, Pan and Lei[113], more precise segmentation could be a useful and interesting study path.

State of the Art models uses fully convolutional networks or U-Nets. Mask-RCNN[75] is one of the most well known model capable of semantic segmentation, but since then many newer and more performant networks have been published such as Deep Lab[114], Fast-FCN[115] or Gated-SCNN[116]. A more comprehensive review of the state of the art should obviously be done, and modifications to those models might be necessary to achieve good results on the particular type of data generated by Archaeological Remote Sensing.

Chapter 18

Conclusion

The aim of this project was to develop an object detection architecture more suited for use with remote sensing data, and inscribe itself in a growing body of research in this area. While Deep Learning is still a relatively novel technique, this work further establishes it as a robust, efficient and high performance method for detection.

This project, while being in essence a *research subject* and not a *engineering subject* has allowed me to put into a application a wide range of state of the art techniques, and to have entire control over.

Indeed, what is usually the case in Deep Learning projects is that a dataset is used *as is* and never modified. One will then create an architecture, train it, and evaluate. More often than not, the architecture of the model is also used as is. In this project, I was provided with a dataset, but I was able to modify it. I was able to chose which Deep Learning framework to use, what type of architecture, what kind of modifications to apply, what kind of training regime to use and so on. This liberty allowed me to tweak the model and its training, and make it more suitable for the task. I applied what I learned at my last internship at SNCF, where I was also tasked with the development of a ML project from end to end.

From an engineering standpoint, and more precisely a project management point of view, those two experiences gave me insight into how a Deep Learning project can be conducted and what are the differences and parallels with more traditional Software Engineering tasks.

A Deep Learning project should start with a thorough review of the state of the art in the field. While this isn't too dissimilar with a review of the technologies that could be used in a Software Engineering project, the main difference is the review will usually be done with recent research papers, and techniques that are young and not necessarily proven. This also means that a high level of familiarity with recent trends in Deep Learning research is required, and that a lot of testing is needed to separates good ideas and techniques from the inefficient and/or ineffective.

Deep Learning moves very fast and new, potentially ground breaking papers are published almost everyday. For example, the paper detailing YOLOv4, the center piece of this project was published at the end of April 2020, right at the end of the allotted time I had to write a State of the Art document. This means that the monitoring of the recent advances needs to be done much more closely. This in turn poses an interesting problem: in a more traditional Software Engineering environment, that simply make use of those

models, how can we follow the break neck speed of development of Deep Learning and apply them ? The Technical Debt accrued by those methods grow much faster: and a model using techniques even a few years old can be entirely outdated. The challenges is to embed those models and techniques into a more traditional software engineering environment while being able to modify them regularly.

Annexes

Acronymes

AP Average Precision 80

BoF Bag of Freebies 61, 62

BoS Bag of Specials 62

cIoU Complete Intersection Over Union 25, 75, 79, 80

CSV Comma Separated Value 85

DEM Digital Elevation Model 17

dIoU Distance Intersection Over Union 25, 75, 79, 80

DNMS Distance Non-Maximum Suppression 82

FNN Feedforward Neural Network 69

FPN Feature Pyramid Network 37–39, 72, 73

FPS Frame Per Seconds 73

GIoU Generalized Intersection Over Union 25, 37–39, 75, 78, 79, 82, 83

GPU Graphics Processing Unit 20, 62

IoU Intersection Over Union 24–26, 37, 38, 51, 75, 78, 79, 82–84, 89

LiDAR LIght Detection And Ranging 5, 10, 11, 13, 17, 18, 29, 30, 45, 48, 49, 65, 71, 76, 85, 86, 89, 92

mAP Mean Average Precision 20, 24, 25, 51, 81–83

MCC Matthews Correlation Coefficient 26

ML Machine Learning 23

MLFF Multi Layer Feature Fusion 37–39, 71–74

MSE Mean Squared Error 21

NMS Non-Maximum Suppression 44, 74, 83

PAN Path Aggregation Network 73

ReLU Rectified Linear Unit 70, 71, 75

RPN Region Proposal Network 48, 51, 72

SAM Spatial Attention Module 74

SELU Scaled Exponential Linear Unit 69, 75

SPP Spatial Pyramidal Pooling 73

SVM Support Vector Machine 45

WKT Well Know Text Format 85, 86

YOLO You Only Look Once 46, 47, 51, 68, 75, 83

Glossary

backpropagation Backpropagation is a learning technique that allows for a computation efficient calculation of the gradient of the loss function. Backpropagation uses the chain rules to compute the gradient each layer at a time, starting from the last layer.[20, p.197] 22

CNN Convolutional Neural Network. Type of neural network, who learns weights for matrices who will be convoluted and produces feature maps. Generaly, those feature maps will be convoluted upon by other convolutional layers. 20, 46, 47, 51, 68

GIS Geographical Information System. Type of specialised software created to deal with maps and geographical data 17, 65, 66, 85

hyperparameter An hyperparameter is a parameter whose value is used to control the model behavior. As opposed to weights, those values are not learned during the training process.[20, p.117] 51, 70

overfit When the capacity for representation of a model is too big in relation to the size of the dataset; either because the model has too much parameters or because the dataset is too small. In those cases, the model can "learn by heart" the training data and it's capacity for generalization will be affected. Overfitting will usually manifest itself with a very good accuracy on the training dataset, but a poor accuracy on the test dataset. See Section6.3 for a more in depth explanation. 21, 48, 76

weights A weight is a value that is learned during the training process.[20, p.14] 21, 22

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