

“Con fundamento en el artículo 21 y 27 de la ley federal del derecho de autor y como titular de los derechos moral y patrimonial de la obra titulada “COMPACIDAD, UN BREVIARIO AL INFINITO”, otorgo de manera gratuita y permanente al instituto tecnológico autónomo de México y a la biblioteca Raúl Baillères Jr. Autorización para que fijen la obra en cualquier medio, incluido el electrónico y la divulguen entre sus usuarios, profesores, estudiantes o terceras personas, sin que pueda percibir por la divulgación una contraprestación”

Amaury Gutiérrez Acosta

FECHA

FIRMA

A la ε -cercanía.

- A Lety por plantar la semilla de lo que soy.
- A Ricardo por regar esa semilla, no sería nada sin ti.

Don't Panic

Contents

Preface	iii
1 Motivation	1
1.1 Motivation	1
1.2 Objective	3
1.3 Scope	3
2 Nothing new under the sun	5
2.1 Computer vision	5
2.2 Remote sensing	7
2.2.1 Data augmentation	8
2.3 Damage Assessment	8
3 Reinventing the wheel	9
3.1 TensorFlow	9
4 Architecture	13
4.1 Ingest	13
4.2 Tag	14
4.3 Data augmentation	14
4.4 Train	14
4.5 Predict	15
4.6 Activation maps	15
4.7 Active learning	15
5 Results	17
6 Future work	19

Bibliography**21**

Preface

It is a very exiting moment for the field of computer vision, machines are now capable of performing task that we thought were impossible reaching new milestones each year. It has been a long time since computers were just huge furniture in cold university rooms. Computer power has grown exponentially since those days. Lately techniques that where discarded because the were computation intense are now being unburied and have been showing great results in today machines.

I wanted to explore the possibilities that these techniques can offer in classic problems such as landcover classification. In particualar, I wanted to teach a neural network how to recognize a specific element in aerial imagery and then use the tailored features as input to train classic classifiers such as random forest or support vector machines.

This work explores the use of Convolutional Neural Networks in the context of a classical remote sensing problem called landcover classification.

This preface serves as an introduction to this work. It gives a short review on the contents of each chapter, and shows how is the thesis structured.

Motivations are explored in chapter 1. We expose why our work is important and we give a clear explanation about the objective of the experiment. Additionally, we mention the scope of the project.

An extensive literature review is shown in chapter 2. All the way back to the famous tecnique to analyse handwritten digits with the convolutional architecture that started the revolution. A review of more modern applications of the techique in more complex situations such as object recognition in images. We explore other experiments that show different uses of the CNNs in remote sensing. Damage assesment in the af-

termath of natural disasters is also explored as it was the main motivation for this study.

Chapter 3 unveils the mathematical details that make this technique to work. The training process using backpropagation is explained. Last layer activations functions such as the sigmoid and softmax are inspected. A brief summary of a convulutional neural network techniques such as the ReLU activation, pooling, and data augmentation is given.

The architecture of our pipeline is explained in chapter 4. This includes the data gathering, data curation, the training of the network and the prediction. Details of the data base are given, including the reasoning behind some decisions. This chapter also explores how did we obtained the images.

The results of the experiment are exposed in chapter 5. Accuracy of the classifier, as well as the validation protocol are clearly exposed here. We also show the final classification map and talk about how it was obtained.

Finally, in chapter 6, we talk about future work, and what are the main conclusions that this work led us to. We include several improvements that can be made to the process in order to obtain better results.

This work was the result of an intership spent on the Stevens Insitute of Technology in Hoboken, New Jersey, during the summer of 2017. It was done under the supervision of Andrea Garca Tapia and Jos Emmanuel Ramirez Marquez.

Chapter 1

Motivation

Good work is not done by ‘humble’ men. (...) A man’s first duty, a young man’s at any rate, is to be ambitious.

A Mathematician’s Apology

G. H. Hardy

In this chapter, we explore the motivation, objective and scope of the present work.

1.1 Motivation

In CONABIO we use landcover maps to analyze and assess the evolution of the environment through time. We make this possible by leveraging classic classification algorithms and a large amount of computing power. While our efforts have been quite productive, these algorithms have certain limits, they rely on the use of the light spectrum. As a consequence, any two categories with similar spectrum footprint will, in all likelihood, confuse the classifier. Curiously enough, humans have little problem distinguish between some of these pairs of categories. For example, crops and grasslands might seem identical to a supervised classifier, but we can certainly tell the difference from one another. This is caused because our brains are not seeing particular pixels and trying to classify them one by one. Instead, our brains look at the whole picture, we focus on zones of the image an all of the information included in them, in other words, we care about context. Convolutional Neural Networks take this into account. Each neuron

of the network cares only about a certain zone of the image when information flows through the layers of the network, there are certain neurons that activate upon certain stimuli. Taking context into account lets the network to recognize certain features that would be invisible to a classic classifier, for example: shapes and geometries. When we ask ourselves why it is so easy to differentiate crops from grasslands geometry comes as a natural answer. Crops have very particular shapes.

The final objective is to build a comprehensive biodiversity monitoring system. It can be thought as two independent efforts. One of these attempts is the Monitoring Activity Data for the Mexican REDD+ program (MADMex) [10] which pretends to monitor the behavior of forest and vegetation across the country by processing satellite imagery. Another effort is the Mexican National Biodiversity and Ecosystem Degradation Monitoring System (SNMB) [9] which gathers information about species in the different ecosystems that exist in Mexico.

Segnet papers: [3] in [13] they enhance their approach by extending their own architecture to include a Bayesian approach. The idea is to add a model of uncertainty to the CNN and use this information to get more accurate guesses on each of the pixels. They report that this feature adds some improvement in the level of accuracy for many types of architectures not only their own SegNet.

A wonderful introduction to neural networks in the context of remote sensing can be found in [4].

In the context of natural disasters other options have been considered [15].

DeCAF paper talks about using the features extracted from a neural convolutional network to use in traditional methods. [8]

This is another attempt that adds to the evidence that features engineered by the Neural Network work pretty good off the shelf. [20]

Transfer learning is explored by Yosinski *et al.* [26]. They propose to use an already trained architecture in new tasks by replacing different layers and retraining.

In [17] they use the features extracted from the CNN to segment an image.

The possibility of having a single model that can perform correctly in many different tasks is explored in [12]

A survey on distinct aspects of how transfer learning is used can be found in [19].

The use of active learning together with semisupervised learning techniques is explored in [27].

Need to take a look into [5]

Everardo suggested to look into the U net [22].

And the books: [4], [21], [24], [11]

1.2 Objective

It is a wonderful time to explore the use of novel technologies in all types of context. It is in human nature to create tools that revolutionize the way it modifies its environment. We want to explore the use of Convolutional Neural Networks in the context of landcover classification. We believe that this field is very promising and will bloom in the next years. By applying this methods we hope to obtain results that match the ones that we are already getting with classic methods. In Mexico, the National Institute of Statistics and Geography has been in charge of producing periodical maps about urban settlements in the country. However, it is hard to keep track of irregular settlements and it is often prohibitively costly to create these maps from on-site visits. We want to offer a cheap and innovative alternative to detect and index urban areas using the inexpensive satellite imagery that is available.

1.3 Scope

It would be far too ambitious to cover every topic that is involved in the process of the classification using CNNs. We want to explain how do the networks work to a certain extent, but it is not in the scope of this work to untangle every single detail. In the same fashion, the field of Remote Sensing is far too big to be explored in this

work. We assume a certain degree of knowledge in related topics and we expose some mathematical details in the appendix. As we already mentioned, the field of Computer Vision is in its climax. Reviewing every single article that has been written would be a daunting task. We offer a brief literature review that gives some context about the state-of-the art and we hope to build upon ideas and efforts done by a myriad of people. We aimed to built a system capable of procesing imagery and that could be deployed into a cluster for efficient computation. We had in mind to offer a wall-to-wall product of the Mexican landscape.

Chapter 2

Nothing new under the sun

Archimides will be remembered
when Aeschylus is forgotten, because
languages die and mathematical
ideas do not.

A Mathematician's Apology

G. H. Hardy

In this chapter, we talk about the state of the art in computer vision and how it has been used for remote sensing problems. We also give a brief account of natural disaster assessment, and how are these machine techniques applied in this sense. We use Sandy Hurricane as a study case because of the data that was publicly made available by the NOAA.

2.1 Computer vision

Le Cun *et al.* [6] propose to use an architecture of a multilayer neural network that was able to learn directly from the data with no prior feature extraction. In contrast to the usual path that was used in the context of pattern classification, they created an architecture that was able to automatically extract the features directly from the data without prior manipulation. Instead of using a fully connected network, they proposed a locally connected net. It was capable of extracting local features and passed them down to the subsequent layers in what they called a *feature map*. Each unit took the information of a 5×5 neighborhood of the pixel in the previous layer. The last layer

of the architecture consisted of ten units that represented each of the possible digits. This architecture was trained using backpropagation and are now known as Convolutional Neural Networks (CNNs). The big leap forward of their result was that their architecture needed very little information about the task it was performing, they were able to extend the use of their method to other symbols, however, they state that the method was not able to be applied to very complex objects.

Before CNNs became widely used in computer vision tasks, the use of neural networks to automatically detect roads was already being explored [18]. They proposed a simple architecture with a single hidden. They use the now standard procedure of cropping small patches from the complete image and worked on the RGB color space. Aerial imagery in addition to vector information on roads is used as training data. Instead of manually tag the images they proposed a model that assumes certain amount of thickness in the roads, which are typically with no dimension. To reduce the input dimensionality, they applied Principal Component Analysis keeping the most informative principal components. As a method of post-processing, they use a CNN to reduce the noise in the images. Effectively getting rid of false positives and false negatives by using context information. Of the important lessons learnt by this experiment is the value of the random rotations in the training data. It is common that road networks in cities form grids, they realised that a model trained with information from a particular city will perform poorly if data from a new city is shown to it. They found that this can be relieved if random orientations are applied to data as when we are dealing with birdseye sight, there is no correct orientation for images. They also found that adding pre-processing such as edge detection techniques showed no improvement to the performance of their pipeline. This was attributed to the fact that the neural network crafts features of this nature when learning to perform the task of recognizing roads.

There have been several attempts to use features extracted from a CNN to be used in a different context. Michael Xie *et al.* [25] examine this approach by training a CNN on top of the well-known VGG F model. First, they replace the fully connected layers on top of that model with a convolutional layer. Then they re-train the features the model learned from ImageNet with aerial images and nighttime images gathered from the National Oceanic and Atmospheric Administration (NOAA). While they get nice accuracy results from using daytime images to predict nighttime light, it was not the purpose of their research. Instead, features crafted by the network are extracted and

used to train a model to predict poverty from satellite imagery. In order to do so, they use these features as input for a logistic regression classifier. To compare their model, they train four other models extracting features from a survey, features from ImageNet itself, features from the nighttime light intensities and features from ImageNet and nighttime light intensities at the same time. The transfer model outperforms every model except for the one based on survey data. This strongly suggests that the transfer learning technique is actually extracting complex information from the aerial scenes. They mention that this approach can be useful when conducting surveys is prohibitively expensive.

With the tremendous advances that computer power has suffered in the late years, this has been proven to be incorrect. In 2009 a big image database was gathered and published [7]. Ever since this database became the defacto dataset to test classification methods. A few years later, in 2012 Krizhevsky *et al.* [14] proposed the use of CNNs in this daunting task.

2.2 Remote sensing

In late years groundbreaking advances in computer vision have led to tremendous advances in other science fields. In particular, we are interested in landcover classification.

The use of CNNs in the context of landcover classification was explored by Kussul *et al.* [16]. They used an ensemble of CNNs to obtain state of the art results in the classification of different types of crops using multitemporal and multisensor satellite data. They explore 2 approaches, first they use a 1-D CNN to perform the convolutions in the spectral domain by stacking the different bands from the Sentinel-1 A and Landsat-8 scenes. This process outputs a pixel-wise classification, then they perform a traditional 2-D CNN on the scenes. In order not to lose resolution with the 2-D CNN, they use a sliding window approach assigning the class to the center pixel of the sliding window. Finally, they ensemble both opinions and filter the result to improve the quality of the map.

The usual approach with landcover classification is the use of classical classification methods such as support vector machines (SVM) and random forests (RF). In order to improve the performance, features must be handcrafted from the original bands. In

[23], Grant *et al.* explore the use of Transfer Learning and Data Augmentation in the context of remote sensing images. By exploring well-known high-resolution datasets, they obtain state of the art results.

Transfer Learning (TF) is the process of using an already trained CNN, to

2.2.1 Data augmentation

Data augmentation is a technique used to artificially increment the size of the training dataset by applying an affine transformation to the images. It is often used when tagged data is scarce and difficult to obtain. The usual transformations include rotations and reflections. When using this technique we should be careful about the orientation of the objects, for example, a building upside down makes no sense, so there is no use to make the network learn features on objects that it won't see in the wild. Fortunately, aerial imagery doesn't present this problem. There is no particular orientation that can be considered correct when the pictures are taken from above. This means that we can dramatically boost the size of our dataset.

The reasoning behind this idea is that when we see a picture, our brain automatically orients it into its correct position. By showing the network with different positions and orientations of an object we enrich its knowledge about it.

We can think of the neural network as a newborn kid, in the beginning, they experience its environment for the first time.

2.3 Damage Assessment

Chapter 3

Reinventing the wheel

We may say, roughly, that a mathematical idea is ‘significant’ if it can be connected, in a natural and illuminating way, with a large complex of other mathematical ideas.

A Mathematician’s Apology
G. H. Hardy

In this chapter the mathematical details of the CNN are exposed. How does back-propagation works, and differences between multiclass and multilabel classification.

3.1 TensorFlow

TensorFlow is a machine learning system developed by the Google Brain Team to supersede its first-generation system, DistBelief. It was built on top of the lessons learned during DistBelief development. One of the fundamental concepts that lead the team to create a new system from scratch was the need for flexibility. TensorFlow was thought as a way to expressing machine learning algorithms using a common interface with implementations targeting a wide range of devices. Complex models that where first implemented in DistBelief such as Inception got a performance boost of a factor of x6 [1] when it was ported to the new system. TensorFlow was opened sourced on November 9, 2015 under the Apache 2.0 license.

In this section, we will untangle some of the details of how TensorFlow and its graph model work [2].

It uses an elegant data-flow system in which both the operations and the state of the algorithm are represented as nodes and edges in a directed graph. This lets the system to pre-calculate an optimal sub-graph before starting the calculations.

With flexibility in mind, this system lets the user define new operations and register them to use within the framework. Additionally, it was developed to target different platforms, from machine clusters to mobile devices, these implementations are known as *kernels*. Using the same programming model, TensorFlow decides in runtime which pieces to use. This is useful when you take into account the whole development process of a data product and how it evolves. We can think of a common scenario, first, the developer experiments with data in a single computer before deploying the system to train with a larger data set in a cluster of computers, when the model is trained, it can be deployed to an online service which will run on a single computer or it can be implemented to be used in a mobile device for offline use. In each of these steps the underlying environment is completely different, however, TensorFlow adapts automatically to each situation. That's where TensorFlow shines.

As a common interchange data format, it uses tensors. With machine learning algorithms, it is often the case to have sparse data, encoding it as dense tensors is a clever way to save space. As we mentioned before, TensorFlow uses a graph to represent both the state and the operations. Nodes represent operations. Edges represent inputs and outputs between these operations. The system takes its name from the tensors flowing through this pipes. Although it is not of particular importance to our experiment, it is worth mentioning that TensorFlow supports algorithms with conditional and iterative control flow, which means that it can be used, without further tuning, to train Recurrent Neural Networks which are very important in fields like speech recognition and language modeling.

The system also provides a library that allows symbolic differentiation. As many machine learning techniques rely on Stochastic Gradient Descent to train a set of pa-

rameters, this feature makes easier to explore new techniques as the backpropagation code is automatically produced for any combination of operation nodes.

TensorFlow was built with huge data-sets in mind. It provides an intern library that allows the distribution of datasets that would be too large to fit in RAM. Instead, data can be sliced, taking advantage of how some algorithms work. Additionally, communication between nodes use lossy compression, taking advantage of the fact that some of the machine learning algorithms are tolerant to reduced precision arithmetic. It is important to mention that it is possible to extract state and information from any particular node in the graph. This fact is very important to our study because we are interested in the features that the system craft to perform the given task. We want to teach the system to excel at our task of interest and then use its knowledge to improve another task.

Another nice feature that TensorFlow brings into the table is its ability to prune the execution graph before starting its computations. Usually several sets of operations are repeated along the graph, by detecting this, the system can automatically replace all incidences of each repeated sub-graph with a single one thus, saving memory and time. The same case happens with communication nodes. If several nodes from a single device are consuming the same data from another device, the system is prepared to detect this and ensure that the data transfer occurs only once.

The framework code is deeply optimized. Implementations of the same interface target the different dispositives that the code can run in. It is built upon known mature frameworks such as cuDNN, a library for deep neural networks that targets NVIDIA GPUs, and Eigen, a C++ library for linear algebra, which was extended to offer tensor arithmetic support. On top of this infrastructure, TensorFlow offers a Python client which is very convenient for fast development.

An interesting tool that is packed with the framework is TensorBoard. With the huge complexity that machine learning models offer at this scale, it is important to know what is happening at any point of the training process. TensorBoard offers a glimpse of how does the architecture for a particular computation graph look like. This will become handy later when describing our model.

There exist several systems that offer similar features to TensorFlow. Theano, Torch, Caffe, Keras to name a few. The purpose of this work is by no means to study the advantages or disadvantages of these systems nor to create a benchmark on their performance. As the pipeline was already written in Python, we choose TensorFlow to minimize the gluing code. Among the examples that come with the system there is one end to end example of how to transfer learning from one trained net to another task.

Chapter 4

Architecture

A mathematical proof should resemble a simple and clear-cut constellation, not a scattered cluster in the Milky Way.

A Mathematician's Apology

G. H. Hardy

In this chapter, we will talk about the implementation of our experiment. The details of the pipeline architecture, and the techniques used to obtain and curate data are unveiled. Details on the data munging and preprocessing are also given. The backend was implemented in Python, while the clients are implemented in javascript.

4.1 Ingest

We built a system to ingest the images from the NOAA service. It lazily downloads the images by checking first if the file is already present in the temporary folder. If the file does not exist it downloads it, then the system tries to add it to the database and persistent file system. To maintain a coherent one to one mapping between the database and the file system, the process of adding a new scene must be successful both in the database and in the filesystem, otherwise, the file is erased from both, and the state of the system remains as it was before the ingestion attempt.

4.2 Tag

Aerial tagged data is scarce. In particular, for the purpose of our experiment, we don't have any useful metadata on the images. We propose a method to tag samples of the scenes using crowd sourcing. We built a service that crops samples from the images and exposes them to an online application that lets any user with access to tag an image. We have three categories: the image has water in it, the image does not have water in it, and it is not possible to tell. When a positive answer is obtained, the system persists the image in the data base with the information of from which scene was it extracted.

4.3 Data augmentation

Given the nature of our task, it is hard to acquire the tagged images. To increment the size of our training dataset, even more, we use a technique known as data augmentation. It relies on the fact that affine transformations do not change the content of the scenes, however, a transformed scene appears as a completely new one to the classifier.

The images were rotated by 10 degrees, and reflected by the x-axis and the y-axis this gives us a $\times 144$ factor, this means that for each tagged image, the training corpus is incremented by 144 images. The problem with this approach is that when a square image is rotated, some information on the corners is lost so we have to adjust the original image so that we can still crop a complete square from the desired size from it. For our experiment, the input size for the neural network is 227×227 pixels, so the original images must be at least $\sqrt{2}$ times 227 on each side. This way no matter how we rotate the original image, we can still crop a 227×227 from the center of the rotation without losing any data.

4.4 Train

Images were tagged by hand.

4.5 Predict

Another simple front end application was developed to predict on new features, it is very similar to the tagging application. Instead of asking the user about the correct tag, it queries the model and exposes the answer to the front end.

4.6 Activation maps

It was shown by (the paper with discrimination zones) that if we use the layers before the fully connected layers, it is possible to extract zones which the network recognizes as to be prone to be for one of the classes.

4.7 Active learning

Chapter 5

Results

A mathematician, like a painter or a poet, is a maker of patterns. The mathematician's patterns, like painter's or the poet's, must be *beautiful*; the ideas, like the colours or the words, must fit together in a harmonious way.

A Mathematician's Apology

G. H. Hardy

In this chapter we will explain the extent of our results, and how it is possible to extract a binary landcover map with the presence and absence of water.

Chapter 6

Future work

If intellectual curiosity, professional pride, and ambition are the dominant incentives to research, then assuredly no one has a fairer chance of gratifying them than a mathematician.

A Mathematician's Apology

G. H. Hardy

This was an important experiment because it let us describe the use of novel techniques in the process of image classification.

Bibliography

- [1] Martín Abadi, Ashish Agarwal, Paul Barham, Eugene Brevdo, Zhifeng Chen, Craig Citro, Greg S. Corrado, Andy Davis, Jeffrey Dean, Matthieu Devin, Sanjay Ghemawat, Ian Goodfellow, Andrew Harp, Geoffrey Irving, Michael Isard, Yangqing Jia, Rafal Jozefowicz, Lukasz Kaiser, Manjunath Kudlur, Josh Levenberg, Dan Mané, Rajat Monga, Sherry Moore, Derek Murray, Chris Olah, Mike Schuster, Jonathon Shlens, Benoit Steiner, Ilya Sutskever, Kunal Talwar, Paul Tucker, Vincent Vanhoucke, Vijay Vasudevan, Fernanda Viégas, Oriol Vinyals, Pete Warden, Martin Wattenberg, Martin Wicke, Yuan Yu, and Xiaoqiang Zheng. TensorFlow: Large-scale machine learning on heterogeneous systems, 2015. Software available from tensorflow.org.
- [2] Martín Abadi, Paul Barham, Jianmin Chen, Zhifeng Chen, Andy Davis, Jeffrey Dean, Matthieu Devin, Sanjay Ghemawat, Geoffrey Irving, Michael Isard, Manjunath Kudlur, Josh Levenberg, Rajat Monga, Sherry Moore, Derek Gordon Murray, Benoit Steiner, Paul A. Tucker, Vijay Vasudevan, Pete Warden, Martin Wicke, Yuan Yu, and Xiaoqiang Zhang. Tensorflow: A system for large-scale machine learning. *CoRR*, abs/1605.08695, 2016.
- [3] Vijay Badrinarayanan, Alex Kendall, and Roberto Cipolla. Segnet: A deep convolutional encoder-decoder architecture for image segmentation. *CoRR*, abs/1511.00561, 2015.
- [4] M.J. Canty. *Image Analysis, Classification and Change Detection in Remote Sensing: With Algorithms for ENVI/IDL and Python, Third Edition*. Taylor & Francis, 2014.
- [5] Liang-Chieh Chen, George Papandreou, Iasonas Kokkinos, Kevin Murphy, and Alan L. Yuille. Semantic image segmentation with deep convolutional nets and fully connected crfs. *CoRR*, abs/1412.7062, 2014.

- [6] Y. Le Cun, O. Matan, B. Boser, J. S. Denker, D. Henderson, R. E. Howard, W. Hubbard, L. D. Jacket, and H. S. Baird. Handwritten zip code recognition with multilayer networks. In *[1990] Proceedings. 10th International Conference on Pattern Recognition*, volume ii, pages 35–40 vol.2, Jun 1990.
- [7] Jia Deng, Wei Dong, Richard Socher, Li jia Li, Kai Li, and Li Fei-fei. Imagenet: A large-scale hierarchical image database. In *In CVPR*, 2009.
- [8] Jeff Donahue, Yangqing Jia, Oriol Vinyals, Judy Hoffman, Ning Zhang, Eric Tzeng, and Trevor Darrell. Decaf: A deep convolutional activation feature for generic visual recognition. *CoRR*, abs/1310.1531, 2013.
- [9] Nashieli Garcia-Alaniz, Miguel Equihua, Octavio Prez-Maqueo, Julin Equihua Bentez, Pedro Maeda, Fernando Pardo Urrutia, Jos J Flores Martnez, Sergio A Villela Gaytn, and Michael Schmidt. The mexican national biodiversity and ecosystem degradation monitoring system. *Current Opinion in Environmental Sustainability*, 26:62 – 68, 2017.
- [10] Steffen Gebhardt, Thilo Wehrmann, Miguel Angel Muoz Ruiz, Pedro Maeda, Jesse Bishop, Matthias Schramm, Rene Kopeinig, Oliver Cartus, Josef Kellndorfer, Rainer Ressler, Lucio Andrs Santos, and Michael Schmidt. Mad-mex: Automatic wall-to-wall land cover monitoring for the mexican redd-mrv program using all landsat data. *Remote Sensing*, 6(5):3923–3943, 2014.
- [11] Trevor Hastie, Robert Tibshirani, and Jerome Friedman. *The Elements of Statistical Learning*. Springer Series in Statistics. Springer New York Inc., New York, NY, USA, 2001.
- [12] Lukasz Kaiser, Aidan N. Gomez, Noam Shazeer, Ashish Vaswani, Niki Parmar, Llion Jones, and Jakob Uszkoreit. One model to learn them all. *CoRR*, abs/1706.05137, 2017.
- [13] Alex Kendall, Vijay Badrinarayanan, and Roberto Cipolla. Bayesian segnet: Model uncertainty in deep convolutional encoder-decoder architectures for scene understanding. *CoRR*, abs/1511.02680, 2015.
- [14] Alex Krizhevsky, Ilya Sutskever, and Geoffrey E Hinton. Imagenet classification with deep convolutional neural networks. In F. Pereira, C. J. C. Burges, L. Bottou,

- and K. Q. Weinberger, editors, *Advances in Neural Information Processing Systems 25*, pages 1097–1105. Curran Associates, Inc., 2012.
- [15] Yury Kryvasheyeu, Haohui Chen, Nick Obradovich, Esteban Moro, Pascal Van Hentenryck, James Fowler, and Manuel Cebrian. Rapid assessment of disaster damage using social media activity. *Science Advances*, 2(3), 2016.
- [16] N. Kussul, M. Lavreniuk, S. Skakun, and A. Shelestov. Deep learning classification of land cover and crop types using remote sensing data. *IEEE Geoscience and Remote Sensing Letters*, 14(5):778–782, May 2017.
- [17] Jonathan Long, Evan Shelhamer, and Trevor Darrell. Fully convolutional networks for semantic segmentation. *CoRR*, abs/1411.4038, 2014.
- [18] Volodymyr Mnih and Geoffrey E. Hinton. Learning to detect roads in high-resolution aerial images. In *Proceedings of the 11th European Conference on Computer Vision: Part VI, ECCV’10*, pages 210–223, Berlin, Heidelberg, 2010. Springer-Verlag.
- [19] S. J. Pan and Q. Yang. A survey on transfer learning. *IEEE Transactions on Knowledge and Data Engineering*, 22(10):1345–1359, Oct 2010.
- [20] Ali Sharif Razavian, Hossein Azizpour, Josephine Sullivan, and Stefan Carlsson. CNN features off-the-shelf: an astounding baseline for recognition. *CoRR*, abs/1403.6382, 2014.
- [21] John A. Richards. *Remote Sensing Digital Image Analysis, Fifth Edition*. Springer-Verlag Berlin Heidelberg, 2013.
- [22] Olaf Ronneberger, Philipp Fischer, and Thomas Brox. U-net: Convolutional networks for biomedical image segmentation. *CoRR*, abs/1505.04597, 2015.
- [23] G. J. Scott, M. R. England, W. A. Starns, R. A. Marcum, and C. H. Davis. Training deep convolutional neural networks for land-cover classification of high-resolution imagery. *IEEE Geoscience and Remote Sensing Letters*, 14(4):549–553, April 2017.
- [24] Brandt Tso and Paul M. Mather. *Classification methods for remotely sensed data*. CRC Press, Boca Raton, 2009.

- [25] Michael Xie, Neal Jean, Marshall Burke, David Lobell, and Stefano Ermon. Transfer learning from deep features for remote sensing and poverty mapping. *CoRR*, abs/1510.00098, 2015.
- [26] Jason Yosinski, Jeff Clune, Yoshua Bengio, and Hod Lipson. How transferable are features in deep neural networks? *CoRR*, abs/1411.1792, 2014.
- [27] X. Zhou and S. Prasad. Active and semisupervised learning with morphological component analysis for hyperspectral image classification. *IEEE Geoscience and Remote Sensing Letters*, 14(8):1348–1352, Aug 2017.