

Project: Image Analysis 2015/2016  
Anomaly Detection for Crop Monitoring

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# Chapter 1

## Scope

### 1.1 Problem

One of the most important tasks to be addressed in intelligent farms is the crop monitoring. Computer Vision and Machine Learning algorithms are typically combined to analyze and classify images acquired by autonomous robots that monitor the growth of crops, and in particular, to discriminate crops (i.e. the good plants) from weeds (any undesirable or unwanted plant growing wild, especially those that takes food or nourishment from crops). Crop/weed discrimination is often tackled as an image-classification problem.

### 1.2 Dataset

The dataset used in this project is the CWFID dataset<sup>1</sup>. It comprises field images, vegetation segmentation masks and crop/weed plant type annotations. The paper<sup>2</sup> provides details, e.g. on the field setting, acquisition conditions, image and ground truth data format. All images were acquired with the autonomous field robot Bonirob in an organic carrot farm while the carrot plants were in early true leaf growth stage.

### 1.3 Assignment

The assignment is to create a Convolutional Neural Network that classifies the images in crop, weed or ground.

---

<sup>1</sup><https://github.com/cwfid/dataset>

<sup>2</sup>see Appendix→Reference document

## Chapter 2

# Extract patches from the dataset

This work was done by two colleagues, Jorge Carpio Lopez de Castro and Andrea Luigi Edoardo Caielli, that work on the same project. Here is the code:

```
% IMAGE ANALYSIS - PROJECT 2015/2016
%
% Script for extracting from CWFID N random image patches centered
% on pixels which are marked in the ground truth as a given class.
% Patches can be extracted for testing or training. Training patches are
% extracted from the first 40 imgs. of the dataset. Testing patches come
% from the last 20.
%
% Requires the CWFID dataset to be downloaded and placed in the workspace.

warning('off', 'Images:initSize:adjustingMag');
close all, clear all
clc

%% Configurable parameters

N = 1000;           % Number of patches for each class.
psz = 51;           % Size of the sides of the patch [pixels].

option = 1;         % 1 for training patches (extracted from first 40 images),
                    % 0 for test patches (extracted from last 20).

se = strel('disk', 8); % Shape for the erosion of the center pixels for the patches.

%% Code

np = N * ones(1,3); % Overall number of remaining patches to be extracted
                    % for each class. One counter is not sufficient since
                    % not all images have information for all three classes.
classes = [1 1 1];  % Class selector for patch extraction
```

```

if option == 0      % Extracting set of patches for training
    n_im = 40;      % Number of images of the dataset for trai.
    bpath = 'patches\training\'; % Base path for folder
elseif option == 1 % Extracting set of patches for testing
    n_im = 20;      % Number of images of the dataset for test.
    bpath = 'patches\testing\'; % Base path for folder
else
    return;
end

mkdir(bpath);      % Create directories
mkdir(bpath, 'weed');
mkdir(bpath, 'crop');
mkdir(bpath, 'ground');

fs = ['%0' num2str(floor(log10(N))+1) 'd']; % Format string used for output
disp('Begin extracting random 51x51 patch images:')
str = [fs '\t' fs '\t' fs];
str2 = ['Remaining patches:\n\tweed\tcrop\tground\n\t' str];
fprintf(str2, np(1), np(2), np(3))

while(sum(np)) % while there are remaining patches
    rand_im_ix = randi(n_im,1,max(np));

    % Image numbers to get patches from.
    % This maintains randomness
    % minimizing image reads.

    imgs = zeros(1,n_im); % Number of patches / each image in
    % rand_im_ix

    for n = 1:max(np)
        imgs(rand_im_ix(n)) = imgs(rand_im_ix(n)) + 1;
    end

    for im = find(imgs)
        ann_path = strcat( 'dataset-1.0\annotations\', sprintf('%03d',im + 40*option),...
            '_annotation.png'); % Path for annotation file

        img_path = strcat( 'dataset-1.0\images\', sprintf('%03d',im + 40*option),...
            '_image.png'); % Path for image file

        A = imread( ann_path, 'png'); % Read annotation mask
        I = imread( img_path, 'png'); % Read corresponding image

        for n = 1:imgs(im) % Each iteration finds a new rand. 51x51 patch

            c = 1:3;
            classes = ~np; % Flags indicating remaining patches != 0
            for c = c(classes) % Main loop for each class (weed, crop, ground)

                switch c % Perform class-oriented operations
                    case 1
                        IMask = im2bw(A(:, :, 1)); % Binary mask (weed)
                        filename = [bpath 'weed\' sprintf(fs,np(c)) '_weed.png'];
                    case 2
                        IMask = im2bw(A(:, :, 2)); % Binary mask (crop)
                        filename = [bpath 'crop\' sprintf(fs,np(c)) '_crop.png'];

```

```

        otherwise
            % Binary mask (ground)
            IMask = ~(im2bw(A(:,:,1)) | im2bw(A(:,:,2)));
            filename = [bpath 'ground\' sprintf(fs,np(c)) '_ground.png'];
        end

Centers = IMask(ceil(psz/2):end-floor(psz/2),...
    ceil(psz/2):end-floor(psz/2)); % Possible center points
Centers = imerode(Centers,se); % Perform erosion
[y, x] = find(Centers); % x,y: coordinate arrays for nonzero elts.

if ~(isempty(y) || isempty(x)) % Then this image has
    % annotations for this class

    np(c) = np(c) - 1; % Decrement remaining patches
    p = randi(length(y)); % Index for (random again) center pix
    P = I(y(p):y(p)+psz-1, x(p):x(p)+psz-1, :); % Patch
    imwrite(P, filename, 'png');
end
end
for i = 1:2+3*floor(log10(N)+1), fprintf('\b'); end % Super stylish output
fprintf(str, np(1), np(2), np(3))
end
end
fprintf('\nDone!!\n')

```

This script creates a dataset of 1000 patches with dimension  $51 \times 51 \times 3$  for each class both for training and for testing. Later I splitted the testing dataset in two parts:

- first half of the patches for validation
- second half of patches for testing

## Chapter 3

# Training the network

### 3.1 MatConvNet library

In order to perform the given assignment I downloaded and installed MatConvNet library<sup>1</sup>. Note that in order to use some functionalities of the library, such as using GPU acceleration, it has some requirements<sup>2</sup>. If you don't know what a convolutional neural network is, there is also a manual<sup>3</sup> that explains all the blocks of a CNN both from the "mathematical" and "code function" view.

### 3.2 Build the architecture of the network

#### 3.2.1 Typical layer of a CNN

The typical layer of a Convolutional Neural Network are:

- **Convolutional layer:** it is the core building block of a Convolutional Network, and its output volume can be interpreted as holding neurons arranged in a 3D volume. The CONV layer's parameters consist of a set of learnable filters. Every filter is small spatially (along width and height), but extends through the full depth of the input volume. During the forward pass, we slide (more precisely, convolve) each filter across the width and height of the input volume, producing a 2-dimensional activation map of that filter. As we slide the filter, across the input, we are computing the dot product between the entries of the filter and the input. Intuitively, the network will learn filters that activate when they see some specific type of feature at some spatial position in the input. Stacking these activation maps for all filters along the depth dimension forms the full output volume. Every entry in the output volume can thus also be interpreted as an

---

<sup>1</sup><http://www.vlfeat.org/matconvnet/>

<sup>2</sup><http://www.vlfeat.org/matconvnet/gpu/>

<sup>3</sup><http://www.vlfeat.org/matconvnet/matconvnet-manual.pdf>



output of a neuron that looks at only a small region in the input and shares parameters with neurons in the same activation map (since these numbers all result from applying the same filter). Three hyperparameters control the size of the output volume: the **depth**, **stride** and **zero-padding**

- **Pooling Layer**: it is common to periodically insert a Pooling layer in-between successive Conv layers in a ConvNet architecture. Its function is to progressively reduce the spatial size of the representation to reduce the amount of parameters and computation in the network, and hence to also control overfitting. The Pooling Layer operates independently on every depth slice of the input and resizes it spatially, using the MAX operation. The most common form is a pooling layer with filters of size 2x2 applied with a stride of 2 downsamples every depth slice in the input by 2 along both width and height, discarding 75% of the activations. Every MAX operation would in this case be taking a max over 4 numbers (little 2x2 region in some depth slice). The depth dimension remains unchanged
- **Fully-connected layer**: neurons in a fully connected layer have full connections to all activations in the previous layer. Their activations can hence be computed with a matrix multiplication followed by a bias offset. In other libraries, fully connected blocks or layers are linear functions where each output dimension depends on all the input dimensions. MatConvNet does not distinguish between fully connected layers and convolutional blocks
- **ReLU**: the rectified linear unit will apply an elementwise activation function, such as the  $f(x) = \max(0, x)$  thresholding at zero. This leaves the size of the volume unchanged
- **SoftMax**: Soft Max is a loss function that makes the score compete through the normalization factor. Softmax can be seen as the combination of an activation function (exponential) and a normalization operator

### 3.2.2 Typical architecture

The most common form of a ConvNet architecture stacks a few CONV-RELU layers, follows them with POOL layers, and repeats this pattern until the image has been merged spatially to a small size. At some point, it is common to transition to fully-connected layers. The last fully-connected layer holds the output, such as the class scores. In other words, the most common ConvNet architecture follows the pattern:

$$INPUT \rightarrow [[CONV \rightarrow RELU] * N \rightarrow POOL?] * M \rightarrow [FC \rightarrow RELU] * K \rightarrow FC \rightarrow LOSS$$

where the \* indicates repetition, and the POOL? indicates an optional pooling layer. Moreover,  $N \geq 0$  (and usually  $N \leq 3$ ),  $M \geq 0$ ,  $K \geq 0$  (and usually  $K < 3$ ).

### 3.2.3 Selected architectures

I selected different network architectures for comparing it, after the training, with the testing set. The architectures are:

1.  $INPUT \rightarrow [CONV \rightarrow RELU \rightarrow POOL] * 2 \rightarrow FC \rightarrow RELU \rightarrow FC \rightarrow LOSS$
2.  $INPUT \rightarrow [CONV \rightarrow RELU \rightarrow POOL] * 3 \rightarrow FC \rightarrow LOSS$
3.  $INPUT \rightarrow [CONV \rightarrow RELU \rightarrow POOL] * 4 \rightarrow FC \rightarrow LOSS$
4.  $INPUT \rightarrow [CONV \rightarrow RELU \rightarrow POOL] * 3 \rightarrow FC \rightarrow LOSS$
5.  $INPUT \rightarrow [CONV \rightarrow RELU \rightarrow POOL] * 3 \rightarrow FC \rightarrow RELU \rightarrow FC \rightarrow LOSS$
6.  $INPUT \rightarrow [CONV \rightarrow RELU \rightarrow POOL] * 3 \rightarrow [FC \rightarrow RELU] * 2 \rightarrow FC \rightarrow LOSS$

Here is the code of the first architecture. The other architectures are in other matlab file, structured as `cnn_cwfid_init_number_of_the_network`.

```
%Function that creates the convolutional neural network
function net = cnn_cwfid_init_1(varargin)

%decide if you want to use batch normalization
opts.batchNormalization = true ;
%decide if you want to use simplenn or dagnn
opts.networkType = 'simplenn' ;
opts = vl_argparse(opts, varargin) ;

rng('default');
rng(0) ;

%create the network layers
f=1/100 ;
net.layers = {} ;
net.layers{end+1} = struct('name', 'convolution1',...
    'type', 'conv', ...
    'weights', {{f*randn(9,9,3,20, 'single'), zeros(1, 20, 'single')}}}, ...
    'stride', 1, ...
    'pad', 0) ;
net.layers{end+1} = struct('name','relu1','type','relu');
net.layers{end+1} = struct('name', 'pooling1',...
    'type', 'pool', ...
    'method', 'max', ...
    'pool', [2 2], ...
    'stride', 2, ...
    'pad', 0) ;
net.layers{end+1} = struct('name', 'convolution2',...
    'type', 'conv', ...
    'weights', {{f*randn(7,7,20,40, 'single'), zeros(1,40, 'single')}}}, ...
    'stride', 1, ...
```

```

                                'pad', 0) ;
net.layers{end+1} = struct('name','relu1','type','relu');
net.layers{end+1} = struct('name', 'pooling2',...
                            'type', 'pool', ...
                            'method', 'max', ...
                            'pool', [2 2], ...
                            'stride', 2, ...
                            'pad', 0) ;
net.layers{end+1} = struct('name', 'convolution3',...
                            'type', 'conv', ...
                            'weights', {{f*randn(7,7,40,200, 'single')},
zeros(1,200,'single')}}}, ...
                            'stride', 1, ...
                            'pad', 0) ;
net.layers{end+1} = struct('name','relu1','type','relu');
net.layers{end+1} = struct('name', 'convolution4',...
                            'type', 'conv', ...
                            'weights', {{f*randn(1,1,200,3, 'single')}, zeros(1,3,'single')}}}, ...
                            'stride', 1, ...
                            'pad', 0) ;
net.layers{end+1} = struct('name', 'loss','type', 'softmaxloss') ;

% optionally switch to batch normalization
if opts.batchNormalization
    net = insertBnorm(net, 1) ;
    net = insertBnorm(net, 5) ;
    net = insertBnorm(net, 9) ;
end

% Meta parameters
net.meta.inputSize = [51 51 3] ;
net.meta.trainOpts.learningRate = 0.001 ;
net.meta.trainOpts.numEpochs = 30 ;
net.meta.trainOpts.batchSize = 500 ;

% Fill in default values
net = vl_simplenn_tidy(net) ;

% Switch to DagNN if requested
switch lower(opts.networkType)
case 'simplenn'
    % done
case 'dagnn'
    net = dagnn.DagNN.fromSimpleNN(net, 'canonicalNames', true) ;
    net.addLayer('error', dagnn.Loss('loss', 'classerror'), ...
                {'prediction','label'}, 'error') ;
otherwise
    assert(false) ;
end

%Function that insert batch normalization
% -----
function net = insertBnorm(net, l)
% -----
assert(isfield(net.layers{1}, 'weights'));
ndim = size(net.layers{1}.weights{1}, 4);
layer = struct('type', 'bnorm', ...

```

```

        'weights', {{ones(ndim, 1, 'single'), zeros(ndim, 1, 'single')}}}, ...
        'learningRate', [1 1 0.05], ...
        'weightDecay', [0 0]) ;
net.layers{1}.biases = [] ;
net.layers = horzcat(net.layers(1:1), layer, net.layers(1+1:end)) ;

```

### 3.3 Train the network

In order to train the network I use this code that prepare the dataset, create the network and train it.

```

%This function create the network and train it with the CWFID dataset
function [net, info] = cnn.cwfid(varargin)

%setup MatConvNet
run(fullfile(fileparts(mfilename('fullpath')),...
    '..', '..', 'matlab', 'vl_setupnn.m')) ;

%Uncomment the line below if you want to use GPU
%vl.compilenn('enableGpu', true);

%batch normalization
opts.batchNormalization = true ;
%network type: simplenn or dagnn
opts.networkType = 'simplenn' ;
[opts, varargin] = vl.parse(opts, varargin) ;

%create the folder (bnorm if opts.batchNormalization = true
sfx = opts.networkType ;
if opts.batchNormalization, sfx = [sfx '-bnorm'] ; end
opts.expDir = fullfile(vl.rootnn, 'data', ['cwfid-baseline' sfx]) ;
[opts, varargin] = vl.parse(opts, varargin) ;
opts.dataDir = fullfile(vl.rootnn, 'data', 'cwfid') ;
opts.imdbPath = fullfile(opts.expDir, 'imdb.mat') ;
opts.train = struct() ;
opts = vl.parse(opts, varargin) ;
if ~isfield(opts.train, 'gpus'), opts.train.gpus = [] ; end;

% -----
%                                     Prepare data
% -----

%if you want to use a different network change the function name
%e.g. cnn.cwfid_init_1
%if you have already a folder with a trained network, please remove it
%before train
net = cnn.cwfid_init_5('batchNormalization', opts.batchNormalization, ...
    'networkType', opts.networkType) ;
imdb = getCwfidImdb(opts) ;
mkdir(opts.expDir) ;
save(opts.imdbPath, '-struct', 'imdb') ;

net.meta.classes.name = arrayfun(@(x) sprintf('%d',x),1:3,'UniformOutput',false) ;

```

```

% -----
%                                     Train
% -----

%switch to different training type depending the network type is simplenn
%or dagnn
switch opts.networkType
    case 'simplenn', trainfn = @cnn_train ;
    case 'dagnn', trainfn = @cnn_train_dag ;
end

[net, info] = trainfn(net, imdb, getBatch(opts), ...
    'expDir', opts.expDir, ...
    net.meta.trainOpts, ...
    opts.train);

% -----
function fn = getBatch(opts)
% -----
switch lower(opts.networkType)
    case 'simplenn'
        fn = @(x,y) getSimpleNNBatch(x,y) ;
    case 'dagnn'
        bopts = struct('numGpus', numel(opts.train.gpus)) ;
        fn = @(x,y) getDagNNBatch(bopts,x,y) ;
end

% -----
function [images, labels] = getSimpleNNBatch(imdb, batch)
% -----
images = imdb.images.data(:,:,batch) ;
labels = imdb.images.labels(1,batch) ;

% -----
function inputs = getDagNNBatch(opts, imdb, batch)
% -----
images = imdb.images.data(:,:,batch) ;
labels = imdb.images.labels(1,batch) ;
if opts.numGpus > 0
    images = gpuArray(images) ;
end
inputs = {'input', images, 'label', labels} ;

% -----
function imdb = getCwfidImdb(opts)
% -----
% Preapre the imdb structure
cropLabel = 1;
weedLabel = 2;
groundLabel = 3;

trainingDir = fullfile(opts.dataDir, 'training');
%only the first half of the testing images are using for validation
validationDir = fullfile(opts.dataDir, 'testing');

trainingCropDir = fullfile(trainingDir, 'crop');

```

```

trainingWeedDir = fullfile(trainingDir, 'weed');
trainingGroundDir = fullfile(trainingDir, 'ground');

validationCropDir = fullfile(validationDir, 'crop');
validationWeedDir = fullfile(validationDir, 'weed');
validationGroundDir = fullfile(validationDir, 'ground');

%get training crop images and labels
listing = dir(trainingCropDir);
listing=listing(~ismember({listing.name},{'.','..','Thumbs.db'}));
for i=1 : size(listing)
    cropImTraining(:,:,i)=imread(fullfile(trainingCropDir,listing(i).name));
    cropLabelTraining(i) = cropLabel;
end

%get training weed images and labels
listing = dir(trainingWeedDir);
listing=listing(~ismember({listing.name},{'.','..','Thumbs.db'}));
for i=1 : size(listing)
    weedImTraining(:,:,i)=imread(fullfile(trainingWeedDir,listing(i).name));
    weedLabelTraining(i) = weedLabel;
end

%get training ground images and labels
listing = dir(trainingGroundDir);
listing=listing(~ismember({listing.name},{'.','..','Thumbs.db'}));
for i=1 : size(listing)
    groundImTraining(:,:,i)=imread(fullfile(trainingGroundDir,listing(i).name));
    groundLabelTraining(i) = groundLabel;
end

%get validation crop images and labels
listing = dir(validationCropDir);
listing=listing(~ismember({listing.name},{'.','..','Thumbs.db'}));
for i=1 : (size(listing,1) - 500)
    cropImValidation(:,:,i)=imread(fullfile(validationCropDir,listing(i).name));
    cropLabelValidation(i) = cropLabel;
end

%get validation weed images and labels
listing = dir(validationWeedDir);
listing=listing(~ismember({listing.name},{'.','..','Thumbs.db'}));
for i=1 : (size(listing,1) - 500)
    weedImValidation(:,:,i)=imread(fullfile(validationWeedDir,listing(i).name));
    weedLabelValidation(i) = weedLabel;
end

%get validation ground images and labels
listing = dir(validationGroundDir);
listing=listing(~ismember({listing.name},{'.','..','Thumbs.db'}));
for i=1 : (size(listing,1) - 500)
    groundImValidation(:,:,i)=imread(fullfile(validationGroundDir,listing(i).name));
    groundLabelValidation(i) = groundLabel;
end

set = [ones(1,numel([cropLabelTraining weedLabelTraining groundLabelTraining]))...
    2*ones(1,numel([cropLabelValidation weedLabelValidation groundLabelValidation]))];

```

```

data = single(reshape(cat(4,cropImTraining,weedImTraining,groundImTraining,...
    cropImValidation,weedImValidation,groundImValidation),51,51,3,[]));
%subtract the data mean
dataMean = mean(data(:,:,set == 1), 4);
data = bsxfun(@minus, data, dataMean) ;

imdb.images.data = data ;
imdb.images.data_mean = dataMean;

imdb.images.data = data ;
imdb.images.labels = cat(2,cropLabelTraining,weedLabelTraining,groundLabelTraining,...
    cropLabelValidation,weedLabelValidation,groundLabelValidation) ;

imdb.images.set = set ;
imdb.meta.sets = {'train','val'} ;
imdb.meta.classes = arrayfun(@(x) sprintf('%d',x),1:3,'uniformoutput',false) ;

```

The code before uses another function that trains the network. This function is already implemented by the library. It is a learner implementing stochastic gradient descent with momentum to train the network. It can be used with different datasets and tasks by providing a suitable `getBatch` function (implemented in `cnn_cwfid.m`). The function automatically restarts after each training epoch by checkpointing. The function supports training on CPU or on one or more GPUs (specify the list of GPU IDs in the 'gpus' option). Multi-GPU support is relatively primitive but sufficient to obtain a noticeable speedup.

Here are the 6 networks training graph. On the left side there is the objective function and on the right side there is the error function.

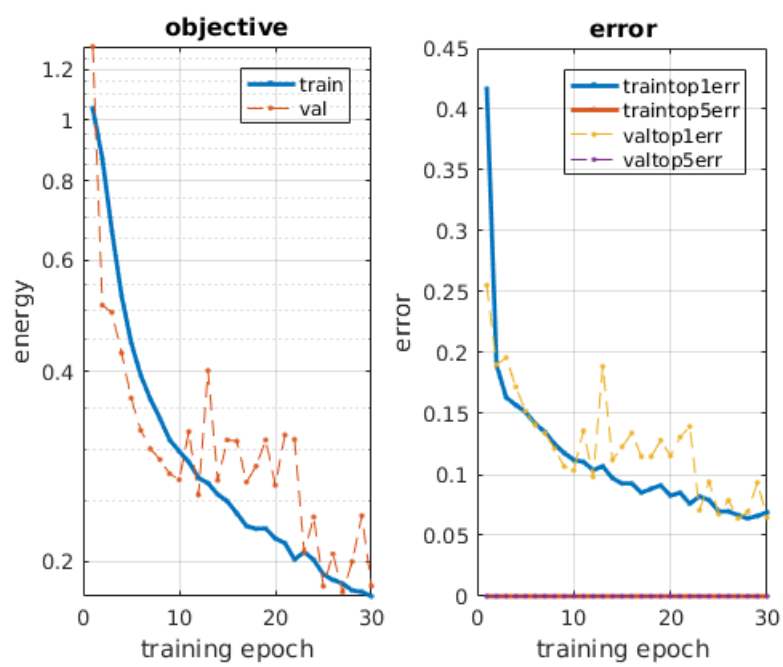


Figure 3.1: network 1 training



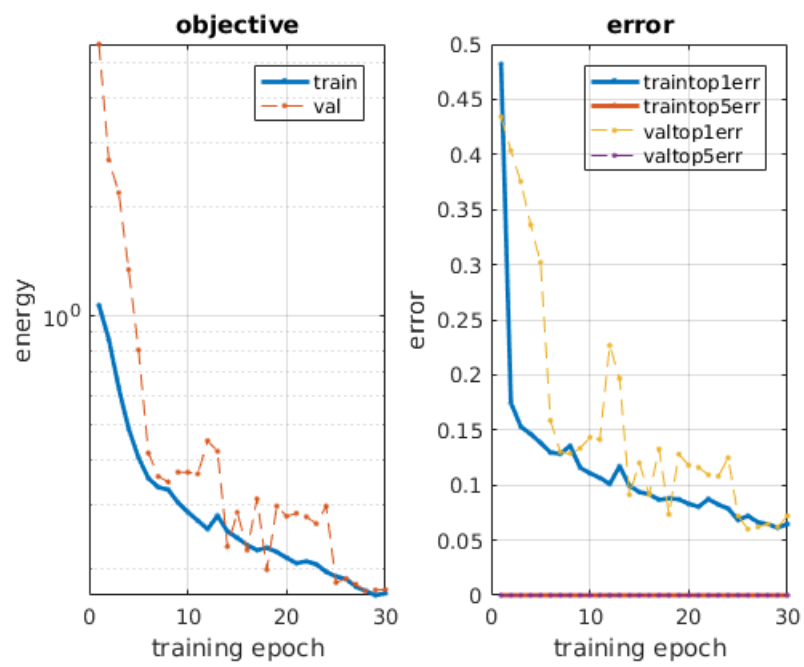


Figure 3.2: network 2 training

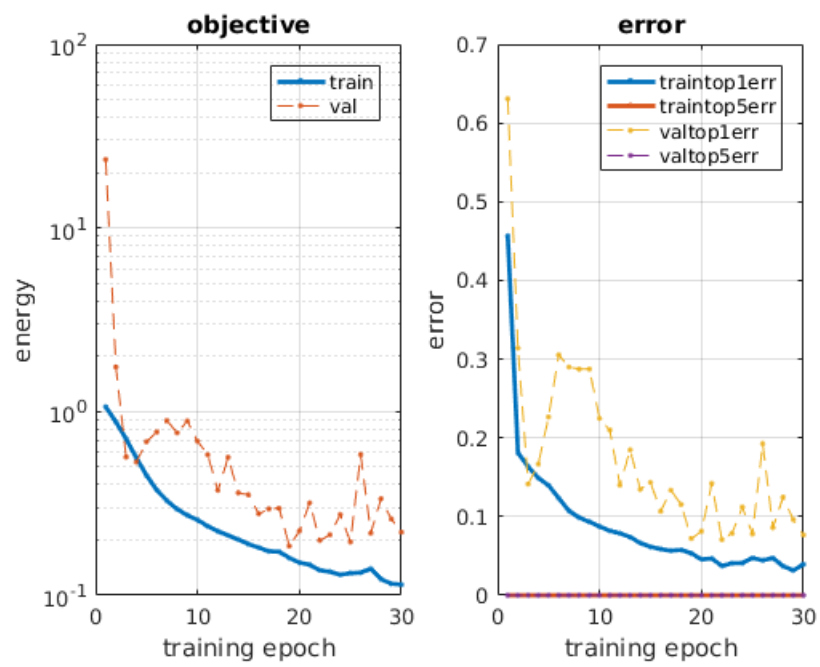


Figure 3.3: network 3 training

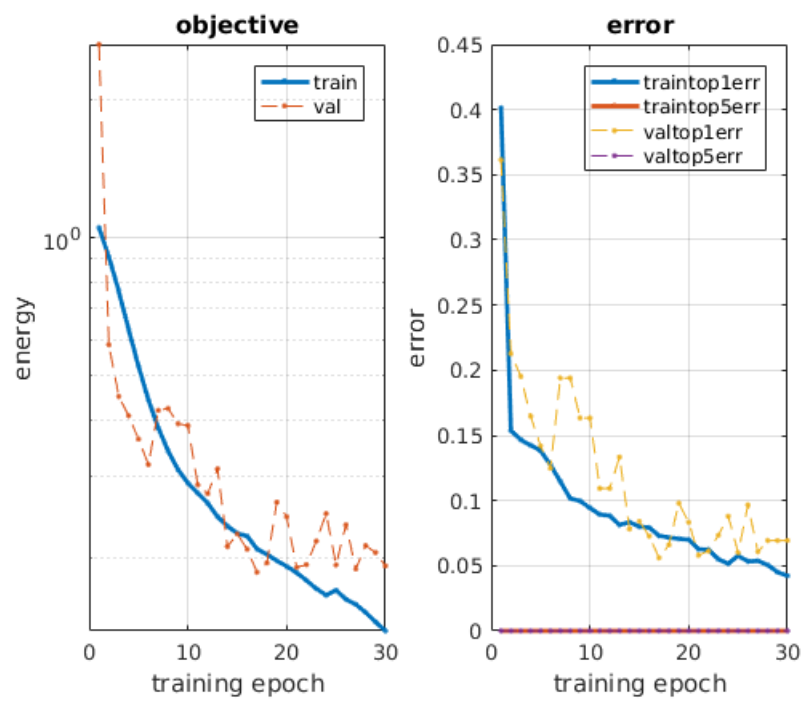


Figure 3.4: network 4 training

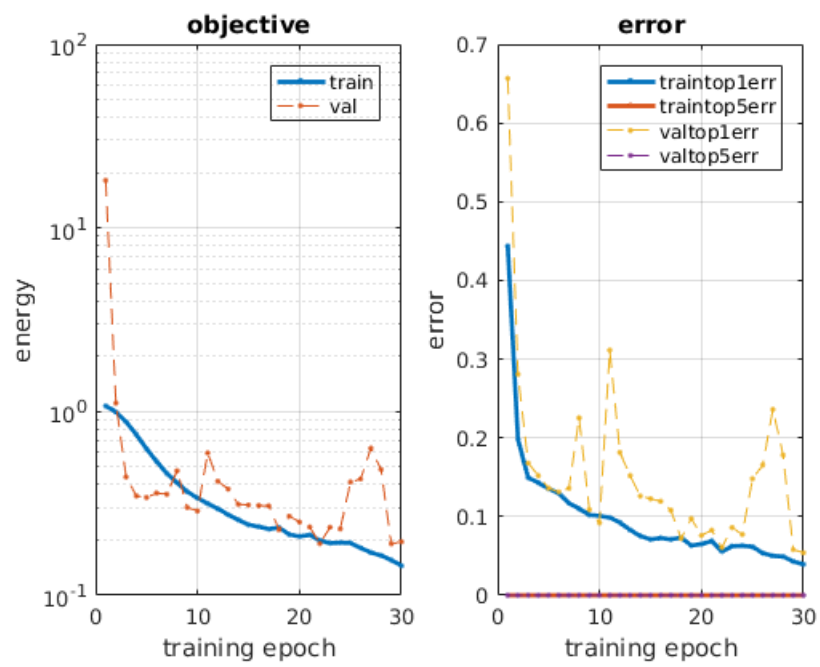


Figure 3.5: network 5 training

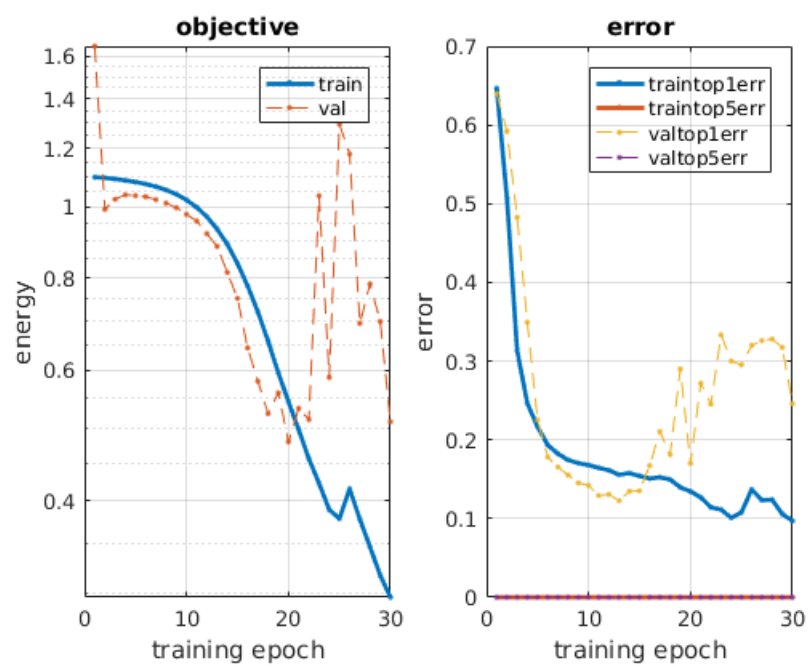


Figure 3.6: network 6 training

## Chapter 4

# Evaluate the network

### 4.1 Compute the accuracy of each network

Here is the code that I used in order to compute the accuracy of the network. It evaluates a training set that is composed, in order, of:

1. 500 crop patches
2. 500 weed patches
3. 500 ground patches

```
clear

% load the pre-trained CNN
net = cnn_cwfid();

testingDir = fullfile(vl_rootnn, 'data', 'cwfid', 'testing');
testingCropDir = fullfile(testingDir, 'crop');
testingWeedDir = fullfile(testingDir, 'weed');
testingGroundDir = fullfile(testingDir, 'ground');

%only the second half of the test images are using
%because the first half is for validation
%get testing crop images
listing = dir(testingCropDir);
listing=listing(~ismember({listing.name},{'.','..','Thumbs.db'}));
for i=1 : (size(listing,1) - 500)
    cropImTesting(:,:,i)=imread(fullfile(testingCropDir,listing(i+500).name));
end

%get testing weed images
listing = dir(testingWeedDir);
listing=listing(~ismember({listing.name},{'.','..','Thumbs.db'}));
for i=1 : (size(listing,1) - 500)
    weedImTesting(:,:,i)=imread(fullfile(testingWeedDir,listing(i+500).name));
end
```

```

%get testing ground images
listing = dir(testingGroundDir);
listing=listing(~ismember({listing.name},{'.','..','Thumbs.db'}));
for i=1 : (size(listing,1) - 500)
    groundImTesting(:, :, i)=imread(fullfile(testingGroundDir, listing(i+500).name));
end

%put the testing image all together
data = single(reshape(cat(4, cropImTesting, weedImTesting, groundImTesting), 51, 51, 3, []));

%remove last layer: softmax
net.layers{end}.type = 'softmax';

% run the CNN
res = vl_simplenn(net, data);

% get the classification result
scores = squeeze(gather(res(end).x)) ;
[bestScore, best] = max(scores) ;

%calculate accuracy
error = 0;
i = 1;
for j= 1:500
    if best(j) ~= i
        error= error+1;
    end
end

%accuracy Crop
accuracyCrop = 1-error/500;

error = 0;
i = 2;
for j= 501:1000
    if best(j) ~= i
        error= error+1;
    end
end

%accuracy weed
accuracyWeed = 1-error/500;

error = 0;
i = 3;
for j= 1001:1500
    if best(j) ~= i
        error= error+1;
    end
end

%accuracy ground
accuracyGround = 1-error/500;

%global accuracy of the network
accuracy = (accuracyCrop+accuracyWeed+accuracyGround)/3;

```

With this code for the 6 networks we have these results:

Network	Accuracy	Accuracy Crop	Accuracy Ground	Accuracy Weed
1	94,00%	92,80%	99,80%	89,40%
2	94,07%	95,60%	99,80%	86,80%
3	92,53%	92,20%	99,80%	85,60%
4	94,13%	93,00%	99,80%	89,60%
<b>5</b>	<b>94,20%</b>	<b>94,00%</b>	<b>99,80%</b>	<b>88,80%</b>
6	92,33%	93,60%	99,80%	83,60%

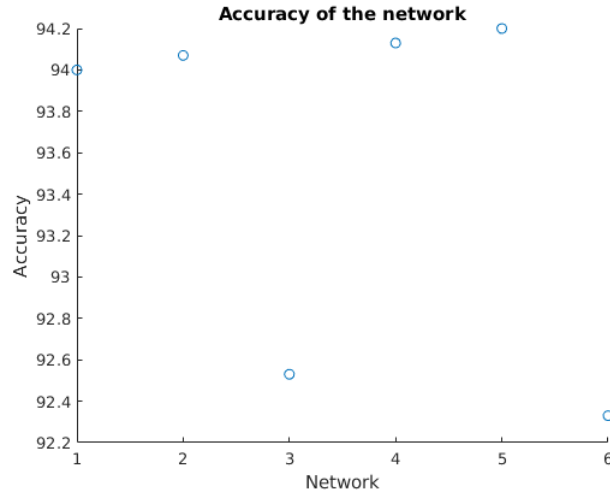


Figure 4.1: accuracy of the networks

The network that has the highest accuracy is network 5. From now on I will discuss and talk about network 5 only because it has the best performance.

## 4.2 Changing the number of maps of each convolutional filter

Once the network has been selected I tried to change the number of maps of each convolutional filter in order to increase the accuracy. Here are some combination of number of maps that I used and the correspondent accuracy.



Filter 1	Filter 2	Filter 3	Filter 4	Accuracy
10	20	40	80	94,20%
15	30	60	120	92,60%
<b>8</b>	<b>16</b>	<b>32</b>	<b>64</b>	<b>94,33%</b>
7	14	28	56	93,73%
9	18	36	72	93,20%
12	24	48	96	92,53%

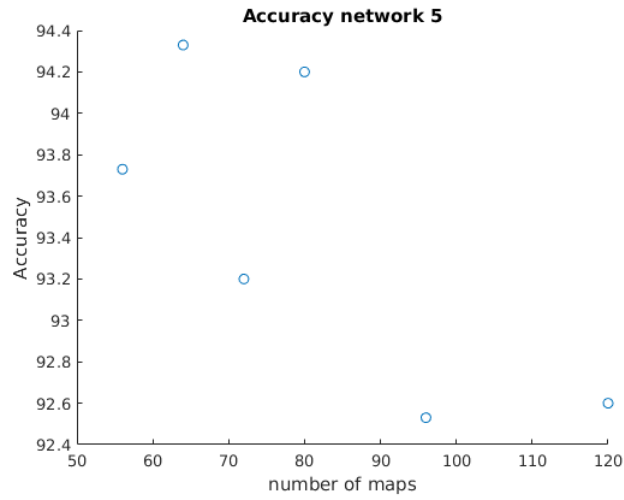


Figure 4.2: accuracy VS number of maps; only the number of maps of the last filter layer is plotted in the graph

This is the training graph with a better combination of number of maps. This configuration is the final one that I used for the given assignment and has a global accuracy of **94,33%** **94,20%** for crop **99,80%** for ground and **89,00%** for weed.

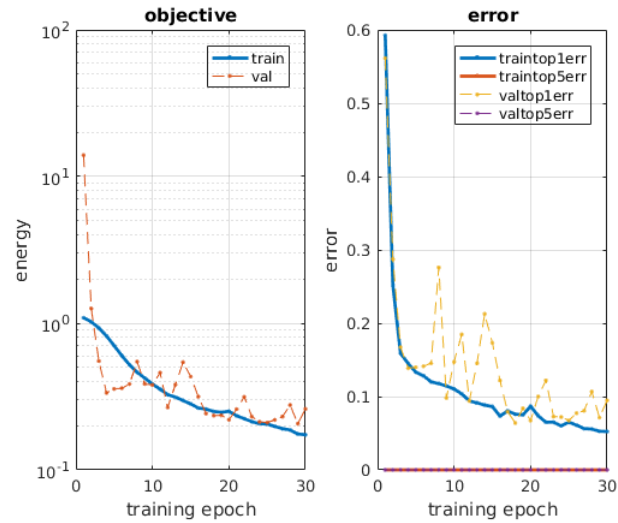


Figure 4.3: final training

### 4.3 Sliding window approach

In order to have a rough segmentation of the training set I also used to evaluate the network the sliding window approach. The code below shows how the approach was implemented. It use a stride of 10 and calculate for each image test the accuracy and the confusion matrix. The ground truth that I used to calculate these metrics was included into the CWFID dataset.

```
close all
clear
clc

%define the size of the patches
dim = 51;
%define the stride of the sliding window
stride = 10;
%crop = 1, weed = 2, ground = 3
crop = 1;
weed = 2;
ground = 3;

% load the pre-trained CNN
net = cnn.cwfid();
%remove last layer: softmax
net.layers{end}.type = 'softmax';
net.mode = 'test';
```

```

testingDir = fullfile(vl_rootnn, 'data', 'cwfid', 'testing');
testingSlidingWindowDir = fullfile(testingDir, 'sliding window');
annotationDir = fullfile(testingDir, 'annotation');

listing = dir(testingSlidingWindowDir);
listing=listing(~ismember({listing.name},{'.','..','Thumbs.db'}));
%get the testing image
for i=1 : size(listing,1)
    slidingWindowImTesting(:, :, i)=imread(fullfile(testingSlidingWindowDir, listing(i).name));
end

listing = dir(annotationDir);
listing=listing(~ismember({listing.name},{'.','..','Thumbs.db'}));
%get the annotation image
for i=1 : size(listing,1)
    AnnotationIm(:, :, i)=imread(fullfile(annotationDir, listing(i).name));
end

%for all the images
for i=1 : size(slidingWindowImTesting,4)
    cont1 = 1;
    for j=1 : stride : (size(slidingWindowImTesting,2)-dim)
        for k=1 : stride : (size(slidingWindowImTesting,1)-dim)
            %get the patches
            im(:, :, :, cont1) = single(ismcrops(slidingWindowImTesting(:, :, :, i), ...
                [j,k,dim-1,dim-1]));
            cont1 = cont1+1;
        end
    end

    %subtract the data mean
    dataMean = mean(im(:, :, :, 3));
    im = bsxfun(@minus, im, dataMean);
    %evaluates the patches
    res = vl_simplenn(net, im);
    scores = squeeze(gather(res(end).x));
    [bestScore, best] = max(scores);

    I = reshape(best, int16((size(slidingWindowImTesting,1)-dim)/stride), ...
        int16((size(slidingWindowImTesting,2)-dim)/stride));
    Icrop = reshape(scores(crop, :), int16((size(slidingWindowImTesting,1)-dim)/stride), ...
        int16((size(slidingWindowImTesting,2)-dim)/stride));
    Icrop = imresize(Icrop, [size(slidingWindowImTesting,1), size(slidingWindowImTesting,2)]);
    Iweed = reshape(scores(weed, :), int16((size(slidingWindowImTesting,1)-dim)/stride), ...
        int16((size(slidingWindowImTesting,2)-dim)/stride));
    Iweed = imresize(Iweed, [size(slidingWindowImTesting,1), size(slidingWindowImTesting,2)]);
    Iground = reshape(scores(ground, :), int16((size(slidingWindowImTesting,1)-dim)/stride), ...
        int16((size(slidingWindowImTesting,2)-dim)/stride));
    Iground = imresize(Iground, [size(slidingWindowImTesting,1), size(slidingWindowImTesting,2)]);

    %create an image with the best class with color: crop=green weed=red
    %ground=black
    for s=1 : size(I,1)
        for v=1 : size(I,2)
            if I(s,v) == crop
                Im((s-1)*stride+1:s*stride, (v-1)*stride+1:v*stride,1) = 0;
                Im((s-1)*stride+1:s*stride, (v-1)*stride+1:v*stride,2) = 255;
            end
        end
    end
end

```

```

        Im((s-1)*stride+1:s*stride, (v-1)*stride+1:v*stride,3) = 0;
    end
    if I(s,v) == weed
        Im((s-1)*stride+1:s*stride, (v-1)*stride+1:v*stride,1) = 255;
        Im((s-1)*stride+1:s*stride, (v-1)*stride+1:v*stride,2) = 0;
        Im((s-1)*stride+1:s*stride, (v-1)*stride+1:v*stride,3) = 0;
    end
    if I(s,v) == ground
        Im((s-1)*stride+1:s*stride, (v-1)*stride+1:v*stride,1) = 0;
        Im((s-1)*stride+1:s*stride, (v-1)*stride+1:v*stride,2) = 0;
        Im((s-1)*stride+1:s*stride, (v-1)*stride+1:v*stride,3) = 0;
    end
end
end

figure
subplot(3,2,1)
imshow(slidingWindowImTesting(:, :, :, i));
title('original')
subplot(3,2,2)
imshow(AnnotationIm(:, :, :, i));
title('annotation')
subplot(3,2,3)
imshow(Im)
title('best')
subplot(3,2,4)
imagesc(Icrop), colorbar
title('crop')
subplot(3,2,5)
imagesc(Iweed), colorbar
title('weed')
subplot(3,2,6)
imagesc(Iground), colorbar
title('ground')

%get the label from annotation and the predicted class
cont = 0;
for s = 1 : size(Im,1)
    for v = 1 : size(Im,2)
        cont= cont+1;
        if AnnotationIm(s,v,1,i) == 255
            label(cont)= weed;
        else if AnnotationIm(s,v,2,i) == 255
            label(cont)= crop;
        else
            label(cont)= ground;
        end
    end
    if Im(s,v,1) == 255
        predicted(cont)= weed;
    else if Im(s,v,2) == 255
        predicted(cont)= crop;
    else
        predicted(cont)= ground;
    end
end
end
end

```

```
end

%calculate confusion matrix
C = confusionmat(label,predicted);
Accuracy = (C(1,1)+C(2,2)+C(3,3)) / (C(1,1)+C(1,2)+C(1,3)+C(2,1)+C(2,2)...
+C(2,3)+C(3,1)+C(3,2)+C(3,3));

end
```

## Chapter 5

# Summary and future extensions

## Chapter 6

# Appendix

### 6.1 Reference document

- [http://rd.springer.com/chapter/10.1007%2F978-3-319-16220-1\\_8](http://rd.springer.com/chapter/10.1007%2F978-3-319-16220-1_8)

### 6.2 Software and tool used

- LaTeX (<http://www.latex-project.org/>) : to redact and to format this document
- Matlab R2016a (<http://uk.mathworks.com/products/matlab/>) : to compute and evaluate the network
- MatConvNet (<http://www.vlfeat.org/matconvnet/>) : MATLAB toolbox implementing Convolutional Neural Networks (CNNs)