



Solution Guide II-D

Classification



How to use classification, Version 12.0.2

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About This Manual

In a broad range of applications classification is suitable to find specific objects or detect defects in images. This Solution Guide leads you through the variety of approaches that are provided by HALCON.

After a short introduction to the general topic in [section 1](#) on page 9, a first example is presented in [section 2](#) on page 13 that gives an idea on how to apply a classification with HALCON.

[Section 3](#) on page 17 then provides you with the basic theories related to the available approaches. Some hints how to select the suitable classification approach, a set of features that is used to define the class boundaries, and some samples that are used for the training of the classifier are given in [section 4](#) on page 29.

[Section 5](#) on page 33 describes how to generally apply a classification for various objects like pixels or regions based on various features like color, texture, or region features. [Section 6](#) on page 67 shows how to apply classification for a pure pixel-based image segmentation and [section 7](#) on page 93 provides a short introduction to the classification for optical character recognition (OCR). For the latter regions are classified by region features.

Finally, [section 8](#) on page 115 provides some general tips that may be suitable when working with complex classification tasks.

The HDevelop example programs that are presented in this Solution Guide can be found under the directory into which the HDevelop example programs have been installed. The path to this directory can be determined with the operator call `get_system ('example_dir', ExampleDir)`.

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Chapter 1

Introduction

What is classification?

Classifying an object means to assign an object to one of several available classes. When working with images, the objects usually are pixels or regions. Objects are described by features, which comprise, e.g., the color or texture for pixel objects, and the size or specific shape features for region objects. To assign an object to a specific class, the individual class boundaries have to be known. These are built in most cases by a training using the features of sample objects for which the classes are known. Then, when classifying an unknown object, the class with the largest correspondence between the feature values used for its training and the feature values of the unknown object is returned.

What can you do with classification?

Classification is reasonable in all cases where objects have similarities, but within unknown variations. If you search for objects of a certain fixed shape, and the points of a found contour may not deviate from this shape more than a small defined distance, a template matching will be faster and easier to apply. But if the shapes of your objects are similar, but you can not define exactly what the similarities are and what distinguishes these objects from other objects in the image, you can show a classifier some samples of known objects (with a set of features that you roughly imagine to describe the characteristics of the object types) and let the classifier find the rules to distinguish between the object types. Classification can be used for a lot of different tasks. You can use classification, e.g., for

- image segmentation, i.e., you segment images into regions of similar color or texture,
- object recognition, i.e., you find objects of a specific type within a set of different object types,
- quality control, i.e., you decide if objects are good or bad,
- novelty detection, i.e., you detect changes or defects of objects, or
- optical character recognition (OCR).

What can HALCON do for you?

To solve the different requirements on classification, HALCON provides different types of classifiers. The most important HALCON classifiers are

- a classifier that uses neural nets, in particular multi-layer perceptrons (MLP, see [section 3.3](#) on page 20),
- a classifier that is based on support-vector machines (SVM, see [section 3.4](#) on page 22),
- a classifier that is based on Gaussian mixture models (GMM, see [section 3.5](#) on page 24), and
- a classifier that is based on the k-nearest neighbors (k-NN, see [section 3.6](#) on page 26).
- Furthermore, for image segmentation also some simple but fast classifiers are available. These comprise a classifier that segments two-channel images based on the corresponding 2D histogram (see [section 6.2](#) on page 87), a hyperbox classifier, and a classifier that can be applied using either a Euclidean or a hyperbox metric (see [section 3.2](#) on page 19 and [section 6.3](#) on page 88).

For specific classification tasks, specific sets of HALCON operators are available. We distinguish between the three following basic tasks:

- You can apply a general classification. Here, arbitrary objects like pixels or regions are classified based on arbitrary features like color, texture, shape, or size. [Section 5](#) on page 33 shows how to apply the suitable operators for MLP, SVM, GMM, and k-NN classification.
- You can apply classification for image segmentation. Here, the classification is used to segment images into regions of different classes. For that, the individual pixels of an image are classified due to the features color or texture and all pixels belonging to the same class are combined in a region. [Section 6](#) on page 67 shows how to apply the suitable operators for MLP, SVM, GMM, and k-NN classification ([section 6.1](#) on page 67) as well as for some simple but fast classifiers that segment the images using the 2D histogram of two image channels ([section 6.2](#) on page 87) or that apply an Euclidean or hyperbox classification ([section 6.3](#) on page 88).
- You can apply classification for OCR, i.e., individual regions are investigated with regard to region features and assigned to classes that typically (but not necessarily) represent individual characters or numbers. [Section 7](#) on page 93 shows how to apply the suitable operators for MLP, SVM, and k-NN classification.

What are the basic steps of a classification with HALCON?

The basic approach for a classification with HALCON is as follows:

1. First, some sample objects, i.e., objects of known classes, are investigated. That is, a set of characteristic features is extracted from each sample object and stored in a so-called feature vector (explicitly by the user or implicitly by a specific operator).
2. The feature vectors of many sample objects are used to train a classifier. With the training, the classifier derives suitable boundaries between the classes.

3. Then, unknown objects, i.e., the objects to classify, are investigated with the help of the same set of features that was already used for the training samples. This step leads to feature vectors for the unknown objects.
4. Finally, the trained classifier uses the class boundaries that were derived during the training to decide for the new feature vectors to which classes they belong.

What information do you find in this solution guide?

This manual provides you with

- basic theoretical background for the provided classifiers ([section 3](#) on page 17),
- tips for the decision making, in particular tips for the selection of a suitable classification approach, the selection of suitable features that describe the objects to classify, and the selection of suitable training samples ([section 4](#) on page 29),
- guidance for the practical application of classification for general classification ([section 5](#) on page 33), image segmentation ([section 6](#) on page 67), and OCR ([section 7](#) on page 93), and
- additional tips that may be useful when applying classification ([section 8](#) on page 115). In particular, tips how to adjust the most critical parameters, tips how to use OCR for the classification of arbitrary regions, and tips how to visualize the feature space for 2D and 3D feature vectors are provided.

What do you have to consider before classifying?

Note that the decision which classifier to use for a specific application is a challenging task. There are no fixed rules which approach works better for which application, as the number of possible fields of applications is very large. At least, [section 4.1](#) on page 29 provides some hints about the advantages and disadvantages of the individual approaches.

Additionally, if you have decided to use a specific classifier, it is not guaranteed that you get a satisfying result within a short time. Actually, in almost any case you have to apply a lot of tests with different parameters until you get the result you aimed at. Classification is very complex! So, plan enough time for your application.

Chapter 2

A First Example

This section shows a first example for a classification that classifies metal parts based on selected shape features. To follow the example actively, start the HDevelop program `solution_guide\classification\classify_metal_parts.hdev`; the steps described below start after the initialization of the application.

Step 1: Create classifier

First, a classifier is created. Here, we want to apply an MLP classification, so a classifier of type MLP is created with `create_class_mlp`. The returned handle `MLPHandle` is needed for all following classification steps.

```
create_class_mlp (6, 5, 3, 'softmax', 'normalization', 3, 42, MLPHandle)
```

Step 2: Add training samples to the classifier

Then, the training images, i.e., images that contain objects of known class, are investigated. Each image contains several metal parts that belong to the same class. The index of the class for a specific image is stored in the tuple `Classes`. In this case, nine images are available (see [figure 2.1](#)). The objects in the first three images belong to class 0, the objects of the next three images belong to class 1, and the last three images show objects of class 2.

```
FileNames := ['nuts_01','nuts_02','nuts_03','washers_01','washers_02', \
              'washers_03','retainers_01','retainers_02','retainers_03']
Classes := [0,0,0,1,1,1,2,2,2]
```

Now, each training image is processed by the two procedures `segment` and `add_samples`.

```
for J := 0 to |FileNames| - 1 by 1
    read_image (Image, 'rings/' + FileNames[J])
    segment (Image, Objects)
    add_samples (Objects, MLPHandle, Classes[J])
endfor
```

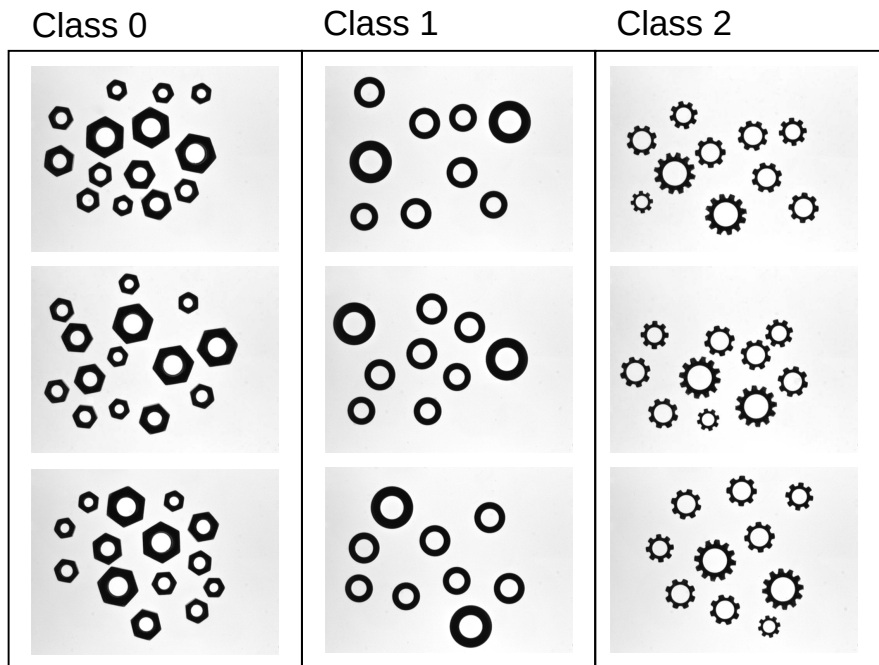


Figure 2.1: Training images.

The procedure `segment` segments and separates the objects that are contained in the image using a simple blob analysis (for blob analysis see Solution Guide I, [chapter 4](#) on page 45).

```

procedure segment (Image, Regions)
  binary_threshold (Image, Region, 'max_separability', 'dark', UsedThreshold)
  connection (Region, ConnectedRegions)
  fill_up (ConnectedRegions, Regions)
  return ()

```

For each region, the procedure `add_samples` determines a feature vector using the procedure `get_features`. The feature vector and the known class index build the training sample, which is added to the classifier with the operator `add_sample_class_mlp`.

```

procedure add_samples (Regions, MLPHandle, Class)
  count_obj (Regions, Number)
  for J := 1 to Number by 1
    select_obj (Regions, Region, J)
    get_features (Region, Features)
    add_sample_class_mlp (MLPHandle, Features, Class)
  endfor
  return ()

```

The features extracted in the procedure `get_features` are region features, in particu-

lar the 'circularity', 'roundness', and the four moments (obtained by the operator `moments_region_central_invar`) of the region.

```
procedure get_features (Region, Features)
select_obj (Region, SingleRegion, 1)
circularity (SingleRegion, Circularity)
roundness (SingleRegion, Distance, Sigma, Roundness, Sides)
moments_region_central_invar (SingleRegion, PSI1, PSI2, PSI3, PSI4)
Features := [Circularity, Roundness, PSI1, PSI2, PSI3, PSI4]
return ()
```

Step 3: Train the classifier

After adding all available samples, the classifier is trained with `train_class_mlp` and the samples are removed from memory with `clear_samples_class_mlp`.

```
train_class_mlp (MLPHandle, 200, 1, 0.01, Error, ErrorLog)
clear_samples_class_mlp (MLPHandle)
```

Step 4: Classify new objects

Now, images with different unknown objects are investigated. The segmentation of the objects and the extraction of their feature vectors is realized by the same procedures that were used for the training images (`segment` and `get_features`). But this time, the class of a feature vector is not yet known and has to be determined by the classification. Thus, opposite to the procedure `add_samples`, within the procedure `classify` the extracted feature vector is used as input to the operator `classify_class_mlp` and not to `add_sample_class_mlp`. The result is the class index that is suited best for the feature vector extracted for the specific region.

```
for J := 1 to 4 by 1
  read_image (Image, 'rings/mixed_' + J$'02d')
  segment (Image, Objects)
  classify (Objects, MLPHandle, Classes)
  disp_obj_class (Objects, Classes)
endfor
```

```
procedure classify (Regions, MLPHandle, Classes)
count_obj (Regions, Number)
Classes := []
for J := 1 to Number by 1
  select_obj (Regions, Region, J)
  get_features (Region, Features)
  classify_class_mlp (MLPHandle, Features, 1, Class, Confidence)
  Classes := [Classes, Class]
endfor
return ()
```

For a visual check of the result, the procedure `disp_obj_class` displays each region with a specific color that depends on the class index (see [figure 2.2](#)).

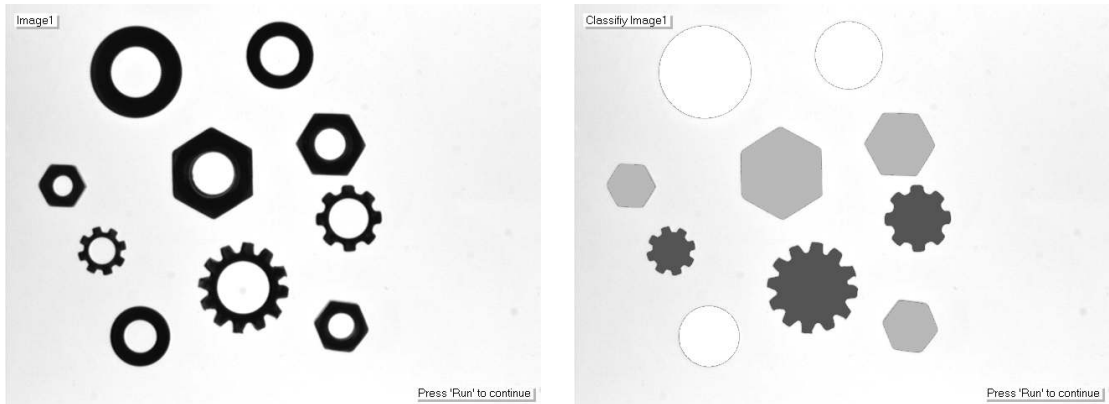


Figure 2.2: Classifying metal parts because of their shape: (left) image with metal parts, (right) metal parts classified into three classes (illustrated by different gray values).

```

procedure disp_obj_class (Regions, Classes)
count_obj (Regions, Number)
Colors := ['yellow','magenta','green']
for J := 1 to Number by 1
    select_obj (Regions, Region, J)
    dev_set_color (Colors[Classes[J - 1]])
    dev_display (Region)
endfor
return ()

```

Step 5: Destroy the classifier

At the end of the program, the classifier is destroyed.

```

clear_class_mlp (MLPHandle)

```


Chapter 3

Classification: Theoretical Background

This section introduces you to the basics of classification ([section 3.1](#)) and the specific classifiers that can be applied with HALCON. In particular, the Euclidean and hyperbox classifiers ([section 3.2](#)), the classifier based on multi-layer perceptrons (neural nets, [section 3.3](#)), the classifier based on support-vector machines ([section 3.4](#)), the classifier based on Gaussian mixture models ([section 3.5](#)), and the classifier based on k-nearest neighbors ([section 3.6](#)) are introduced.

3.1 Classification in General

Generally, a classifier is used to assign an object to one of several available classes. For example, you have gray value images containing citrus fruits. You have extracted regions¹ from the images and each region represents a fruit. Now, you want to separate the oranges from the lemons. To distinguish the fruits, you can apply a classification. Then, the extracted regions of the fruits are your objects and the task of the classification is to decide for each region if it belongs to the class 'oranges' or to the class 'lemons'.

For the decision to which class a region belongs you need knowledge about the differences between the classes and the similarities within each individual class. This knowledge can be obtained by analyzing typical features of the objects to classify. Given the example with the citrus fruits (the actual program is described in more detail in [section 8.3.1](#) on page 119), suitable features can be, e.g., the 'area' (an orange is in most cases bigger than a lemon) and the shape, in particular the 'circularity' of the regions (the outline of an orange is closer to a circle than that of a lemon). [Figure 3.1](#) shows some oranges and lemons for which the regions are extracted and the region features 'area' and 'circularity' are calculated.

The features are arranged in an array that is called feature vector. The features of the feature vector span a so-called feature space, i.e., a vector space in which each feature is represented by an axis. Generally,

¹How to extract regions from images is described, e.g., in Solution Guide I, [chapter 4](#) on page 45

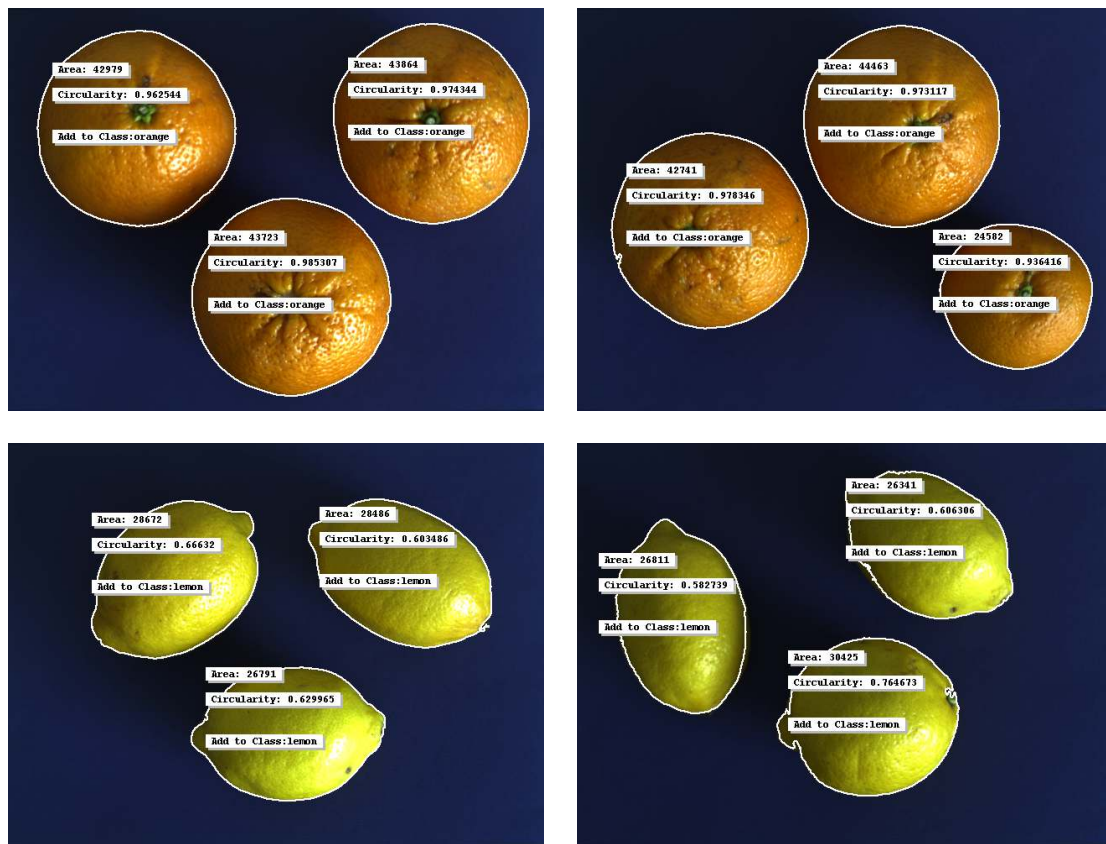


Figure 3.1: Region features of oranges and lemons are extracted and can be added as samples to the classifier.

a feature space can have any dimension, depending on the number of features contained in the feature vector. For visualization purpose, here a 2D feature space is shown. In practice, feature spaces of higher dimension are very common.

In [figure 3.2](#) the feature vectors of the fruits shown in [figure 3.1](#) are visualized in a 2D graph, for which one axis represents the 'area' values and the other axis represents the 'circularity' values. Although the regions vary in size and circularity, we can see that they are similar enough to build clusters. The goal of a classifier is to separate the clusters and to assign each feature vector to one of the clusters. Here, the oranges and lemons can be separated, e.g., by a straight line. All objects on the lower left side of the line are classified as lemons and all objects on the upper right side of the line are classified as oranges.

As we can see, the feature vector of a very small orange and that of a rather circular lemon are close to the separating line. With a little bit different data, e.g., if the small orange additionally would be less circular, the feature vectors may be classified incorrectly. To minimize errors, a lot of different samples and in many cases also additional features are needed. An additional feature for the citrus fruits may be, e.g., the gray value. Then, not a line but a plane is needed to separate the clusters. If color images

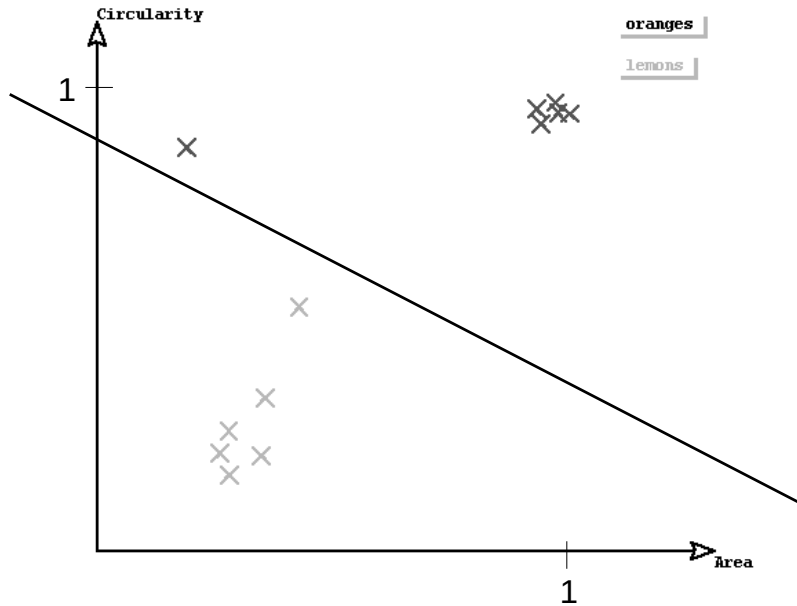


Figure 3.2: The normalized values for the 'area' and 'circularity' of the fruits span a feature space. The two classes can be separated by a line.

are available, you can combine the area and the circularity with the gray values of three channels. For feature vectors of more than three features, an n -dimensional plane, also called hyperplane, is needed.

Classifiers that use separating lines or hyperplanes are called linear classifiers. Other classifiers, i.e., non-linear classifiers, can separate clusters using arbitrary surfaces and may be able to separate clusters more conveniently in some cases.

Summarized, we need a suitable set of features and we have to select the classifier that is suited best for a specific classification application. To select the most appropriate approach, we have to know some basics about the available classifiers and the algorithms they use.

3.2 Euclidean and Hyperbox Classifiers

One of the simple classifiers is the Euclidean or minimum distance classifier. With HALCON, the Euclidean classification is available for image segmentation, i.e., the objects to classify are pixels and the feature vectors contain the gray values of the pixels. The dimension of the feature space depends on the number of channels used for the image segmentation. Geometrically interpreted, this classifier builds circles (in 2D; see [figure 3.3a](#)) or n -dimensional hyperspheres (in n D) around the cluster centers to separate the clusters from each other. In [section 6.3](#) on page 88 it is described how to apply the Euclidean classifier for image segmentation. With HALCON, the Euclidean metric is used only for image segmentation, not for the classification of general features or OCR. This is because the approach is stable only

for feature vectors of low dimension.

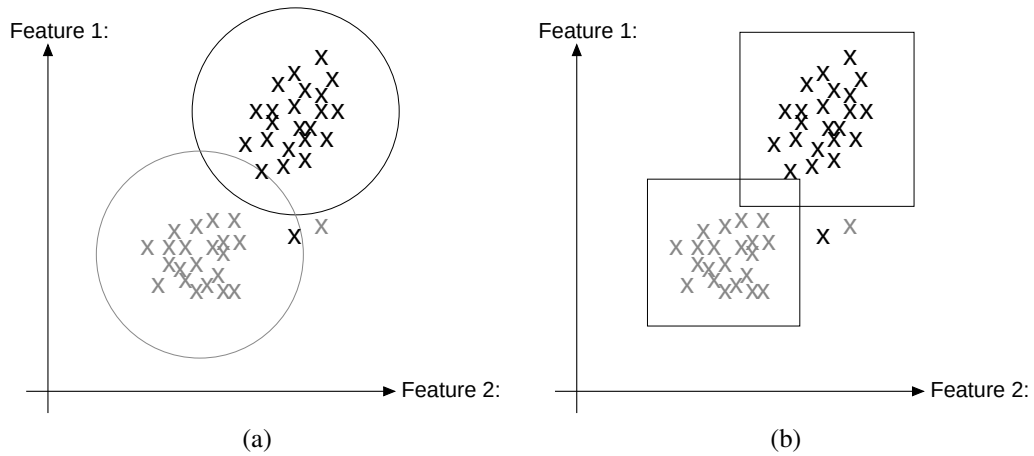


Figure 3.3: (a) Euclidean classifier and (b) hyperbox classifier.

Whereas the Euclidean classifier uses n -dimensional spheres, the hyperbox approach uses axis-parallel cubes, so-called hyperboxes (see [figure 3.3b](#)). This can be imagined as a threshold approach in multidimensional space. That is, for each class specific value ranges for each axis of the feature space are determined. If a feature vector lies within all the ranges of a specific class, it will be assigned to this class. The hyperboxes can overlap. For objects that are ambiguous, the hyperbox approach can be combined with another classification approach, e.g., an Euclidean classification or a maximum likelihood classification. Within HALCON, the Euclidean distance is used and additionally weighted with the variance of the feature vector. In [section 6.3](#) on page 88 it is described how to apply the hyperbox classifier for image segmentation.

HALCON provides also operators for hyperbox classification of general features as well as for OCR, but these show almost no advantage but a lot of disadvantages compared to the MLP, SVM, GMM, and k-NN approaches, and thus are not described further in this solution guide.

3.3 Multi-Layer Perceptrons (MLP)

Neural nets directly determine the separating hyperplanes between the classes. For two classes the hyperplane actually separates the feature vectors of the two classes, i.e., the feature vectors that lie on one side of the plane are assigned to class 1 and the feature vectors that lie on the other side of the plane are assigned to class 2. In contrast to this, for more than two classes the planes are chosen such that the feature vectors of the correct class have the largest positive distance of all feature vectors from the plane.

A linear classifier can be built, e.g., using a neural net with a single layer like shown in [figure 3.4 \(a,b\)](#). There, so-called processing units (neurons) first compute the linear combinations of the feature vectors and the network weights and then apply a nonlinear activation function.

A classification with single-layer neural nets needs linearly separable classes, which is not sufficient in many classification applications. To get a classifier that can separate also classes that are not linearly sep-

arable, you can add more layers, so-called hidden layers, to the net. The obtained multi-layer neural net (see figure 3.4, c) then consists of an input layer, one or several hidden layers and an output layer. Note that one hidden layer is sufficient to approximate any separating hypersurface and any output function with values in $[0,1]$ as long as the hidden layer has a sufficient number of processing units.

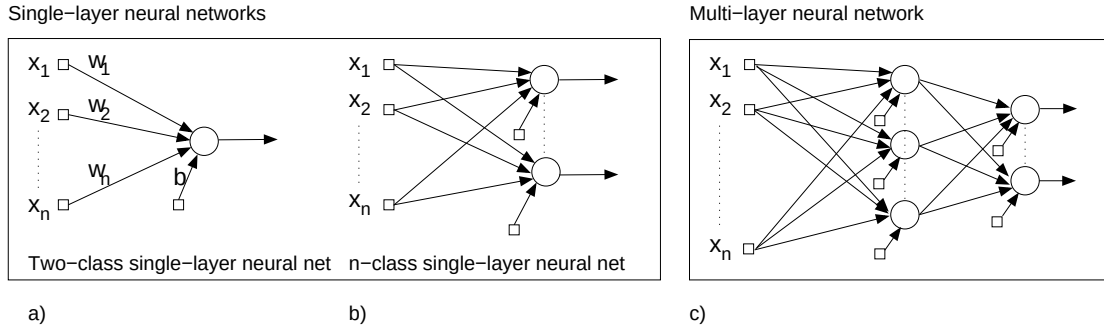


Figure 3.4: Neural networks: single-layered for (a) two classes and (b) n classes, (c) multi-layered: (from left to right) input layer, hidden layer, output layer.

Within the neural net, the processing units of each layer (see figure 3.5) compute the linear combination of the feature vector or of the results from a previous layer. That is, each processing unit first computes its activation as a linear combination of the input values:

$$a_j^{(l)} = \sum_{i=1}^{n_l} w_{ij}^{(l)} x_i^{(l-1)} + b_j^{(l)}$$

with

- x_i^0 : feature vector
- $x_i^{(j)}$: result vector of layer l
- $w_{ji}^{(l)}$ and $b_j^{(l)}$: weights of layer l

Then the results are passed through a nonlinear activation function:

$$x_j^{(l)} = f(a_j^{(l)})$$

With HALCON, for the hidden units the activation function is the hyperbolic tangent function:

$$f(x) = \tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$$

For the output function (when using the MLP for classification) the softmax activation function is used:

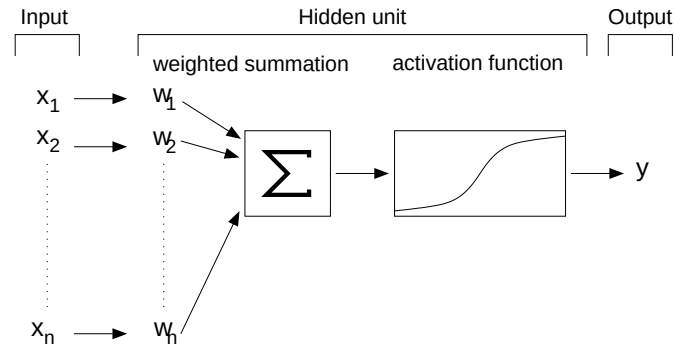


Figure 3.5: Processing unit of an MLP.

$$f(x) = \frac{e^{x_i}}{\sum_{j=1}^n e^{x_j}}$$

To derive the separating hypersurfaces for a classification using a multi-layer neural net, the network weights have to be adjusted. This is done by a training. That is, data with known output is inserted to the input layer and processed by the hidden units. The output is then compared to the expected output. If the output does not correspond to the expected output (within a certain error tolerance), the weights are incrementally adjusted so that the error is minimized. Note that the weight adjustment using HALCON is realized by a very stable numeric algorithm that leads to better results than obtained by the classical back propagation algorithm.

MLP works for classification of general features, image segmentation, and OCR. Note that MLP can be used also for least squares fitting (regression) and for classification problems with multiple independent logical attributes.

3.4 Support-Vector Machines (SVM)

Another classification approach that can handle classes that are not linearly separable uses support-vector machines (SVM). Here, no non-linear hypersurface is obtained, but the feature space is transformed into a space of higher dimension, so that the features become linearly separable. Then, the feature vectors can be classified with a linear classifier.

In [figure 3.6](#), e.g., two classes in a 2D feature space are illustrated by black and white squares, respectively. In the 2D feature space, no line can be found that separates the classes. When adding a third dimension by deforming the plane built by Feature1 and Feature2, the classes become separable by a plane.

To avoid the curse of dimensionality (see [section 3.5](#) on page 24) for SVM, not the features but a kernel is transformed. The challenging task is to find the suitable kernel to transform the feature space into a higher dimension so that the black squares in [figure 3.6](#) go up and the white ones stay in their place (or

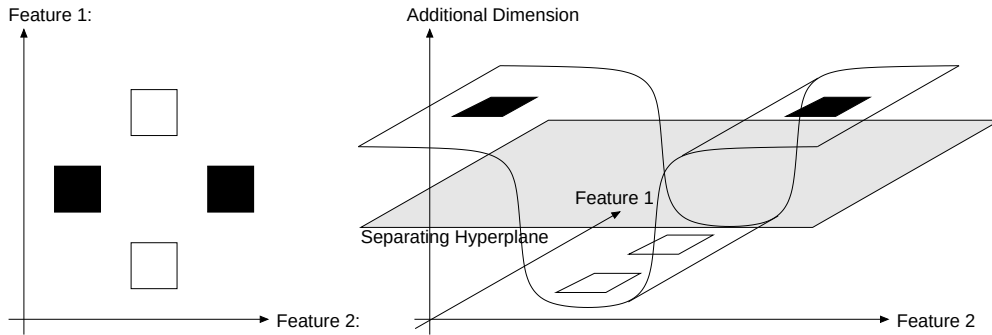


Figure 3.6: Separate two classes (black and white squares): (left) In the 2D feature space the classes can not be separated by a straight line, (right) by addition of a further dimension, the classes become linearly separable.

at least stay in another value range of the axis for the additional dimension). Common kernels are, e.g., the inhomogeneous polynomial kernel or the Gaussian radial basis function kernel.

With SVM, the separating hypersurface for two classes is constructed such that the margin between the two classes becomes as large as possible. The margin is defined as the closest distance between the separating hyperplane and any training sample. That is, several possible separating hypersurfaces are tested and the surface with the largest margin is selected. The training samples from both classes that have exactly the closest distance to the hypersurface are called 'support vectors' (see [figure 3.7](#) for two linearly separable classes).

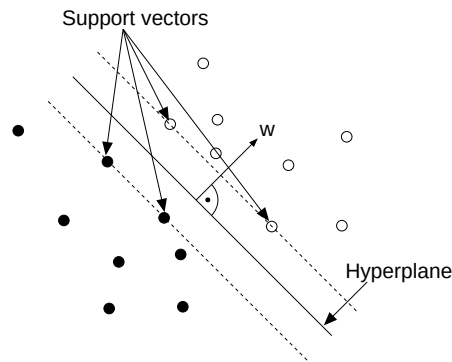


Figure 3.7: Support vectors are those feature vectors that have exactly the closest distance to the hyperplane.

By nature SVM can handle only two-class problems. Two approaches can be used to extend the SVM to a multi-class problem: With the first approach pairs of classes are built and for each pair a binary classifier is created. Then, the class that wins most of the comparisons is the best suited class. With the second approach, each class is compared to the rest of the training data and then, the class with the maximum distance to the hypersurface is selected (see also [section 5.4.1](#) on page 50).

SVM works for classification of general features, image segmentation, and OCR.

3.5 Gaussian Mixture Models (GMM)

The theory for the classification with Gaussian mixture models (GMM) is a bit more complex. One of the basic theories when dealing with classification comprises the Bayes decision rule. Generally, the Bayes decision rule tells us to minimize the probability of erroneously classifying a feature vector by maximizing the probability for the feature vector x to belong to a class. This so-called 'a posteriori probability' should be maximized over all classes. Then, the Bayes decision rule partitions the feature space into mutually disjoint regions. The regions are separated by hypersurfaces, e.g., by points for 1D data or by curves for 2D data. In particular, the hypersurfaces are defined by the points in which two neighboring classes are equally probable.

The Bayes decision rule can be expressed by

$$P(w_i|x) = \frac{P(x|w_i) \times P(w_i)}{P(x)}$$

with

- $P(w_i|x)$: a posteriori probability
- $P(x|w_i)$: a priori probability that the feature vector x occurs given that the class of the feature vector is w_i
- $P(w_i)$: Probability, that the class w_i occurs
- $P(x)$: Probability that the feature vector x occurs

For classification, the a posteriori probability should be maximized over all classes. Here, we coarsely show how to obtain the a posteriori probability for a feature vector x . First, we can remark that $P(x)$, i.e., the probability of the class, is a constant if x exists.

The first problem of the Bayes classifier is how to obtain $P(w_i)$, i.e., the probability of the occurrence of a class. Two strategies can be followed. First, you can estimate it from the used training set. This is recommended only if you have a training set that is representative not only with regard to the quality of the samples but also with regard to the frequency of the individual classes inside the set of samples. As this strategy is rather uncertain, a second strategy is recommended in most cases. There, it is assumed that each class has the same probability to occur, i.e., $P(w_i)$ is set to $1/m$ with m being the number of available classes.

The second problem of the Bayes classifier is how to obtain the a priori probability $P(x|w_i)$. In principle, a histogram over all feature vectors of the training set can be used. The apparent solution is to subdivide each dimension of the feature space into a number of bins. But as the number of bins grows exponentially with the dimension of the feature space, you face the so-called 'curse of dimensionality'. That is, to get a good approximation for $P(x|w_i)$, you need more memory than can be handled properly. With another solution, instead of keeping the size of a bin constant and varying the number of samples in the bin, the number of samples k for a class w_i is kept constant while varying the volume of the region in space around the feature vector x that contains the k samples ($v(x, w_i)$). The volume depends on the k nearest neighbors of the class w_i , so the solution is called k nearest-neighbor density estimation. It has

the disadvantage that all training samples have to be stored with the classifier and the search for the k nearest neighbors is rather time-consuming. Because of that, it is seldom used in practice. A solution that can be used in practice assumes that $P(x|w_i)$ follows a certain distribution, e.g., a normal distribution. Then, you only have to estimate the two parameters of the normal distribution, i.e., the mean vector μ_i and the covariance matrix Σ_i . This can be achieved, e.g., by a maximum likelihood estimator.

In some cases, a single normal distribution is not sufficient, as there are large variations inside a class. The character 'a', e.g., can be represented by 'a' or 'a', which have significantly different shapes. Nevertheless, both belong to the same character, i.e., to the same class. Inside a class with large variations, a mixture of l_i different densities exists. If these are again assumed to be normal distributed, we have a Gaussian mixture model. Classifying with a Gaussian mixture model means to estimate to which specific mixture density a sample belongs. This is done by the so-called expectation minimization algorithm.

Coarsely spoken, the GMM classifier uses probability density functions of the individual classes and expresses them as linear combinations of Gaussian distributions (see [figure 3.8](#)). Comparing the approach to the simple classification approaches described in [section 3.2](#) on page 19, you can imagine the GMM to construct n-dimensional error (covariance) ellipsoids around the cluster centers (see [figure 3.9](#)).

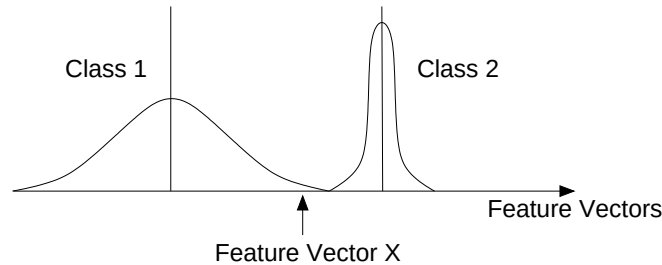


Figure 3.8: The variance of class 1 is significantly larger than that of class 2. In such a case, the distance to the Gauss error distribution curve is a better criteria for the class membership than the distance to the cluster center.

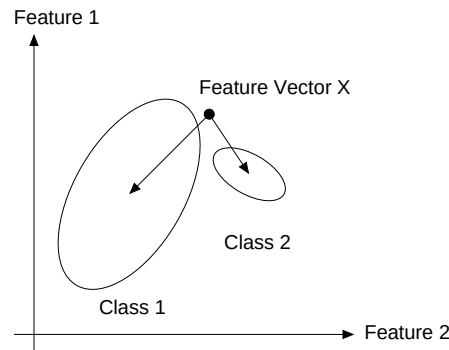


Figure 3.9: The feature vector X is nearer to the error ellipse of class 1 although the distance to the cluster center of class 1 is larger than the distance to the cluster center of class 2.

GMM are reliable only for low dimensional feature vectors (approximately up to 15 features), so HALCON provides GMM only for the classification of general features and image segmentation, but not for

OCR. Typical Applications are image segmentation and novelty detection. Novelty detection is specific for GMM and means that feature vectors that do not belong to one of the trained classes can be rejected. Note that novelty detection can also be applied with SVM, but then a specific parameter has to be set and only two-class problems can be handled, i.e., a single class can be trained and the feature vectors that do not belong to that single class are rejected.

There are two general approaches for the construction of a classifier. First, you can estimate the a posteriori probability from the a priori probabilities of the different classes (statistical approach), which we have introduced here for classification with the GMM classifier. Second, you can explicitly construct the separating hypersurfaces between the classes (geometrical approach). This can be realized in HALCON either with a neural net using multi-layer perceptrons (see [section 3.3](#) on page 20) or with support-vector machines (see [section 3.4](#) on page 22).

3.6 K-Nearest Neighbors (k-NN)

K-Nearest Neighbors (k-NN) is a simple yet powerful approach that stores the features and classes of all given training data and classifies each new sample based on its k-nearest neighbors in the training data.

The following example illustrates the basic principle of k-NN classification. Here, a two dimensional feature space is used, i.e., each training sample consists of two feature values and a class label (see [figure 3.10](#)). The two classes A and B are represented by three training samples, each. We can now use the training data to classify the new sample N. For this, the k-nearest neighbors of N are determined in the training data.

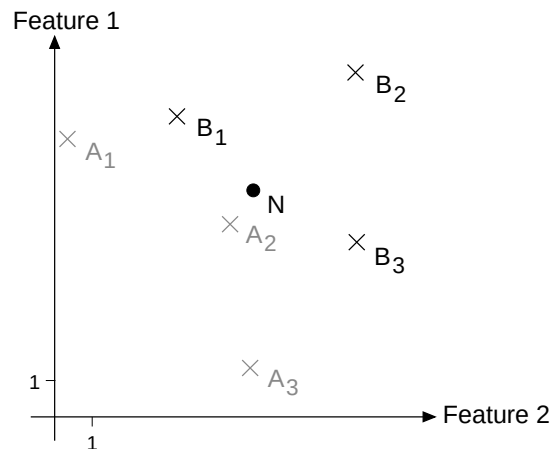


Figure 3.10: Example for k-NN classification. Class A is represented by the three samples A_1 , A_2 , and A_3 , and class B is represented by the three samples B_1 , B_2 , and B_3 . The class of the new sample N is to be determined with k-NN classification.

If we are using $k=1$, only the nearest neighbor of N is determined and we can directly assign its class label to the new sample. Here, the training sample A_2 is closest to N. Therefore, the new sample N is classified as being of class A.

In case k is set to a value larger than 1, the class of the new sample N must be derived from its k -nearest neighbors in the training data. The two approaches, which are most frequently used for this task, are a simple majority vote and a weighted majority vote that takes into account the distances to the k nearest neighbors.

For example, if we are using $k=3$, we need to determine the three nearest neighbors of N . In the above example, the distances from N to the training samples are:

	Distance
A_1	5.2
A_2	1.1
A_3	4.7
B_1	2.8
B_2	4.2
B_3	3.1

Thus, the three nearest neighbors of N are A_2 , B_1 , and B_3 .

A simple majority vote would assign class B to the new sample N , because two of the three nearest neighbors of N belong to the class B.

The weighted majority vote takes into account the distances from N to the k -nearest neighbors. In the example, class A would be assigned to N , because N lies very close to A_2 and significantly further away from B_1 and B_3 .

Despite the simplicity of this approach, k -NN typically yields very good classification results. One big advantage of the k -NN classifier is that it works directly on the training data, which leads to a blazingly fast training step. Due to this, it is especially well suited for testing various configurations of training data. Furthermore, newly available training data can be added to the classifier at any time. However, the classification itself is slower than, e.g., the MLP classification, and the k -NN classifier may consume a lot of memory because it contains the complete training data.

Chapter 4

Decisions to Make

This section gives you some hints how to select a suitable classification approach ([section 4.1](#)), the suitable features that build the feature vectors ([section 4.2](#) on page 31), and the suitable training samples ([section 4.3](#) on page 32). Note that only some hints but no absolute rules can be given for almost all decisions that are related to classification, as the best suited approach, features, and samples depend strongly on the specific application.

4.1 Select a Suitable Classification Approach

In most cases, we recommend to use either the MLP, SVM, GMM, or k-NN classifier, as these classification approaches are the most powerful and flexible ones. In [table 4.1](#), the characteristics of these four classification approaches are put together in a very brief way.

Based on the requirements and restrictions imposed by your application, you can use [table 4.1](#) to select the best suited classification approach. If you are not satisfied with the quality of the classification results, it is typically not because of the chosen classifier but because of the used features or because of the quality and amount of the training samples. Only if you are sure that the training data describes all the relevant characteristics of the objects to be classified, it is worth to test if another classifier may produce better results.

For image segmentation, the four classification approaches MLP, SVM, GMM, and k-NN can be sped up significantly using a look-up table (see [section 6.1.7](#) on page 84). But note that the so-called LUT-accelerated classification is only suitable for images with a maximum of three channels. Furthermore, LUT-accelerated classification leads to a slower offline phase and to higher memory requirements.

- The **MLP classifier** is especially well suited for applications that require a fast classification but allow for a slow offline training phase. The complete training data should be available right from the beginning because otherwise the time consuming training must be repeated from scratch. MLP classification does not support novelty detection.
- The **SVM classifier** may often be tuned to achieve a slightly higher classification quality than the other classifiers. But the classification speed is typically significantly slower than that of the

	MLP	SVM	GMM	k-NN
Training speed	slow	medium	fast	fast
Classification speed	fast	medium	fast	medium
Highest classification speed is reached for (besides having a low dimensional feature space)	low number of hidden nodes and classes	low number of support vectors ¹	low number of classes	low number of training samples
Memory requirements (after removing the training samples from the classifier)	low	medium	low	high ²
Use of additional training data is possible without the need to retrain the whole classifier from scratch	no	not recommended	not recommended	yes
Suited for high dimensional feature spaces	yes	yes	no	yes
Suited for novelty detection	no	yes	yes	yes

¹The number of support vectors can be reduced with `reduce_class_svm` or `reduce_ocr_class_svm`

²The training samples cannot be removed from the k-NN classifier

Table 4.1: Comparison of the characteristics of the four classifiers MLP, SVM, GMM, and k-NN.

MLP classifier. The training of the SVM classifier is substantially faster than that of the MLP classifier, but it is typically too slow for being used in the online phase. The SVM classifier requires significantly more memory than the MLP classifier, while it requires less memory than the k-NN classifier. Typically, the memory requirements rise with the number of training samples, i.e., for classification tasks with a huge number of training samples, like OCR, the SVM classifier may become very large.

- The **GMM classifier** is very fast both in training and classification, especially if the number of classes is low. It is also very well suited for novelty detection. However it is restricted to applications that do not require a high dimensional feature space.
- The **k-NN classifier** is especially well suited to test various configurations of features and training data because the training of a k-NN classifier is very fast and it has no restrictions concerning the dimensionality of the feature space. Furthermore, the classifier can be extended with additional training data very quickly. Note that the k-NN classification is typically slower than the MLP classification and it requires substantially more memory, which might be prohibitive in some applications.
- The **classifier based on a 2D histogram** is suitable for the pixel-based image segmentation of two-channel images. It provides a very fast alternative if a 2D feature vector is sufficient for the classification task.
- The **hyperbox and Euclidean classifiers** are suitable for feature vectors of low dimension, e.g., when applying a color classification for image segmentation. Especially for classes that are built by rather compact clusters, they are very fast. Compared to a LUT-accelerated classification using

MLP, SVM, GMM, or k-NN, the storage requirements are low and the feature space can easily be visualized.

4.2 Select Suitable Features

The features that are suitable for a classification strongly depend on the specific application and the objects that have to be classified. Thus, no fixed rules for their selection can be provided. For each application, you have to individually decide, which features describe the object best. Generally, the following features can be used for the different classification tasks:

- For a **general classification** all types of features, i.e., region features as well as color or texture, can be used to build the feature vectors. The feature vectors have to be explicitly built by feature values that are derived with a set of suitable operators.
- For **image segmentation**, the pixel values of a multi-channel color or texture image are used as features. Here, you do not have to explicitly extract the feature vectors as they are derived automatically by the corresponding image segmentation operators from the color or texture image.
- For **OCR**, a restricted set of region features is used to build the feature vectors. Here, you do not have to explicitly calculate the features but select the feature types that are implicitly and internally calculated by the corresponding OCR specific operators. The dimension of the resulting feature vector is equal or larger than the number of selected feature types, as some feature types lead to several feature values (see [section 7.6](#) on page 111 for the list of available features).

If your objects are described best by texture, you can follow different approaches. You can, e.g., create a texture image by applying the operator `texture_laws` with different parameters and combining the thus obtained individual channels into a single image, e.g., using `compose6` for a texture image containing six channels. Another common approach is to use, e.g., the operator `cooc_feature_image` to calculate texture features like energy, correlation, homogeneity, and contrast. We refer to Solution Guide I, [chapter 14](#) on page 207 for further information about texture.

If your objects are described best by region features, you can use any of the operators that are described in the Reference Manual in section Regions/Features. For OCR, the set of available region features is restricted to the set of features introduced in [section 7.6](#) on page 111.

HDevelop provides convenience procedures (see `calculate_features`) to calculate multiple features with given properties like rotational invariance, etc. in just a few calls. Additionally, HALCON offers functionality to select suitable features automatically using the operators `select_feature_set_mlp`, `select_feature_set_svm`, `select_feature_set_gmm`, and `select_feature_set_knn`. If you are not sure which features to choose, you can use the HDevelop example programs `hdevelop/Classification/Feature-Selection/auto_select_region_features.hdev` and `hdevelop/Applications/Object-Recognition-2D/classify_pills_auto_select_features.hdev` as a starting point, which make use of both, the procedures and the automatic feature selection.

4.3 Select Suitable Training Samples

In [section 1](#) on page 9 we learned that classification is reasonable in all cases where objects have similarities, but within undefined variations. To learn the similarities and variations, the classifier needs representative samples. That is, the samples should not only show the significant features of the objects to classify but should also show a large variety of allowed deviations. That is, if an object is described by a specific texture, small deviations from the texture that are caused, e.g., by noise, should be covered by the samples. Or if an object is described by a region having a specific size and orientation, the samples should contain several objects that deviate from both 'ideal' values within a certain tolerance. Otherwise, only objects that exactly fit to the 'ideal' object are found in the later classification. In other words, the classifier has no sufficient generalization ability.

Generally, for the training of a classifier a large amount of samples with a realistic set of variations for the calculated features should be provided for every available class. Otherwise, the result of the later classification may be unsatisfying as the unknown objects show deviations from the trained data that were not considered during the training. Nevertheless, if for any reason no sufficient number of samples can be provided, some tricks can be applied:

- One trick is to generate artificial samples by copying the few available samples and slightly modifying them. The modifications depend on the object to classify and the features used to find the class boundaries. When working with texture images, e.g., noise can be added to slightly modify the copies of the samples. Or given the example with the objects of a specific size and orientation, you can modify copies of the samples by, e.g., slightly changing their size using an erosion or dilation. And you can change their orientation by rotating the image by different, but small angles. Ideally, you create several copies and modify them so that several deviations in all allowed directions are covered.
- A second trick can be applied if the number of samples is unequally distributed for the different classes. For example, you want to apply classification for quality inspection and you have a large amount of samples for the good objects, but only a few samples for each of several error classes. Then, you can split the classification task into two classification tasks. In the first instance, you merge all error classes into one class, i.e., you have reduced the multi-class problem to a two-class problem. You have now a class with good objects and the rejection class contains all erroneous objects, which in the sum are represented by a larger number of samples. Then, if the type of error attached to the rejected objects is of interest, you apply a second classification, this time without the lot of good examples. That is, you only use the samples of the different error classes for the training and classify the objects that were rejected during the first classification into one of these error classes.

Chapter 5

Classification of General Features

This section shows how to apply the different classifiers to general features, i.e., arbitrary objects like pixels or regions are classified due to arbitrary features like color, texture, shape, or size. In contrast to the image segmentation approach described in [section 6](#) on page 67, which classifies only pixels, or the OCR approach in [section 7](#) on page 93, which classifies regions with focus on optical character recognition, here pixels as well as regions can be classified.

The general approach for a classification of arbitrary features, i.e., the sequence of operators used for the individual approaches is similar for the MLP, SVM, GMM, and k-NN classification. In [section 5.1](#), the general approach is illustrated by an example, which checks the quality of halogen bulbs using shape features. In [section 5.2](#), the steps of a classification and the involved operators are listed for a brief overview. The parameters used for the operators are in many cases specific to the individual approach because of the different underlying algorithms (see [section 3](#) on page 17 for the theoretical background). They are introduced in more detail in [section 5.3](#) for MLP, [section 5.4](#) for SVM, [section 5.5](#) for GMM, and [section 5.6](#) for k-NN.

5.1 General Approach

The general approach is similar for MLP, SVM, GMM, and k-NN classification (see [figure 5.1](#)). In all cases, a classifier with specific properties is created. Then, known objects are investigated, i.e., you extract the features of objects for which the classes are known and add the feature vectors together with the corresponding known class ID to the classifier. With a training, the classifier then derives the rules for the classification, i.e., it decides how to separate the classes from each other. To investigate unknown objects, i.e., to classify them, you extract the same set of features for them that was used for the training, and classify the feature vectors with the trained classifier. Finally, you clear the classifier from memory.

In the following, we illustrate the general approach with the example `solution_guide\classification\classify_halogen_bulbs.hdev`. Here, halogen bulbs are classified into good, bad, and not existent halogen bulbs (see [figure 5.2](#)). For that, the regions representing the insulation of the halogen bulbs are investigated. The classification is applied with the SVM approach. The operator names for the MLP, GMM, and k-NN classification differ only in their ending. That is, if you want to

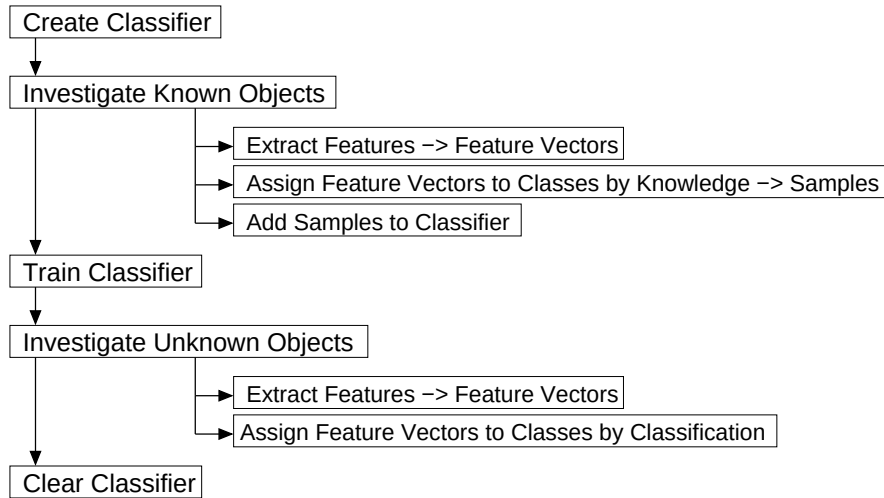


Figure 5.1: The basic steps of a general classification.

apply an MLP, GMM, or k-NN classification, you mainly have to replace the 'svm' by 'mlp', 'gmm', or 'knn' in the corresponding operator names and adjust different parameters. The parameters and their selection are described in [section 6.1.3](#) for MLP, [section 6.1.4](#) for SVM, [section 6.1.5](#) for GMM, and [section 6.1.6](#) for k-NN.

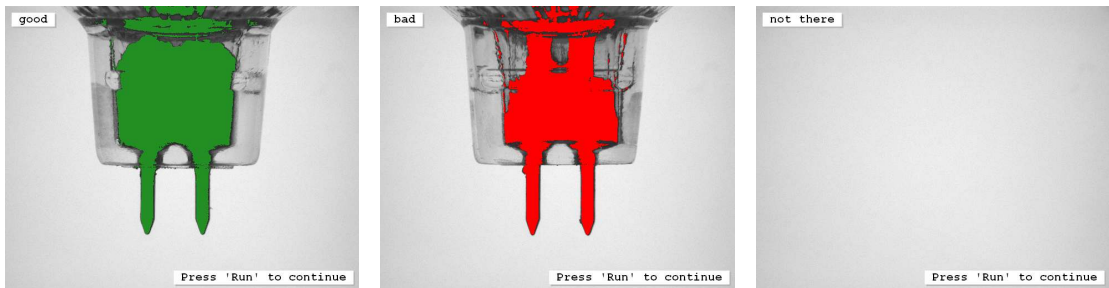


Figure 5.2: Classifying halogen bulbs into (from left to right): good, bad, and not existent halogen bulbs.

The program starts with the assignment of the available classes. The halogen bulbs can be classified into the classes 'good' (halogen bulb with sufficient insulation), 'bad' (halogen bulb with insufficient insulation), or 'none' (no halogen bulb can be found in the image).

```
ClassNames := ['good','bad','none']
```

As the first step of the actual classification, an SVM classifier is created with the operator [create_class_svm](#). The returned handle of the classifier SVMHandle is needed for all classification specific operators that are applied afterwards.

```
Nu := 0.05
KernelParam := 0.02
create_class_svm (7, 'rbf', KernelParam, Nu, |ClassNames|, 'one-versus-one', \
                'principal_components', 5, SVMHandle)
```

As each classification application is unique, the classifier has to be trained for the current application. That is, the rules for the classification have to be derived from a set of samples. In case of the SVM approach, e.g., the training determines the optimal support vectors that separate the classes from each other (see [section 3.4](#) on page 22).

A sample is an object for which the class membership is known. Generally, each kind of object can be classified with the general classification approach as long as it can be described by a set of features or respectively the feature's values. Common objects for image processing are regions, pixels, or a combination of both. For the example with the halogen bulbs, the objects that have to be trained and classified are the regions that represent insulations of halogen bulbs. For each known object, the feature vector, which consists of values that are derived from the extracted region, and the corresponding (known) class name build the training sample. For each class a representative set of training samples must be provided to achieve suitable class boundaries. In the example, the samples are added within the procedure `add_samples_to_svm`.

Within the procedure, for each class the corresponding images are obtained. Note that different methods can be used to assign the class memberships for the objects of an image. In the example described in [section 2](#) on page 13, a tuple was used to assign the class name for each image. There, the sequence of the images and the sequence of the elements in the tuple had to correspond. Here, the images of each class are stored in a directory that is named like the class. Thus, the procedure `add_samples_to_svm` uses the directory names to assign the feature vectors to the classes. For example, the images containing the good halogen bulbs are stored in the directory 'good'. Then, for each class, all images are read from the corresponding directory.

Now, for each image the region of the halogen bulb's insulation is extracted by the operator `threshold`, the features of the region are extracted inside the procedure `calculate_features`, and the feature vector is added together with the corresponding class ID to the classifier using the operator `add_sample_class_svm`.

```
procedure add_samples_to_svm (ClassNames, SVMHandle, WindowHandle, ReadPath)::
for ClassNumber := 0 to |ClassNames| - 1 by 1
  list_files (ReadPath + ClassNames[ClassNumber], 'files', Files)
  Selection := regexp_select(Files, '.*[.]png')
  for Index := 0 to |Selection| - 1 by 1
    read_image (Image, Selection[Index])
    threshold (Image, Region, 0, 40)
    calculate_features (Region, Features)
    add_sample_class_svm (SVMHandle, Features, ClassNumber)
  endfor
endfor
return ()
```

The feature vectors that are used to train the classifier and those that are classified for new objects must consist of the same set of features. In the example program, the features are calculated inside the procedure `calculate_features` and comprise

- the 'area' of the region,
- the 'compactness' of the region,
- the four geometric moments ('PSI1', 'PSI2', 'PSI3', and 'PSI4') of the region, which are invariant to translation and general linear transformations, and
- the 'convexity' of the region.

Note that feature vectors have to consist of real values. As some of the calculated features are described by integer values, e.g., the feature 'area', which corresponds to the number of pixels contained in a region, the feature vector is transformed into a tuple of real values before it is added to the classifier.

```
procedure calculate_features (Region, Features)
area_center (Region, Area, Row, Column)
compactness (Region, Compactness)
moments_region_central_invar (Region, PSI1, PSI2, PSI3, PSI4)
convexity (Region, Convexity)
Features := real([Area,Compactness,PSI1,PSI2,PSI3,PSI4,Convexity])
return ()
```

After adding all samples to the classifier with the procedure `add_samples_to_svm`, the actual training is applied with the operator `train_class_svm`. In this step, the classifier derives its classification rules.

```
train_class_svm (SVMHandle, 0.001, 'default')
```

These classification rules are applied now inside the procedure `classify_regions_with_svm` to halogen bulbs of unknown classes. The procedure works similar as the procedure for adding the training samples. But now, the images that contain the unknown types of halogen bulbs are read, no class information is available, and instead of adding samples to the classifier, the operator `classify_class_svm` is applied to classify the unknown feature vectors with the derived classification rules.

```
procedure classify_regions_with_svm (SVMHandle, Colors, ClassNames,
                                   ReadPath)::
list_files (ReadPath, ['files','recursive'], Files)
Selection := regexp_select(Files,'.*[.]png')
read_image (Image, Selection[0])
for Index := 0 to |Selection| - 1 by 1
  read_image (Image, Selection[Index])
  threshold (Image, Region, 0, 40)
  calculate_features (Region, Features)
  classify_class_svm (SVMHandle, Features, 1, Class)
endfor
return ()
```

At the end of the program the handle of the classifier is destroyed with `clear_class_svm` to clear it from memory.

```
clear_class_svm (SVMHandle)
```

The example shows the application of operators that are essential for a classification. Further operators are provided that can be used, e.g., to separate the training from the classification. That is, you run a program that applies the training offline, save the trained classifier to file with `write_class_svm`, and in another program you read the classifier from file again with `read_class_svm` to classify your data in an online process. When closing the training program, the samples are not stored automatically. To store them to file for later access you apply the operator `write_samples_class_svm`. A later access using `read_samples_class_svm` may be necessary, e.g., if you want to repeat the training with additional training samples. If you do not separate the training and the classification process, you can save memory by clearing the samples manually from memory before applying the classification (if you do not need the samples anymore). This is done with `clear_samples_class_svm`.

The following sections provide you with a list of involved operators ([section 5.2](#)) and go deeper into the specific parameter adjustment needed for MLP ([section 5.3](#)), SVM ([section 5.4](#)), GMM ([section 5.5](#)), and k-NN ([section 5.6](#)).

5.2 Involved Operators (Overview)

This section gives a brief overview on the operators that are provided for a general MLP, SVM, GMM, and k-NN classification. First, the operators for the basic steps of a classification are introduced in [section 5.2.1](#). Then, some advanced operators are introduced in [section 5.2.2](#) on page 39.

5.2.1 Basic Steps

Summarizing the information obtained in [section 5.1](#) on page 33, the classification consists of the following basic steps and operators, which are applied in the same order as listed here:

1. Create a classifier. Here, some important properties of the classifier are defined. The returned handle is needed in all later classification steps.

- `create_class_mlp`
- `create_class_svm`
- `create_class_gmm`
- `create_class_knn`

2. Predefine the sequence in which the classes are defined and later accessed, i.e., define the correspondences between the class IDs and the class names. This step may as well be applied before the creation of the classifier.
3. Get feature vectors for sample objects of known class IDs. The operators that are suitable to obtain the features depend strongly on the specific application and thus are not part of this overview.
4. Successively add samples, i.e., feature vectors and their corresponding class IDs to the classifier.

- `add_sample_class_mlp`
- `add_sample_class_svm`

- `add_sample_class_gmm`
 - `add_sample_class_knn`
5. Train the classifier. Here, the boundaries between the classes are derived from the training samples.
- `train_class_mlp`
 - `train_class_svm`
 - `train_class_gmm`
 - `train_class_knn`
6. Store the used samples to file and access them in a later step (optionally).
- `write_samples_class_mlp` and `read_samples_class_mlp`
 - `write_samples_class_svm` and `read_samples_class_svm`
 - `write_samples_class_gmm` and `read_samples_class_gmm`
 - Note that there are no operators for writing and reading the samples of a k-NN classifier separately because the samples are an intrinsic component of the k-NN classifier. Use `write_class_knn` and `read_class_knn` instead.
7. Store the trained classifier to file and read it from file again or, if the offline and online part is not separated, clear the samples manually from memory.
- `write_class_mlp` (default file extension: `.gmc`) and `read_class_mlp` or `clear_samples_class_mlp`
 - `write_class_svm` (default file extension: `.gsc`) and `read_class_svm` or `clear_samples_class_svm`
 - `write_class_gmm` (default file extension: `.ggc`) and `read_class_gmm` or `clear_samples_class_gmm`
 - `write_class_knn` (default file extension: `.gnc`) and `read_class_knn`
Note that the samples cannot be deleted from a k-NN classifier because they are an intrinsic component of this classifier.
8. Get feature vectors for objects of unknown class. These feature vectors have to contain the same features (in the same order) that were used to define the training samples.
9. Classify the new feature vectors. That is, insert the new feature vector to one of the following operators and get the corresponding class ID.
- `classify_class_mlp`
 - `classify_class_svm`
 - `classify_class_gmm`
 - `classify_class_knn`
10. Clear the classifier from memory.
- `clear_class_mlp` or `clear_class_mlp`
 - `clear_class_svm` or `clear_class_svm`

- `clear_class_gmm` or `clear_class_gmm`
- `clear_class_knn` or `clear_class_knn`

Besides the basic steps of a classification, some additional steps and operators can be applied if suitable. These advanced operators are listed in the following section.

5.2.2 Advanced Steps

Especially if the training and classification do not lead to a satisfying result, it is helpful to access some information that is implicitly contained in the model. Available steps to query information are:

- Access an individual sample from the training data. This is needed, e.g., to check the correctness of its class assignment. The sample had to be stored previously by the operator `add_sample_class_mlp`, `add_sample_class_svm`, `add_sample_class_gmm`, or `add_sample_class_knn`, respectively.
 - `get_sample_class_mlp`
 - `get_sample_class_svm`
 - `get_sample_class_gmm`
 - `get_sample_class_knn`
- Get the number of samples that are stored in the training data. The obtained number is needed, e.g., to access the individual samples or to know how much individual samples you can access.
 - `get_sample_num_class_mlp`
 - `get_sample_num_class_svm`
 - `get_sample_num_class_gmm`
 - `get_sample_num_class_knn`
- Get information about the content of the preprocessed feature vectors. This information is reasonable, if the parameter Preprocessing was set to 'principal_components' or 'canonical_variates' during the creation of the classifier. Then, you can check if the information that is contained in the preprocessed feature vector still contains significant data or if a different preprocessing parameter, e.g., 'normalization', is to be preferred.
 - `get_prep_info_class_mlp`
 - `get_prep_info_class_svm`
 - `get_prep_info_class_gmm`
 - Note that this information cannot be retrieved from a k-NN classifier because the respective kind of preprocessing is not available for k-NN classifiers.
- Get the parameter values that were set during the creation of the classifier. This is needed if the offline training and the online classification are separated and the information about the training part is not available anymore.

- `get_params_class_mlp`
- `get_params_class_svm`
- `get_params_class_gmm`
- `get_params_class_knn`

Furthermore, there are operators that are available only for specific classifiers:

- For MLP and GMM you can evaluate the probabilities of a feature vector to belong to a specific class. That is, you can determine the probabilities for each available class and not only for the most probable classes. If only the most probable classes are of interest, no explicit evaluation is necessary, as these probabilities are returned also when classifying the feature vector.

- `evaluate_class_mlp`
- `evaluate_class_gmm`

- For SVM you can reduce the number of support vectors returned by the offline training to speed up the following online classification.

- `reduce_class_svm`

- Additionally, for SVM the number or index of the support vectors can be determined after the training. This is suitable for the visualization of the support vectors and for diagnostic reasons.

- `get_support_vector_num_class`
- `get_support_vector_class`

- For k-NN you can set various parameters that control the behavior of the classifier with the operator

- `set_params_class_knn`.

This includes the number k of nearest neighbors, the kind of result that is to be returned by the classifier, and parameters that control the trade-off between quality and speed of the classification.

The following sections introduce the individual parameters for the basic operators and provide tips for their adjustment.

5.3 Parameter Setting for MLP

This section goes deeper into the parameter adjustment for an MLP classification. We recommend to first adjust the parameters so that the classification result is satisfying. The most important parameter that has to be adjusted to get the MLP classifier work optimally is

- `NumHidden (create_class_mlp)`.

If the classification generally works, you can start to tune the speed. The most important parameters to enhance the speed are

- **Preprocessing** / **NumComponents** (`create_class_mlp`) and
- **MaxIterations** (`train_class_mlp`).

In the following, we introduce the parameters of the basic MLP operators. The focus is on the parameters for which the setting is not immediately obvious or for which it is not immediately obvious how they influence the classification. These are mainly the parameters needed for the creation and training of the classifier. Further information about these operators as well as the usage of the operators with obvious parameter settings can be found in the Reference Manual entries for the individual operators.

5.3.1 Adjusting `create_class_mlp`

An MLP classifier is created with the operator `create_class_mlp`. There, several properties of the classifier are defined that are important for the following classification steps. The returned handle is needed (and modified) in all following steps. The following parameters can be adjusted:

Parameter NumInput

The input parameter `NumInput` specifies the dimension of the feature vectors used for the training as well as for the classification. Opposite to the GMM classifier (see [section 5.5](#) on page 54), a number of 500 features is still realistic.

Parameter NumHidden

The input parameter `NumHidden` defines the number of units of the hidden layer of the multi-layer neural net (see [section 3.3](#) on page 20) and significantly influences the result of the classification and thus should be adjusted very carefully. Its value should be in a similar value range as `NumInput` and `NumOutput`. Smaller values lead to a less complex separating hyperplane, but in many cases nevertheless may lead to good results. With a very large value for `NumHidden`, you run the risk of overfitting (see [figure 5.3](#)). That is, the classifier uses unimportant details like noise to build the class boundaries. That way, the classifier works very well for the training data, but fails for unknown feature vectors that do not contain the same unimportant details. In other words, overfitting means that the classifier loses its generalization ability.

To adjust `NumHidden`, it is recommended to apply tests with independent test data, e.g., using the cross validation introduced in [section 8.1](#) on page 115. Note that the example `hdevelop\Classification\Neural-Nets\class_overlap.hdev` provides further hints about the influence of different values for `NumHidden`.

Parameter NumOutput

The input parameter `NumOutput` specifies the number of classes.

Parameter OutputFunction

The input parameter `OutputFunction` describes the functions used by the output unit of the neural net. Available values are 'softmax', 'logistic', and 'linear'. In almost all classification applications, `OutputFunction` should be set to 'softmax'. The value 'logistic' can be used for classification problems with multiple independent logical attributes as output, but this kind of classification problems is very rare in practice. The value 'linear' is used for least squares fitting (regression) and not for classification. Thus, you can ignore it here.

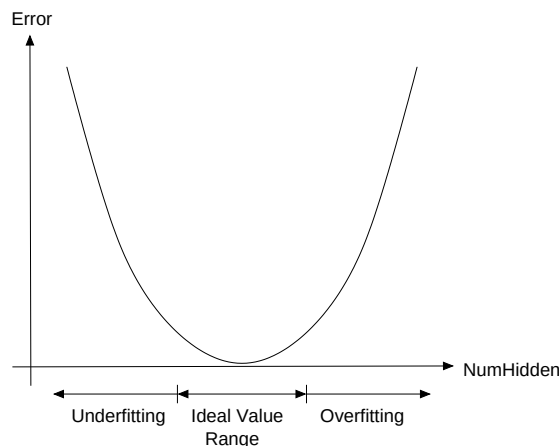


Figure 5.3: The value of NumHidden should be adjusted carefully to avoid under- or overfitting (note that the illustrated curve is idealized and in practice would be less straight).

Parameters Preprocessing/NumComponents

The input parameter [Preprocessing](#) defines the type of preprocessing applied to the feature vector for the training as well as later for the classification or evaluation. A preprocessing of the feature vector can be used to speed up the training as well as the classification. Sometimes, even the recognition rate can be enhanced.

Available values are 'none', 'normalization', 'principal_components', and 'canonical_variates'. In most cases, the preprocessing should be set to 'normalization' as it enhances the speed without losing relevant information compared to using no preprocessing ('none'). The feature vectors are normalized by subtracting the mean of the training vectors and dividing the result by the standard deviation of the individual components of the training vectors. Hence, the transformed feature vectors have a mean of 0 and a standard deviation of 1. The normalization does not change the length of the feature vector.

If speed is important and your data is expected to be highly correlated, you can reduce the dimension of the feature vector using a principal component analysis ('principal_components'). There, the feature vectors are normalized and additionally transformed such that the covariance matrix becomes a diagonal matrix. Thus, the amount of data can be reduced without losing a large amount of information.

If you know that your classes are linearly separable, you can also use canonical variates ('canonical_variates'). This approach is known also as linear discriminant analysis. There, the transformation of the normalized feature vectors decorrelates the training vectors on average over all classes. At the same time, the transformation maximally separates the mean values of the individual classes. This approach combines the advantages of a principal component analysis with an optimized separability of the classes after the data reduction. But note that the parameter 'canonical_variates' is recommended only for linearly separable classes. For MLP, 'canonical_variates' can only be used if OutputFunction is set to 'softmax'.

[Figure 5.4](#) and [figure 5.5](#) illustrate how 'principal_components' and 'canonical_variates', dependent on the distribution of the feature vectors, can reduce the feature vectors to a lower number of

components by transforming the feature space and projecting the feature vectors to one of the principal axes.

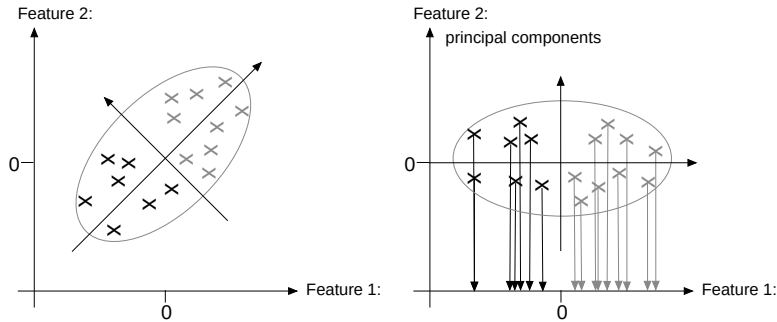


Figure 5.4: After transforming the feature space via principal component analysis, the illustrated linearly separable classes can be separated using only one feature.

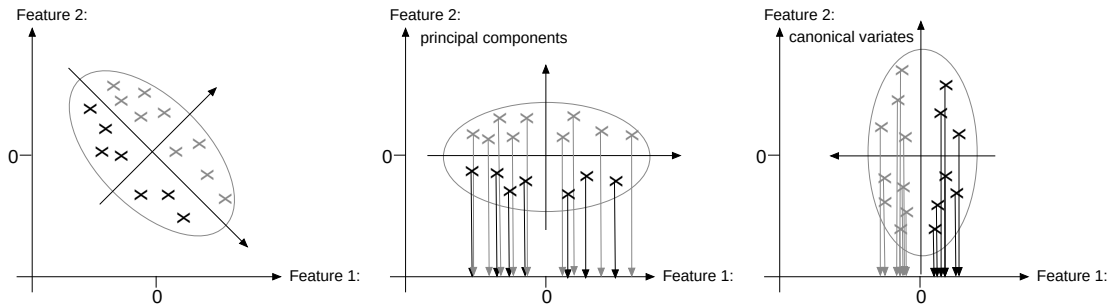


Figure 5.5: Here, after transforming the feature space via principal component analysis, the illustrated linearly separable classes still need two features to be separated. After transforming the feature space using canonical variates they can be separated by a single feature.

The input parameter `NumComponents` defines the number of components to which the feature vector is reduced if a preprocessing is selected that reduces the dimension of the feature vector. In particular, `NumComponents` has to be adjusted only if `Preprocessing` is set to `'principal_components'` or `'canonical_variates'`.

If `Preprocessing` is set to `'principal_components'` or `'canonical_variates'` you can use the operator `get_prep_info_class_mlp` to check if the content of the transformed feature vectors still contain significant data. Furthermore, you can use the operator to determine the optimum number of components. Then, you first create a test classifier with, e.g., `NumComponents` set to `NumInput`, generate and add the training samples to the classifier, and then apply `get_prep_info_class_mlp`. The output parameter `CumInformationCont` is a tuple containing numbers between 0 and 1. These numbers describe the amount of the original data that is covered by the transformed data. That is, if you want to have at least 90% of the original data covered by the transformed data, you search for the first value that is larger than 0.9 and use the corresponding index number of the tuple `CumInformationCont` as value for a new `NumComponents`. Then, you destroy the test classifier and create a new classifier for the final training (this time `NumComponents` is set to the new value). Note that it is suitable to store the samples

into a file during the test training (`write_samples_class_mlp`) so that you do not have to successively add the training samples again but simply read in the sample file using `read_samples_class_mlp`.

Parameter `RandSeed`

The weights of the MLP (see [section 3.3](#) on page 20) are initialized by a random number. For the sake of reproducibility the seed value for this random number is stored in the input parameter `RandSeed`.

Parameter `MLPHandle`

The output parameter of `create_class_mlp` is the `MLPHandle`, which is needed for all following classification specific operators.

5.3.2 Adjusting `add_sample_class_mlp`

A single sample is added to the MLP classifier using `add_sample_class_mlp`. For the training, several samples have to be added by successively calling `add_sample_class_mlp` with different samples. The following parameters can be adjusted:

Parameter `MLPHandle`

The input and output parameter `MLPHandle` is the handle of the classifier that was created with `create_class_mlp` and to which the samples subsequently were added with `add_sample_class_mlp`. After applying `add_sample_class_mlp` for all available samples, the handle is prepared for the actual training of the classifier.

Parameter `Features`

The input parameter `Features` contains the feature vector of a sample to be added to the classifier with `add_sample_class_mlp`. This feature vector is a tuple of values. Each value describes a specific numeric feature. Note that the feature vector must consist of real numbers. If you have integer numbers, you have to transform them into real numbers. Otherwise, an error message is raised.

Parameter `Target`

The input parameter `Target` describes the target vector, i.e., you assign the corresponding class ID to the feature vector.

If `OutputFunction` is set to `'softmax'`, the target vector is a tuple that contains exactly one element with the value 1 and several elements with the value 0. The size of the vector corresponds to the number of available classes specified by `NumOutput` inside `create_class_mlp`. The index of the element with the value 1 defines the class the feature vector `Features` belongs to. Alternatively, a single integer containing the class number (counted from 0) can be specified.

For `OutputFunction` set to `'logistic'`, the target vector consists of values that are either 0 or 1. Each 1 shows that the corresponding feature is present.

If `OutputFunction` is set to `'linear'`, the target vector can contain arbitrary real numbers. As this parameter value is used for least squares fitting (regression) and not for classification, it is not explained further.

5.3.3 Adjusting `train_class_mlp`

The training of the MLP classifier is applied with `train_class_mlp`. Training the MLP means to determine the optimum values of the MLP weights (see [section 3.3](#) on page 20). For this, a sufficient number of training samples is necessary. Training is performed by a complex nonlinear optimization process that minimizes the discrepancy of the MLP output and the target vectors that were defined with `add_sample_class_mlp`. The following parameters can be adjusted:

Parameter `MLPHandle`

The input and output parameter `MLPHandle` is the handle of the classifier that was created with `create_class_mlp` and for which samples were stored either by adding them via `add_sample_class_mlp` or by reading them in with `read_samples_class_mlp`. After applying `train_class_mlp`, the handle is prepared for the actual classification of unknown data. That is, it then contains information about how to separate the classes.

Parameters `MaxIterations` / `WeightTolerance` / `ErrorTolerance`

The input parameters `MaxIterations`, `WeightTolerance`, and `ErrorTolerance` control the nonlinear optimization algorithm. `MaxIterations` specifies the number of iterations of the optimization algorithm. The optimization is terminated if the weight change is smaller than `WeightTolerance` and the change of the error is smaller than `ErrorTolerance`. In any case, the optimization is terminated after at most `MaxIterations` iterations. For the latter, values between 100 and 200 are sufficient in most cases. The default value is 200. By reducing this value, the speed of the training can be enhanced. For the parameters `WeightTolerance` and `ErrorTolerance` the default values do not have to be changed in most cases.

Parameter `Error`

The output parameter `Error` returns the error of the MLP with the optimal weights on the training samples.

Parameter `ErrorLog`

The output parameter `ErrorLog` returns the error value as a function of the number of iterations. This function can be used to decide if a second training with the same training samples but a different value for `RandSeed` should be applied, which is the case if the function runs into a local minimum.

5.3.4 Adjusting `evaluate_class_mlp`

The operator `evaluate_class_mlp` can be used to evaluate the probabilities for a feature vector to belong to each of the available classes. If only the probabilities for the two classes to which the feature vector most likely belongs are searched for, no evaluation is necessary, as these probabilities are returned also for the final classification of the feature vector. The following parameters can be adjusted:

Parameter `MLPHandle`

The input parameter `MLPHandle` is the handle of the classifier that was previously trained with the operator `train_class_mlp`.

Parameter `Features`

The input parameter `Features` contains the feature vector that is evaluated. The feature vector must consist of the same features as the feature vectors used for the training samples within `add_sample_class_mlp`.

Parameter `Result`

The output parameter `Result` returns the result of the evaluation. This result has different meanings, dependent on the `OutputFunction` that was set with `create_class_mlp`. If `OutputFunction` was set to 'softmax', which should be the case for most classification applications, the returned tuple consists of probability values. Each value describes the probability of the given feature vector to belong to the corresponding class. If `OutputFunction` was set to 'logistic', the elements of the returned tuple represent the presences of the respective independent attributes.

5.3.5 Adjusting `classify_class_mlp`

The operator `classify_class_mlp` classifies a feature vector according to the class boundaries that were derived during the training. It can only be called if `OutputFunction` was set to 'softmax' in `create_class_mlp`. The following parameters can be adjusted:

Parameter `MLPHandle`

The input parameter `MLPHandle` describes the handle that was created with `create_class_mlp`, to which samples were added with `add_sample_class_mlp`, and that was trained with `train_class_mlp`. The handle contains all the information that the classifier needs to assign an unknown feature vector to one of the available classes.

Parameter `Features`

The input parameter `Features` contains the feature vector of the object that is to be classified. The feature vector must consist of the same features as the feature vectors used for the training samples within `add_sample_class_mlp`.

Parameter `Num`

The input parameter `Num` specifies the number of best classes to be searched for. Generally, `Num` is set to 1 if only the class with the best probability is searched for, and to 2 if the second best class is also of interest, e.g., because the classes overlap.

Parameter Class

The output parameter `Class` returns the result of classifying the feature vector with the trained MLP classifier, i.e., a tuple containing Num elements. That is, if Num is set to 1, a single value is returned that corresponds to the class with the highest probability. If Num is set to 2, the first element contains the class with the highest probability and the second element contains the second best class.

Parameter Confidence

The output parameter `Confidence` outputs the confidence of the classification. Note that in comparison to the probabilities returned for a GMM classification, here the returned values can be influenced by outliers, which is caused by the specific way an MLP is calculated. For example, the confidence may be high for a feature vector that is far from the rest of the training samples of the specific class but significantly on the same side of the separating hypersurface. On the other side, the confidence can be low for objects that are significantly within the cluster of training samples of a specific class but near to the separating hypersurface as two classes overlap at this part of the cluster (see figure 5.6).

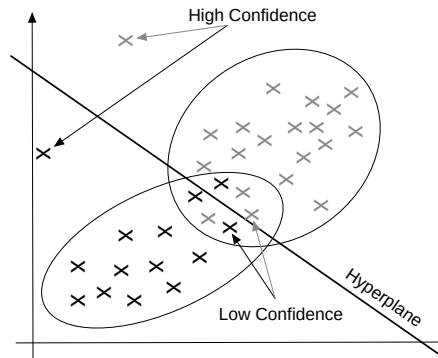


Figure 5.6: The confidence calculated for an MLP classification can be unexpected for outliers. That is, feature vectors that are far away from their class centers can be classified with high confidence or those that are near to the class centers but inside an overlapping area between two classes can be classified with low confidence.

5.3.6 Adjusting `clear_class_mlp`

Parameter `MLPHandle`

To destroy the classifier, the operator `clear_class_mlp` is applied only with the input parameter `MLPHandle`.

5.4 Parameter Setting for SVM

This section goes deeper into the parameter adjustment for an SVM classification. We recommend to first adjust the parameters so that the classification result is satisfying. The most important parameters that have to be adjusted to get the SVM classifier work optimally are:

- `Nu (create_class_svm)`
- `KernelParam (create_class_svm)`

If the classification generally works, you can start to tune the speed. The most important parameters to enhance the speed are:

- `Preprocessing (create_class_svm)`:
A combination of `KernelType` set to `'rbf'` and the `Preprocessing` set to `'principal_components'` speeds up the SVM significantly (even faster than MLP), as the features are reduced and thus the dimension for the support vectors are reduced as well.
- `MaxError (reduce_class_svm)`

In the following, we introduce the parameters of the basic SVM operators. The focus is on the parameters for which the setting is not immediately obvious or for which it is not immediately obvious how they influence the classification. These are mainly the parameters needed for the creation and training of the classifier. Further information about these operators as well as the usage of the operators with obvious parameter settings are provided in the Reference Manual entries for the individual operators.

5.4.1 Adjusting `create_class_svm`

An SVM classifier is created with the operator `create_class_svm`. There, several properties of the classifier are defined that are important for the following classification steps. The returned handle is needed (and modified) in all following steps. For the operator, the following parameters can be adjusted:

Parameter `NumFeatures`

The input parameter `NumFeatures` specifies the dimension of the feature vectors used for the training as well as for the classification. Opposite to the GMM classifier (see [section 5.5](#) on page 54), a number of 500 features is still realistic.

Parameters `KernelType` / `KernelParam`

In [section 3.4](#) on page 22 we saw for an SVM classification that the feature space is transformed into a higher feature space by a kernel to get linearly separable classes. The input parameter `KernelType` defines how the feature space is mapped into this higher dimension. The mapping that is suitable and recommended in most cases uses a kernel that is based on the Gauss error distribution curve and is called Gaussian radial basis function kernel (`'rbf'`).

If `KernelType` is set to `'rbf'`, the input parameter `KernelParam` is used to adjust the γ of the error curve (see [figure 5.7](#)) and should be adjusted very carefully. If the value for γ is very high, the number of support vectors increases, which results on one hand in an overfitting, i.e., the generalization ability of the classifier is lost (for overfitting see also the description of `NumHidden` in [section 5.3.1](#) on page 41) and on the other hand the speed is reduced. On the other side, with a very low value for γ , an underfitting occurs, i.e., the number of support vectors is not sufficient to obtain a satisfying classification result.

It is recommended to start with a small γ and then progressively increase it. Generally, it is recommended to simultaneously search for a suitable $\text{Nu}-\gamma$ pair, as these together define how complex the separating hypersurface becomes. The search can be applied, e.g., using the cross validation that is described in [section 8.1](#) on page 115.

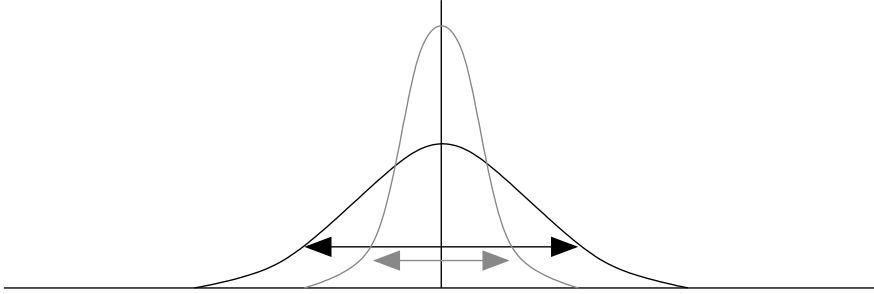


Figure 5.7: γ describes the amount of influence of a support vector upon its surrounding.

Besides 'rbf', you can also select a linear or polynomial kernel for `KernelType`, but these kernels should be used only in very special cases (see below).

The linear kernel (`KernelType` set to 'linear') transforms the feature space using a dot product. The linear kernel should be used only if the classes are expected to be linearly separable. If a linear kernel is selected, the parameter `KernelParam` has no meaning and can be ignored.

The polynomial kernels (`KernelType` set to 'polynomial_homogeneous' or 'polynomial_inhomogeneous') in very rare cases can be used if the classification with 'rbf' was not successful, but in most cases, 'rbf' leads to a better result. If a polynomial kernel is selected, the parameter `KernelParam` describes the degree 'd' of the polynomial. Note that a degree higher than 10 might result in numerical problems.

Parameter `Nu`

For classes that are not linearly separable, data from different classes may overlap. The input parameter `Nu` regularizes the separation of the classes, i.e., with `Nu`, the upper bound for training errors within the overlapping areas between the classes is adjusted (see [figure 5.8](#)) and at the same time the lower bound for the number of support vectors is determined. `Nu` should be adjusted very carefully. Its value must be a real number between 0 and 1. As a rule of thumb, it should be set to the expected error ratio of the specific data set, e.g., to 0.05 when expecting a maximum training error of 5%. The training error occurs because of, e.g., overlapping classes. Note that a very large `Nu` results in a large data set and thus reduces the speed significantly. Additionally, with a very large `Nu` the training may be aborted and an error handling message is raised. Then, `Nu` has to be chosen smaller. On the other hand, a very small `Nu` leads to instable numerics, i.e., many feature vectors would be classified incorrectly.

To select a suitable value for `Nu`, it is recommended to start with a small value and then progressively increase it. Generally, it is recommended to simultaneously search for a suitable $\text{Nu}-\gamma$ pair, as these together define how complex the separating hypersurface becomes. The search can be applied, i.e., using the cross validation that is described in [section 8.1](#) on page 115.

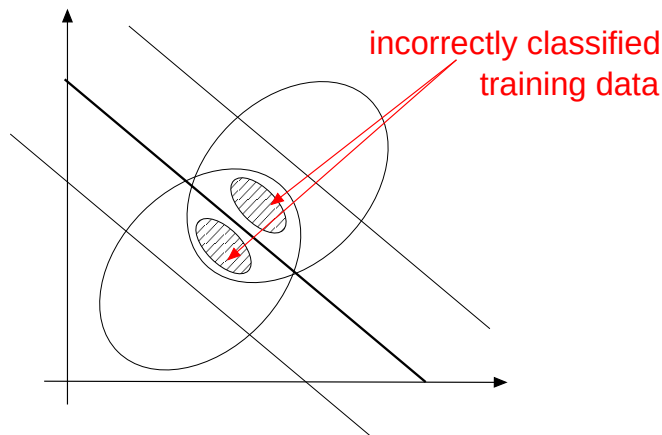


Figure 5.8: The parameter `Nu` determines the amount of the incorrectly classified training data within the overlap between two classes.

Parameter `NumClasses`

The input parameter `NumClasses` specifies the number of classes.

Parameter `Mode`

As we saw in [section 3.4](#) on page 22, SVM can handle only two-class problems. With the input parameter `Mode` you define if your application is a two-class problem or if you want to extend the SVM to a multi-class problem.

Having a two-class problem, you have training data for a single class and decide during the classification if a feature vector belongs to the trained class or not. That is, the hyperplane lies around the training data and implicitly separates the training data from a rejection class. This `Mode` is called 'novelty-detection' and can only be applied if `KernelType` is set to 'rbf'.

If you want to extend the SVM to a multi-class problem, you have to divide the decision into binary sub-cases. There, you have two possibilities. Either, you set `Mode` to 'one-versus-one' or you set it to 'one-versus-all'.

When using the mode 'one-versus-one', for each pair of classes a binary classifier is created and the class that wins most comparisons is selected. Here, n classes result in $n(n-1)/2$ classifiers. This approach is fast but suitable only for a small number of classes (approximately up to 10).

For 'one-versus-all', each class is compared to the rest of the training data and the class with the maximum distance to the hypersurface is selected. Here, the number of needed binary classifiers corresponds to the number of classes. This approach is not as fast as 'one-versus-one', but can and should be used for a higher number of classes.

Parameters `Preprocessing` / `NumComponents`

The input parameter `Preprocessing` defines the type of preprocessing applied to the feature vector for the training as well as later for the classification or evaluation. A preprocessing of the feature vector can

be used to speed up the training as well as the classification. Sometimes, even the recognition rate can be enhanced.

Available values are 'none', 'normalization', 'principal_components', and 'canonical_variates'. In most cases, the preprocessing should be set to 'normalization' as it enhances the speed without losing relevant information compared to using no preprocessing ('none'). The values 'principal_components' and in rare cases 'canonical_variates' can be used to enhance the speed. As the preprocessing types are the same as used for an MLP classification, we refer to [section 5.3.1](#) on page 42 for further information.

The input parameter `NumComponents` defines the number of components to which the feature vector is reduced if a preprocessing is selected that reduces the dimension of the feature vector. In particular, `NumComponents` has to be adjusted only if `Preprocessing` is set to 'principal_components' or 'canonical_variates'. If `Preprocessing` is set to 'principal_components' or 'canonical_variates' you can use the operator `get_prep_info_class_svm` to determine the optimum number of components as described in [section 5.3.1](#) on page 42.

Parameter SVMHandle

The output parameter of `create_class_svm` is the `SVMHandle`, which is needed for all following classification specific operators.

5.4.2 Adjusting `add_sample_class_svm`

A single sample is added to the SVM classifier using `add_sample_class_svm`. For the training, several samples have to be added by successively calling `add_sample_class_svm` with different samples. The following parameters can be adjusted:

Parameter SVMHandle

The input and output parameter `SVMHandle` is the handle of the classifier that was created with `create_class_svm` and to which the samples subsequently are added with `add_sample_class_svm`. After applying `add_sample_class_svm` for all available samples, the handle is prepared for the actual training of the classifier.

Parameter Features

The input parameter `Features` contains the feature vector of a sample to be added to the classifier with `add_sample_class_svm`. This feature vector is a tuple of values. Each value describes a specific numeric feature. Note that the feature vector must consist of real numbers. If you have integer numbers, you have to transform them into real numbers. Otherwise, an error message is raised.

Parameter Class

The input parameter `Class` contains the ID of the class the feature vector belongs to. The ID is an integer number between 0 and 'Number of Classes - 1'. If you created a tuple with class names, the class ID is the index of the corresponding class name in the tuple.

5.4.3 Adjusting `train_class_svm`

The training of the SVM classifier is applied with `train_class_svm`. The following parameters can be adjusted:

Parameter `SVMHandle`

The input and output parameter `SVMHandle` is the handle of the classifier that was created with `create_class_svm` and for which samples were stored either by adding them via `add_sample_class_svm` or by reading them in with `read_samples_class_svm`. After applying `train_class_svm`, the handle is prepared for the actual classification of unknown data. That is, it then contains information about how to separate the classes.

Parameter `Epsilon`

Training the SVM means to gradually optimize the function that determines the class boundaries. This optimization stops if the gradient of the function falls below a certain threshold. This threshold is set with the input parameter `Epsilon`. In most cases it should be set to the default value, which is 0.001. With a too small threshold, the optimization becomes slower without leading to a better recognition rate. With a too large threshold, the optimization stops before the optimum is found, i.e., the recognition rate may be not satisfying.

There are two cases, in which changing the value of `Epsilon` might be reasonable. First, when having a very small Nu and a small or unbalanced set of training data, it may be suitable to set `Epsilon` smaller than the default value to enhance the resulting recognition rate. Second, when applying a cross validation to search for a suitable Nu - γ pair (see [section 8.1](#) on page 115), it is recommended to select a larger value for `Epsilon` during the search. Thus, the cross validation is sped up without significantly changing the parameters for the optimal kernel. Having found the optimal Nu - γ pair, the final training is applied again with the small (default) value.

Parameter `TrainMode`

The input parameter `TrainMode` determines the mode for the training. We recommend to use the mode 'default' in most cases. There, the whole set of available samples is trained in one step. Appending a new set of samples to a previously applied training is possible with the mode 'add_sv_to_train_set'. This mode has some advantages that are listed in the Reference Manual entry for `train_class_svm`, but you have to be aware that only the support vectors that resulted from the previously applied training are reused. The samples of the previously applied training are ignored. This most likely leads to a different hypersurface than obtained with a training that uses all available training samples in one step. The risk of obtaining a hypersurface that is not suitable for all available samples is illustrated in [figure 5.9](#).

5.4.4 Adjusting `reduce_class_svm`

The operator `reduce_class_svm` can be used to reduce the number of support vectors that were returned by the training. This is suitable to speed up the online classification. The following parameters can be adjusted:

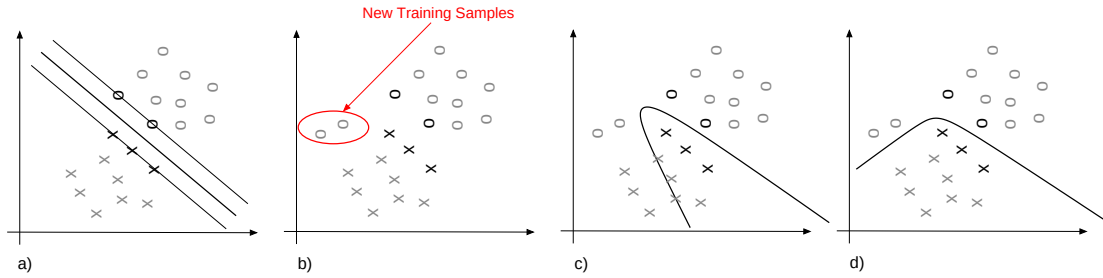


Figure 5.9: Risk of appending a second training: a) training samples of the first training and the obtained hypersurface, b) new samples added for a second training, c) hypersurface obtained by a second training using the new samples with the support vectors obtained by the first training, d) hypersurface obtained by a new training that uses all available samples.

Parameter SVMHandle

The input parameter `SVMHandle` is the handle of the classifier that was created with `create_class_svm`, to which training samples were added with `add_sample_class_svm`, and which was trained with `train_class_svm`. `reduce_class_svm` does not modify the handle but creates a copy of it (`SVMHandleReduced`) and modifies the copy.

Parameters Method / MinRemainingSV / MaxError

The input parameter `Method` defines the method used to reduce the number of support vectors. Momentarily, only the method 'bottom_up' is available. There, the number of support vectors is reduced by iteratively merging the support vectors until either the minimum number of support vectors that is set with `MinRemainingSV` is reached, or until the accumulated maximum error exceeds the threshold that is set with `MaxError`.

Note that the approximation of the original support vectors by a reduced number of support vectors reduces also the complexity of the hypersurface and thus can lead to a poor classification rate. A common approach is to start with a small value for `MaxError`, e.g. 0.0001, and to increase it step by step. To control the reduction ratio, the number of remaining support vectors is checked by `get_support_vector_num_class` and the classification rate is checked by classifying a separate test data with `classify_class_svm`.

Parameter SVMHandleReduced

The output parameter `SVMHandleReduced` returns the copied and modified handle of a classifier that has the same parameterization as the original handle but a different support vector expansion. Additionally, it does not contain the training samples that are stored with the original handle.

5.4.5 Adjusting `classify_class_svm`

The operator `classify_class_svm` is used to decide to which of the trained classes an unknown feature vector belongs. The following parameters can be adjusted:

Parameter SVMHandle

The input parameter `SVMHandle` describes the handle that was created with `create_class_svm`, to which samples were added with `add_sample_class_svm`, and that was trained with `train_class_svm`. The handle contains all the information that the classifier needs to assign an unknown feature vector to one of the available classes.

Parameter Features

The input parameter `Features` contains the feature vector of the object that is to be classified. The feature vector must consist of the same features as the feature vectors used for the training samples within `add_sample_class_svm`.

Parameter Num

The input parameter `Num` specifies the number of best classes to be searched for. Generally, `Num` is set to 1 if only the class with the best probability is searched for, and to 2 if the second best class is also of interest, e.g., because the classes overlap. If `Mode` was set to 'novelty-detection' in `create_class_svm`, `Num` must be set to 1.

Parameter Class

The output parameter `Class` returns the result of classifying the feature vector with the trained SVM classifier. This result depends on the `Mode` that was selected in `create_class_svm`. If `Mode` was set to 'one-versus-one', it contains the classes ordered by the number of votes of the sub-classifiers. That is, the first element of the returned tuple is the class with the most votes, the second is the class with the second most votes etc. If `Mode` was set to 'one-versus-all', it contains the classes ordered by the value of each sub-classifier. That is, the first element of the returned tuple is the class with the highest value, the second element is the class with the second best value. If `Mode` was set to 'novelty-detection', a single value is returned (`Num` must be set to 1). In particular, the value is 1 if the feature vector belongs to the trained class and 0 if the feature vector belongs to the rejection class.

5.4.6 Adjusting `clear_class_svm`

To destroy the classifier, the operator `clear_class_svm` is applied only with the input parameter `SVMHandle`.

5.5 Parameter Setting for GMM

This section goes deeper into the parameter adjustment for a GMM classification. We recommend to first adjust the parameters so that the classification result is satisfying. The most important parameters that have to be adjusted to get the GMM classifier work optimally are:

- `NumDim` (`create_class_gmm`)
- `NumCenters` (`create_class_gmm`)

- `CovarType` (`create_class_gmm`)
- `ClassPriors` (`train_class_gmm`)

If the classification generally works, you can start to tune the speed. The most important parameters to enhance the speed are:

- `CovarType` (`create_class_gmm`)
- `Preprocessing` / `NumComponents` (`create_class_gmm`)

In the following, we introduce the parameters of the basic GMM operators. The focus is on the parameters for which the setting is not immediately obvious or for which it is not immediately obvious how they influence the classification. These are mainly the parameters needed for the creation and training of the classifier. Further information about these operators as well as the usage of the operators with obvious parameter settings are provided in the Reference Manual entries for the individual operators.

5.5.1 Adjusting `create_class_gmm`

A GMM classifier is created with the operator `create_class_gmm`. There, several properties of the classifier are defined that are important for the following classification steps. The returned handle is needed (and modified) in all following steps. The following parameters can be adjusted:

Parameter `NumDim`

The input parameter `NumDim` specifies the dimension of the feature vectors used for the training as well as for the classification.

Note that GMM works optimally only for a limited number of features! If the result of the classification is not satisfying, maybe you have used too much features as input. As a rule of thumb, a number of 15 features should not be exceeded (although some applications work also for larger feature vectors). If your application needs significantly more features, in many cases an MLP, SVM, or k-NN classification is to be preferred.

Parameter `NumClasses`

The input parameter `NumClasses` specifies the number of classes.

Parameter `NumCenters`

As we learned in [section 3.5](#) on [page 24](#) a GMM class can consist of different Gaussian centers (see also [figure 5.10](#)). The input parameter `NumCenters` defines the number of Gaussian centers per class. You can specify this number in different ways. That is, you can either specify a single number of centers, then each class has exactly this number of class centers. Or you can specify the allowed lower and upper bound for the number of centers. This can be done either with a single range for all classes or with a range for each class individually. From these bounds, the optimum of centers is determined with the help of the Minimum Message Length Criterion (MML). In most cases, it is recommended to specify a range

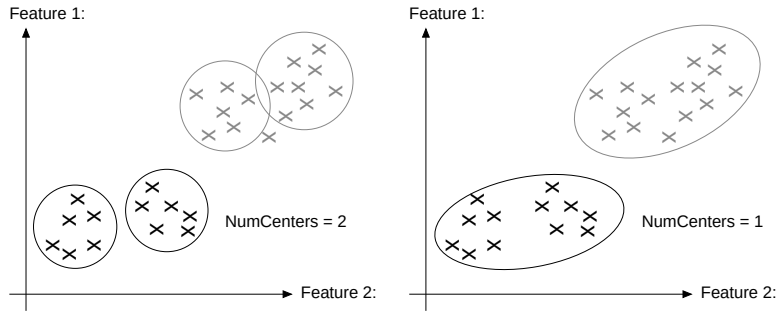


Figure 5.10: Number of Gaussian centers of a class: (left) 2 and (right) 1.

for all classes and to start with a high value as upper bound and the expected number of centers as lower bound. If the classification is successful, you can try to reduce the range to enhance the speed.

Note that if the training is canceled with the error message 3335 ('Internal error while training the GMM'), most probably the value for `NumCenters` is not optimal.

Parameter CovarType

The input parameter `CovarType` defines the type of the covariance matrix used to calculate the probabilities. With this, you can further constrain the MML, which is used to determine the optimum of centers. Three types of covariance matrices are available. If you use the default, 'spherical', the covariance matrix is a scalar multiple of the identity matrix. With the value 'diag' a diagonal matrix is obtained and with 'full' the covariance matrix is positive definite (see figure 5.11). Note that the flexibility of the centers but also the complexity of the calculations increases from 'spherical' over 'diag' to 'full'. That is, you have to decide whether you want to increase the flexibility of the classifier or if you want to increase the speed.

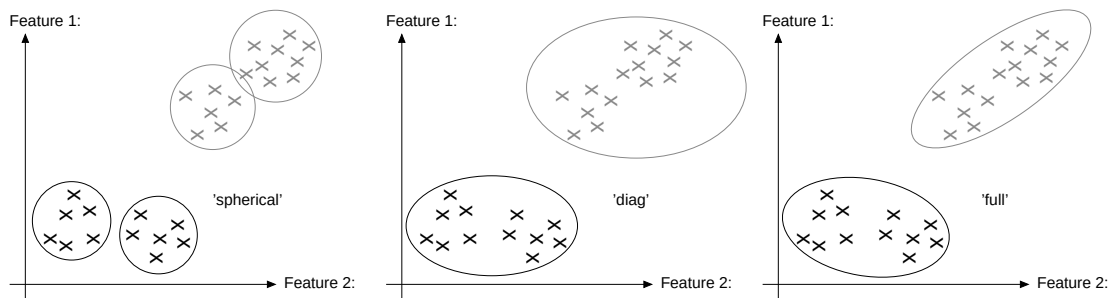


Figure 5.11: The covariance type set to (from left to right) 'spherical', 'diag', and 'full'.

Parameters Preprocessing / NumComponents

The input parameter `Preprocessing` defines the type of preprocessing applied to the feature vector for the training as well as later for the classification or evaluation. A preprocessing of the feature vector can

be used to speed up the training as well as the classification. Sometimes, even the recognition rate can be enhanced.

Available values are 'none', 'normalization', 'principal_components', and 'canonical_variates'. In most cases, Preprocessing should be set to 'normalization' as it enhances the speed without losing relevant information compared to using no preprocessing ('none'). The values 'principal_components' and in rare cases 'canonical_variates' can be used to enhance the speed. As the preprocessing types are the same as used for an MLP classification, we refer to [section 5.3.1](#) on page 42 for further information.

The input parameter `NumComponents` defines the number of components to which the feature vector is reduced if a preprocessing is selected that reduces the dimension of the feature vector. In particular, `NumComponents` has to be adjusted only if `Preprocessing` is set to 'principal_components' or 'canonical_variates'. If `Preprocessing` is set to 'principal_components' or 'canonical_variates' you can use the operator `get_prep_info_class_gmm` to determine the optimum number of components as described in [section 5.3.1](#) on page 42.

Parameter `RandSeed`

The coordinates of the centers are initialized by a random number. For the sake of reproducibility the seed value for this random number is stored in the input parameter `RandSeed`.

Parameter `GMMHandle`

The output parameter of `create_class_gmm` is the `GMMHandle`, which is needed for all following classification specific operators.

5.5.2 Adjusting `add_sample_class_gmm`

A single sample is added to the GMM classifier using `add_sample_class_gmm`. For the training, several samples have to be added by successively calling `add_sample_class_gmm` with different samples. The following parameters can be adjusted:

Parameter `GMMHandle`

The input and output parameter `GMMHandle` is the handle of the classifier that was created with `create_class_gmm` and to which the samples subsequently were added with `add_sample_class_gmm`. After applying `add_sample_class_gmm` for all available samples, the handle is prepared for the actual training of the classifier.

Parameter `Features`

The input parameter `Features` contains the feature vector of a sample to be added to the classifier with `add_sample_class_gmm`. This feature vector is a tuple of values. Each value describes a specific numeric feature. Note that the feature vector must consist of real numbers. If you have integer numbers, you have to transform them into real numbers. Otherwise, an error message is raised.

Parameter `ClassID`

The input parameter `ClassID` contains the ID of the class the feature vector belongs to. The ID is an integer number between 0 and 'Number of Classes - 1'. If you created a tuple with class names, the class ID is the index of the corresponding class name in the tuple.

Parameter `Randomize`

The input parameter `Randomize` defines the standard deviation of the Gaussian noise that is added to the training data. This value is needed mainly for originally integer feature values. There, the modeled Gaussians may be aligned along axis directions and thus lead to an unusually high number of centers returned by `train_class_gmm` (see figure 5.12). This effect can be prevented by setting `Randomize` to a value larger than 0. According to experience, a value between 1.5 and 2 in most cases leads to a satisfying result. If the feature vector has been created from integer data by scaling, `Randomize` must be scaled with the same scale factor that was used to scale the original data.

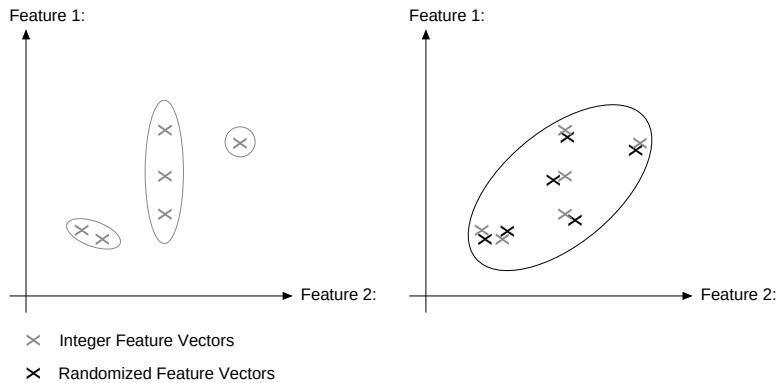


Figure 5.12: Adding noise to integer values: (left) the integer feature vectors lead to many classes, whereas for the (right) randomized feature vectors one class is obtained.

5.5.3 Adjusting `train_class_gmm`

The training of the GMM classifier is applied with `train_class_gmm`. The following parameters can be adjusted:

Parameter `GMMHandle`

The input and output parameter `GMMHandle` is the handle of the classifier that was created with `create_class_gmm` and for which samples were stored either by adding them via `add_sample_class_gmm` or by reading them in with `read_samples_class_gmm`. After applying `train_class_gmm`, the handle is prepared for the actual classification of unknown data. That is, it then contains information about how to separate the classes.

Parameters `MaxIter` / `Threshold`

The input parameter `MaxIter` defines the maximum number of iterations used for the expectation minimization algorithm. The input parameter `Threshold` defines the threshold for the relative change of the error for the expectation minimization algorithm to terminate. By reducing the number of iterations, the speed can be optimized for specific applications. But note that in most cases, the parameters `MaxIter` and `Threshold` should be used with the default values.

Parameter `ClassPriors`

The input parameter `ClassPriors` is used to select the mode for determining the probability of the occurrence of a class (see also [section 3.5](#) on page 24). That is, `ClassPriors` determines if a weighting of the classes is used that is derived from the proportion of the corresponding sample data used for the training (`ClassPriors` set to `'training'`) or if all classes have the same weight (`ClassPriors` set to `'uniform'`), i.e., the weight is $1/\text{NumClasses}$ for all classes (see [figure 5.13](#)). By default, the mode `'training'` is selected, i.e., the probability of the occurrence of a class is derived from the frequency of the class in the training set. If your training data is not representative for the frequency of the individual classes, you should use `'uniform'` instead.

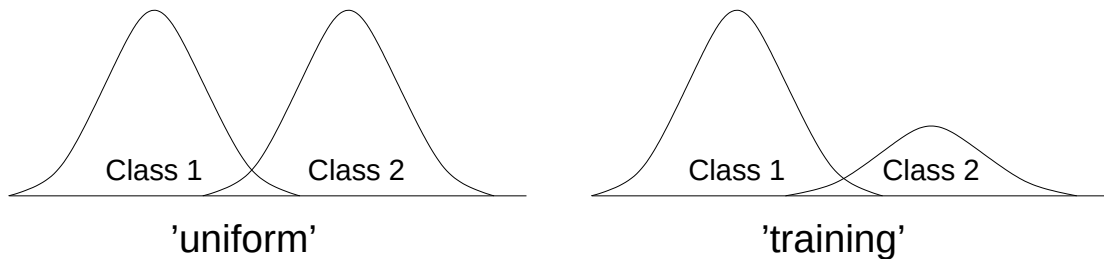


Figure 5.13: Probability of the occurrence of a class set to (left) `'uniform'` and (right) `'training'`.

Parameter `Regularize`

The input parameter `Regularize` is used to prevent the covariance matrix from a collapse which can occur for linearly dependent data. Here, we recommend to use the default value, which is 0.0001.

Parameter `Centers`

The output parameter `Centers` returns the number of found centers per class.

Parameter `Iter`

The output parameter `Iter` returns the number of iterations that were executed for the expectation minimization algorithm for each class.

5.5.4 Adjusting `evaluate_class_gmm`

The operator `evaluate_class_gmm` can be used to evaluate the probabilities for a feature vector to belong to each of the available classes. If only the probabilities for the most probable classes are searched for, no evaluation is necessary, as these probabilities are returned also for the final classification of the feature vector. The following parameters can be adjusted:

Parameter `GMMHandle`

The input parameter `GMMHandle` is the handle of the classifier that was previously trained with the operator `train_class_gmm`.

Parameter `Features`

The input parameter `Features` contains the feature vector that is evaluated. The feature vector must consist of the same features as the feature vectors used for the training samples within `add_sample_class_gmm`.

Parameter `ClassProb`

The output parameter `ClassProb` returns the a-posteriori probabilities of the given feature vector to belong to each of the classes.

Parameter `Density`

The output parameter `Density` returns the probability density of the feature vector.

Parameter `KSigmaProb`

The output parameter `KSigmaProb` describes the probability that another sample lies farther away from the mean. This value can be used for novelty detection. Then, all feature vectors with a `KSigmaProb` value below a certain k-sigma probability, e.g., 0.0001, can be rejected.

5.5.5 Adjusting `classify_class_gmm`

The operator `classify_class_gmm` is used to decide to which of the trained classes an unknown feature vector belongs. The following parameters can be adjusted:

Parameter `GMMHandle`

The input parameter `GMMHandle` describes the handle that was created with `create_class_gmm`, to which samples were added with `add_sample_class_gmm`, and that was trained with `train_class_gmm`. The handle contains all the information that the classifier needs to assign an unknown feature vector to one of the available classes.

Parameter Features

The input parameter `Features` contains the feature vector of the object that is to be classified. The feature vector must consist of the same features as the feature vectors used for the training samples within `add_sample_class_gmm`.

Parameter Num

The input parameter `Num` specifies the number of best classes to be searched for. Generally, `Num` is set to 1 if only the class with the best probability is searched for, and to 2 if the second best class is also of interest, e.g., because the classes overlap.

Parameter ClassID

The output parameter `ClassID` returns the result of classifying the feature vector with the trained GMM classifier, i.e., a tuple containing `Num` elements. That is, if `Num` is set to 1, a single value is returned that corresponds to the class with the highest probability. If `Num` is set to 2, the first element contains the class with the highest probability and the second element contains the second best class.

The following parameters output the probabilities of the classes. In comparison to the confidence value returned for an MLP classification (see [section 5.3.5](#) on page 46), the returned values are rather reliable.

Parameter ClassProb

The output parameter `ClassProb` returns the a-posteriori probabilities of the given feature vector to belong to each of the classes. In contrast to the `ClassProb` returned by `evaluate_class_gmm`, the probability is further normalized.

Parameter Density

The output parameter `Density` returns the probability density of the feature vector.

Parameter KSigmaProb

The output parameter `KSigmaProb` describes the probability that another sample lies farther away from the mean. This value can be used for novelty detection. Then, all feature vectors with a `KSigmaProb` value below a certain k-sigma probability, e.g., 0.0001, can be rejected.

5.5.6 Adjusting `clear_class_gmm`

To destroy the classifier, the operator `clear_class_gmm` is applied only with the input parameter `GMMHandle`.

5.6 Parameter Setting for k-NN

This section goes deeper into the parameter adjustment for a k-NN classification. We recommend to first adjust the parameters so that the classification result is satisfying. The most important parameters that have to be adjusted to get the k-NN classifier work optimally are:

- `NumDim` (`create_class_knn`)
- The kind of results that is returned by `classify_class_knn` (controlled by the parameter `'method'`, which is set with `set_params_class_knn`).

If the classification generally works, you can start to tune the speed. The most important parameters to enhance the speed are:

- The number of neighbors (`'k'`).
- The maximum number of returned classes (`'max_num_classes'`).
- The accuracy of the search for nearest neighbors, which is controlled by the parameters `'num_checks'` and `'epsilon'`.

All these parameters can be set with the operator `set_params_class_knn`.

In the following, we introduce the parameters of the basic k-NN operators. The focus is on the parameters for which the setting is not immediately obvious or for which it is not immediately obvious how they influence the classification. These are mainly the parameters needed for controlling the kind of result that is returned as well as the parameters that are used to speed up the classification. Further information about these operators as well as the usage of the operators with obvious parameter settings is provided in the Reference Manual entries for the individual operators.

5.6.1 Adjusting `create_class_knn`

A k-NN classifier is created with the operator `create_class_knn`. The returned handle is needed in all following steps. The only parameter that can be set is

Parameter `NumDim`

The input parameter `NumDim` specifies the dimension of the feature vectors used for the training as well as for the classification.

5.6.2 Adjusting `add_sample_class_knn`

A single sample is added to the k-NN classifier using `add_sample_class_knn`. For the training, several samples have to be added by successively calling `add_sample_class_knn` with different samples. The following parameters can be adjusted:

Parameter `KNNHandle`

The input and output parameter `KNNHandle` is the handle of the classifier that was created with `create_class_knn` and to which the samples subsequently were added with `add_sample_class_knn`. After applying `add_sample_class_knn` for all available samples, the handle is prepared for the actual training of the classifier.

Parameter Features

The input parameter `Features` contains the feature vector of a sample to be added to the classifier with `add_sample_class_knn`. This feature vector is a tuple of values. Each value describes a specific numeric feature.

Parameter ClassID

The input parameter `ClassID` contains the ID of the class the feature vector belongs to. The ID is an integer number between 0 and 'Number of Classes -1'. If you have created a tuple with class names, the class ID is the index of the corresponding class name in the tuple.

5.6.3 Adjusting `train_class_knn`

The training of the k-NN classifier is applied with `train_class_knn`. The following parameters can be adjusted:

Parameter `KNNHandle`

The input and output parameter `KNNHandle` is the handle of the classifier that was created with `create_class_knn` and for which samples were stored by adding them via `add_sample_class_knn`. After applying `train_class_knn`, the handle is prepared for the actual classification of unknown data, i.e., the internal representation of the samples is optimized for an efficient search.

Generic parameter 'num_trees'

This parameter influences the internal representation of the samples and thus the accuracy of the k-NN classification as well as its runtime. The default value for 'num_trees' is 4. To speed up the classification, the number of trees must be set to a lower value. To achieve a more accurate classification result, 'num_trees' must be set to a higher value.

Generic parameter 'normalization'

If 'normalization' is set to 'true', the feature vectors are normalized by subtracting the mean of the individual components of the training vectors and dividing the result by the standard deviation of the individual components of the training vectors. Hence, the normalized feature vectors have a mean of 0 and a standard deviation of 1. The normalization does not change the length of the feature vector.

Note that the training samples stored in the k-NN classifier are modified if `train_class_knn` is called with 'normalization' set to 'true', but the original data can be restored at any time by calling `train_class_knn` with 'normalization' set to 'false'. If normalization is used, the operator `classify_class_knn` interprets the input data as unnormalized and performs normalization internally as it has been defined in the last call to `train_class_knn`.

If you know the relation between the dimensions of the different features, it is best to apply the normalization explicitly. For example, if the first feature is given in 'mm' and the second feature is given in 'm', scaling the first with 0.001 (or the second with 1000.0) will typically produce better classification results than using the built-in normalization of `train_class_knn`.

5.6.4 Adjusting `set_params_class_knn`

With `set_params_class_knn`, some parameters can be set that control the behaviour of `classify_class_knn`.

Generic parameter `'k'`

The parameter `'k'` defines the number of nearest neighbors that are determined during the classification. The selection of a suitable value for `'k'` depends heavily on the classification task. Generally, larger values of `'k'` lead to higher robustness against noise, smooth the boundaries between the classes, and lead to longer runtimes during the classification.

In practice, the best way of finding a suitable value for `'k'` is indeed to try different values and to select the value for `'k'` that yields the best classification results under the constraint of an acceptable runtime.

Generic parameters `'method'` and `'max_num_classes'`

The parameter `'method'` controls the kind of result that is returned by `classify_class_knn` while the parameter `'max_num_classes'` controls how many different classes may be returned. Note that `'max_num_classes'` is an upper bound for the number of returned classes because the `'k'` nearest neighbors may contain less than `'max_num_classes'` classes.

The default value for `'max_num_classes'` is `1`. In this case, only the best rated class is returned, which is often sufficient. If you need information about the reliability of the classification result, `'max_num_classes'` should be set to a value larger than `1` and the ratings of the returned classes, which are given in the output parameter `Rating` of the operator `classify_class_knn`, should be analysed. For example, you can check if the rating of the first returned class is significantly better than that of the second one. If this is not the case, the classification of this specific sample is not reliable. In this case, application knowledge may help to decide, which of the best rated results is the correct one.

If `'method'` is set to `'classes_distance'`, `classify_class_knn` returns each class that exists in the set of the `k`-nearest neighbors. For each returned class, its smallest distance to the sample to be classified is returned. The returned classes are sorted according to this distance, i.e., the first element of the returned classes contains the nearest neighbor. `'classes_distance'` is the default value for the `'method'`.

If `'method'` is set to `'classes_frequency'`, `classify_class_knn` performs a simple majority vote (see [section 3.6](#) on page 26) and returns those classes that occur among the `'k'` nearest neighbors sorted according to their relative frequency. For example, if `'k'` is set to `10` and among the 10 nearest neighbors, there are 7 samples that belong to class 9 and 3 samples that belong to class 4, the tuple `[9, 4]` is returned.

If `'method'` is set to `'classes_weighted_frequencies'`, `classify_class_knn` performs a weighted majority vote (see [section 3.6](#) on page 26) and returns those classes that occur among the `'k'` nearest neighbors sorted according to their relative frequency weighted with the distances of the individual neighbors from the sample to be classified. Thus, classes are better rated if they provide neighbors very close to the sample to be classified.

If `'method'` is set to `'neighbors_distance'`, `classify_class_knn` returns the indices of the `'k'` nearest neighbors and their distances. This may be useful if none of the above described options fits your requirements. In this case, you can use the information about the nearest neighbors and their distances to the sample to be classified to implement your own voting scheme.

Generic parameters 'num_checks' and 'epsilon'

In order to provide a really fast k-NN classifier, HALCON uses an approximate algorithm for the search for the '*k*' nearest neighbors. The two parameters 'num_checks' and 'epsilon' allow to control the trade-off between speed and accuracy of this search. Typically, adjusting the parameter 'num_checks' has a greater effect than adjusting the parameter 'epsilon'.

'num_checks' sets the maximum number of runs through the internal search trees. The default value is 32. To speed up the search, use a lower value (that is greater than 0). To perform an exact search, 'num_checks' must be set to 0.

'epsilon' sets a stop criterion for the search. The default value is 0.0. To potentially speed up the search, use a higher value.

5.6.5 Adjusting `classify_class_knn`

The operator `classify_class_knn` is used to decide to which of the trained classes an unknown feature vector belongs. The following parameters can be adjusted:

Parameter `KNNHandle`

The input parameter `KNNHandle` describes the handle that was created with `create_class_knn`, to which samples were added with `add_sample_class_knn`, and that was trained with `train_class_knn`. The handle contains all the information that the classifier needs to assign an unknown feature vector to one of the available classes.

Parameter `Features`

The input parameter `Features` contains the feature vector of the object that is to be classified. The feature vector must consist of the same kind of features as the feature vectors used for the training samples within `add_sample_class_knn`.

Parameter `Result`

The output parameter `Result` returns the result of classifying the feature vector with the trained k-NN classifier. This result depends on the '*method*' that was selected in `set_params_class_knn` (see [section 5.6.4](#) on page 64 above for a detailed description of `set_params_class_knn`).

Parameter `Rating`

The output parameter `Rating` returns the distances of the returned classes from their nearest neighbor(s). This result depends on the '*method*' that was selected in `set_params_class_knn` (see [section 5.6.4](#) on page 64 for the description of `set_params_class_knn`).

5.6.6 Adjusting `clear_class_knn`

To destroy the classifier, the operator `clear_class_knn` is applied only with the input parameter `KNNHandle`.

Chapter 6

Classification for Image Segmentation

If classification is used to find objects in an image, the individual pixels of an image are classified according to the features 'color' or 'texture' and all pixels belonging to the same class are combined in a region representing the desired object. That is, the image is segmented into regions of different classes.

For image segmentation, the pixels of an image are classified according to a set of available classes, which are defined by the training samples. The training samples are image regions of known classes. The features used for the training of the classes as well as for the classification are color or texture. Such a pixel-based classification can be realized by several approaches in HALCON. These are MLP, SVM, GMM, and k-NN classifiers (see [section 6.1](#)) and some simple but fast classifiers that use a 2D histogram to segment two-channel images (see [section 6.2](#) on page 87) or that apply a hyperbox or Euclidean classification for multi-channel images (see [section 6.3](#) on page 88).

6.1 Approach for MLP, SVM, GMM, and k-NN

The set of operators used for image segmentation with MLP, SVM, GMM, and k-NN in parts corresponds to the set of operators used for the general classification described in [section 5](#) on page 33. Operators that are specific for image segmentation are those that add the training samples to the classifier and the operators used for the actual classification. These are used instead of the corresponding general operators.

In [section 6.1.1](#), the general approach for image segmentation is illustrated by different examples that on the one hand show how to segment different citrus fruits from the background using color and on the other hand show how to apply novelty detection for a regular mesh using texture. In [section 6.1.2](#) the steps of an image segmentation and the involved operators are listed for a brief overview. The parameters of the operators that are specific for image segmentation are introduced in more detail in [section 6.1.3](#) for MLP, [section 6.1.4](#) for SVM, [section 6.1.5](#) for GMM, and [section 6.1.6](#) for k-NN.

Finally, [section 6.1.7](#) shows how to speed up image segmentation for images with a maximum of three image channels by applying a classification that is based on look-up tables (LUT). Here, the trained

classifier is used to create a look-up table that stores every possible response of the MLP, SVM, GMM, or k-NN classifier, respectively. Using the LUT-accelerated classifier instead of the original trained classifier, the class of every image point can be taken directly from the LUT instead of being calculated expensively. But note that for a LUT-accelerated classification also additional memory is needed and the runtime for the offline part is increasing.

6.1.1 General Approach

Figure 6.1 shows the general approach for image segmentation. The main difference to the general classification approach is that on the one hand the objects to classify are restricted to pixels and on the other hand the features are not explicitly extracted but automatically derived from the different channels of a color or texture image. Thus, you do not have to apply a feature extraction for the training and once again for the classification, but simply apply a training using some sample regions of multi-channel images. Then you can immediately use the trained classifier to segment images into regions of the trained color or texture classes.

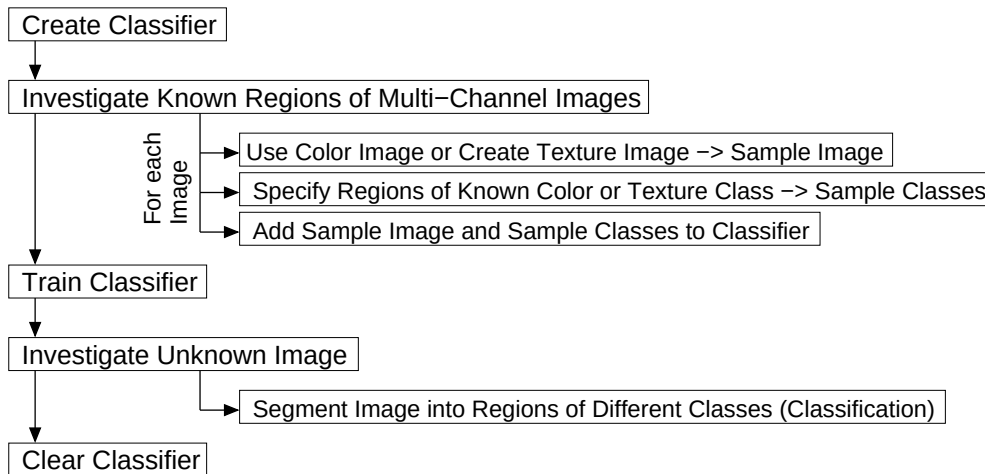


Figure 6.1: The basic steps of image segmentation.

Besides the classical image segmentation, the operators for SVM, GMM, and k-NN can be used also for novelty detection. In this case, for SVM only one class is trained and the classification returns the pixels that significantly deviate from the class. For GMM and k-NN, one or more classes can be trained and the classification rejects the pixels that significantly deviate from any of the classes. That is, the “novelties” (or defects, respectively) within an image are those pixels that are not assigned to one of the trained classes. The following examples demonstrate how to apply classical image segmentation and novelty detection.

6.1.1.1 Image Segmentation

The example `solution_guide\classification\segment_citrus_fruits.hdev` shows how to segment an image to separate lemons and oranges from their background. The lemons and oranges

were already introduced in [section 3](#) on page 17. There, a general classification with shape features was proposed to distinguish between lemons and oranges. The corresponding example can be found in [section 8.3.1](#) on page 119. Here, the lemons and oranges are separated from the background using their color, i.e., the feature vectors are built by the gray values of three image channels. The classification is applied with the MLP approach. The operator names for the GMM, SVM, and k-NN classification differ only in their ending. That is, if you want to apply a GMM, SVM, or k-NN classification, you mainly have to replace 'mlp' by 'gmm', 'svm', or 'knn', respectively in the specific operator names and adjust different parameters. The parameters of the operators that correspond to the general classification and their selection are described in [section 5.3](#) for MLP, [section 5.4](#) for SVM, [section 5.5](#) for GMM, and [section 5.6](#) for k-NN. The parameters of the operators that are specific for image segmentation and their selection are described in [section 6.1.3](#) for MLP, [section 6.1.4](#) for SVM, [section 6.1.5](#) for GMM, and [section 6.1.6](#) for k-NN.

The program starts with the creation of an MLP classifier. Following the instructions given in [section 5.3.1](#) on page 41 the parameter `NumInput` is set to 3 as the images consist of three channels, which leads to three features for the feature vectors, the parameter `NumHidden` is set to 3 so that it is in a similar value range as `NumInput` and `NumOutput`. `NumOutput` is set to 3 as three classes are used: one for the oranges, one for the lemons, and one for the background. `OutputFunction` must be set to 'softmax' for image segmentation. `Preprocessing` is set to 'normalization', so `NumComponents` can be ignored. The operator returns the handle of the new classifier that is needed for the following steps.

```
create_class_mlp (3, 3, 3, 'softmax', 'normalization', 10, 42, MLPHandle)
```

Now, an image containing oranges is read and a region for the class 'orange' and one for the class 'background' are created (see [figure 6.2](#), left). As no lemon is contained in the image, an empty region is created by `gen_empty_region`. All three regions are concatenated to a tuple with `concat_objj` and are then added together with the input image and the handle of the classifier to the classifier with `add_samples_image_class_mlp`.

```
read_image (Image, 'color/citrus_fruits_01')
gen_rectangle1 (OrangeRegion, 100, 130, 230, 200)
gen_rectangle1 (BackgroundRegion, 30, 20, 50, 50)
gen_empty_region (EmptyRegion)
gen_empty_objj (TrainingRegions1)
concat_objj (TrainingRegions1, OrangeRegion, TrainingRegions1)
concat_objj (TrainingRegions1, EmptyRegion, TrainingRegions1)
concat_objj (TrainingRegions1, BackgroundRegion, TrainingRegions1)
add_samples_image_class_mlp (Image, TrainingRegions1, MLPHandle)
```

A second image is read that contains lemons. Now, a region for the class 'lemons' and one for the class 'background' are generated (see [figure 6.2](#), right) and are concatenated together with an empty region to a tuple of regions. The sequence of the contained regions is the same as for the image with the oranges, i.e., the first element contains the region for oranges (in this case an empty region), the second element contains the region for lemons, and the third element contains the region for the background. Then, the operator `add_samples_image_class_mlp` is called again to extend the samples that are already added to the classifier.

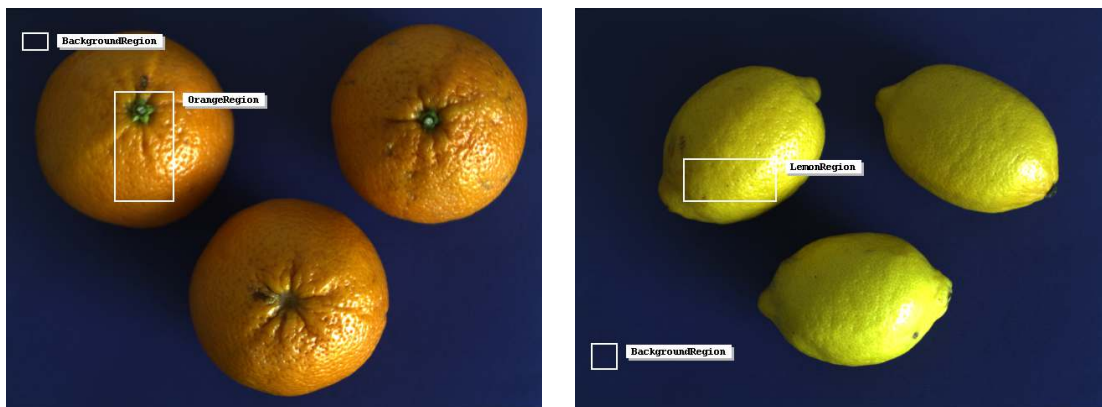


Figure 6.2: Regions from two images are used as training regions.

```
read_image (Image, 'color/citrus_fruits_03')
gen_rectangle1 (LemonRegion, 180, 130, 230, 240)
gen_rectangle1 (BackgroundRegion, 400, 20, 430, 50)
gen_empty_obj (TrainingRegions2)
concat_obj (TrainingRegions2, EmptyRegion, TrainingRegions2)
concat_obj (TrainingRegions2, LemonRegion, TrainingRegions2)
concat_obj (TrainingRegions2, BackgroundRegion, TrainingRegions2)
add_samples_image_class_mlp (Image, TrainingRegions2, MLPHandle)
```

After adding all training regions, the classifier is trained.

```
train_class_mlp (MLPHandle, 200, 1, 0.01, Error, ErrorLog)
```

Now, a set of images is read and segmented according to the rules that the classifier derived from the training. The result is a region for each class.

```
for I := 1 to 15 by 1
    read_image (Image, 'color/citrus_fruits_' + I$.2d)
    classify_image_class_mlp (Image, ClassRegions, MLPHandle, 0.5)
    select_obj (ClassRegions, ClassOranges, 1)
    select_obj (ClassRegions, ClassLemons, 2)
    select_obj (ClassRegions, ClassBackground, 3)
    dev_set_draw ('fill')
    dev_display (Image)
    dev_set_color ('slate blue')
    dev_display (ClassBackground)
    dev_set_color ('goldenrod')
    dev_display (ClassOranges)
    dev_set_color ('yellow')
    dev_display (ClassLemons)
```

The result of the segmentation is visualized by three different colors. Note that the colors applied in the example and the colors used for the representation in [figure 6.3](#) vary because different colors are suited for print purposes and for the presentation on a screen. Note further, that the erroneously classified pixels are caused by the overlapping classes that occur because of gray shadings that affected both types of fruits.

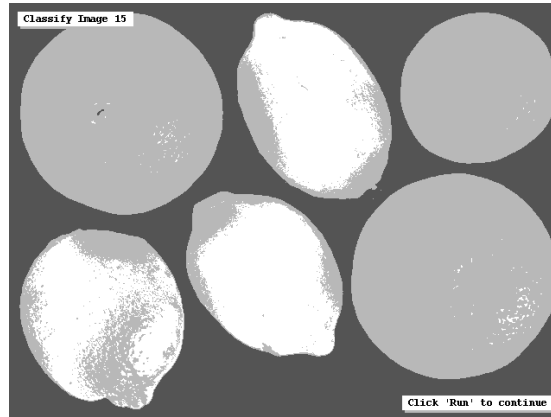


Figure 6.3: Segmentation of the image into the classes (dim gray) 'background', (gray) 'oranges', and (white) 'lemons'. Erroneously classified pixels at the border of the lemons occur, because the shadows at the border of both fruit types have the same color.

For a better result, the illumination could have been adjusted more carefully to avoid shadings and reflections of the fruits. Additionally, many more samples would have been required for a 'real' application. Note that this example mainly aims to demonstrate the general approach of an image segmentation. But even with the few erroneously classified pixels, a class decision can be found for each fruit. For that, we apply a post processing. That is, for each fruit class we use morphological operators to close small gaps, apply the operator [connection](#) to separate connected components, and then select those shapes from the connected components that exceed a specific size. Additionally, holes inside the regions are filled up with [fill_up](#) and the shapes of the regions are transformed to their convex hulls with [shape_trans](#). The result is shown in [figure 6.4](#). At the end of the program, the classifier is cleared.

```

closing_circle (ClassOranges, RegionClosingOranges, 3.5)
connection (RegionClosingOranges, ConnectedRegionsOranges)
select_shape (ConnectedRegionsOranges, SelectedRegionsOranges, 'area', \
              'and', 20000, 99999)
fill_up (SelectedRegionsOranges, RegionFillUpOranges)
shape_trans (RegionFillUpOranges, RegionFillUpOranges, 'convex')
closing_circle (ClassLemons, RegionClosingLemons, 3.5)
connection (RegionClosingLemons, ConnectedRegionsLemons)
select_shape (ConnectedRegionsLemons, SelectedRegionsLemons, 'area', \
              'and', 15000, 99999)
fill_up (SelectedRegionsLemons, RegionFillUpLemons)
shape_trans (RegionFillUpLemons, RegionFillUpLemons, 'convex')
dev_display (Image)
dev_set_draw ('margin')
dev_set_color ('goldenrod')
dev_display (RegionFillUpOranges)
dev_set_color ('yellow')
dev_display (RegionFillUpLemons)
endfor
clear_class_mlp (MLPHandle)

```

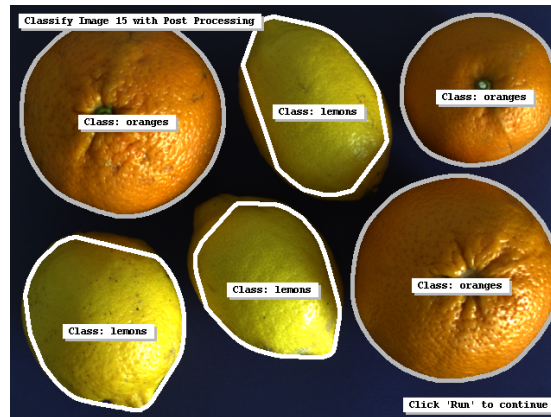


Figure 6.4: Segmentation result after postprocessing.

For the images at hand, alternatively also a general classification using shape features can be applied like described in [section 8.3.1](#) on page 119.

6.1.1.2 Novelty Detection with SVM

The example program `hdevelop\Segmentation\Classification\novelty_detection_svm.hdev` shows how to apply a novelty detection with SVM. For a novelty detection with SVM, a single class is trained and the classification is used to find all regions of an image that do not belong to this class.

The program trains the texture of a regular plastic mesh. Before creating a classifier, a rectangle is generated that is used later as region of interest. This region of interest is necessary, because the images of the plastic mesh to be inspected do not contain an integer number of mesh cells. Thus, if the original image would have been trained and classified, the texture filters that are applied to create a multi-channel texture image would probably return artifacts at the image borders.

```
gen_rectangle1 (Rectangle, 10, 10, Height / 2 - 11, Width / 2 - 11)
```

The SVM classifier is created with `create_class_svm`. With SVM, novelty detection is a two-class problem (see also [section 5.4.1](#) on page 50) and the classifier must be explicitly set to 'novelty-detection' using the parameter `Mode`. Additionally, the `KernelType` must be set to 'rbf'.

```
create_class_svm (5, 'rbf', 0.01, 0.0005, 1, 'novelty-detection', \
                  'normalization', 5, SVMHandle)
```

Then, all training images, i.e., images containing a good mesh, are read in a loop and scaled down by a factor of two. This is done, so that the textures can be optimally filtered with a filter size of 5x5 when creating a multi-channel texture image within the procedure `gen_texture_image`. Theoretically, also the original size could be used with a filter size of 10x10, but this would need too much time and the accuracy for the smaller image is sufficient for the application. The procedure `gen_texture_image` creates a multi-channel texture image for each image. This is then passed together with the region of interest to the operator `add_samples_image_class_svm` to add the sample region to the classifier.

```
for J := 1 to 5 by 1
  read_image (Image, 'plastic_mesh/plastic_mesh_' + J$'02')
  zoom_image_factor (Image, ImageZoomed, 0.5, 0.5, 'constant')
  disp_message (WindowHandle, 'Adding training samples...', 'window', -1, \
                -1, 'black', 'true')
  gen_texture_image (ImageZoomed, ImageTexture)
  add_samples_image_class_svm (ImageTexture, Rectangle, SVMHandle)
endfor
```

The procedure `gen_texture_image` creates the multi-channel image by applying the texture filter `texture_laws` to the zoomed image with varying parameters and combining the differently filtered images to one image using `compose5`. The result is additionally smoothed before the procedure returns the final texture image.

```
texture_laws (Image, ImageEL, 'el', 5, 5)
texture_laws (Image, ImageLE, 'le', 5, 5)
texture_laws (Image, ImageES, 'es', 1, 5)
texture_laws (Image, ImageSE, 'se', 1, 5)
texture_laws (Image, ImageEE, 'ee', 2, 5)
compose5 (ImageEL, ImageLE, ImageES, ImageSE, ImageEE, ImageLaws)
smooth_image (ImageLaws, ImageTexture, 'gauss', 5)
```

After adding all training regions to the classifier, the classifier is trained with `train_class_svm`. To speed up the classification, the resulting support vectors are reduced with `reduce_class_svm`, which leads to the new classifier `SVMHandleReduced`. Note, that this operator is specific for SVM.

```
train_class_svm (SVMHandle, 0.001, 'default')
reduce_class_svm (SVMHandle, 'bottom_up', 2, 0.001, SVMHandleReduced)
```

Now, the novelty detection is applied to several images. That is, each image is transformed to a multi-channel texture image like described for the training part. This time, as `classify_class_svm` needs only the image and not a region as input, the image is additionally reduced to the domain of the region of interest. The reduced image is then passed to the operator `classify_class_svm` for novelty detection. The output parameter `ClassRegions` (here called `Errors`) returns all pixels of the image that do not belong to the trained texture. With a set of morphological operators and a blob analysis it is checked if connected components that exceed a certain size exist, i.e., if the image contains significant 'novelties'.

```
for J := 1 to 14 by 1
  read_image (Image, 'plastic_mesh/plastic_mesh_' + J$'02')
  zoom_image_factor (Image, ImageZoomed, 0.5, 0.5, 'constant')
  gen_texture_image (ImageZoomed, ImageTexture)
  reduce_domain (ImageTexture, Rectangle, ImageTextureReduced)
  classify_image_class_svm (ImageTextureReduced, Errors, SVMHandleReduced)
  opening_circle (Errors, ErrorsOpening, 3.5)
  closing_circle (ErrorsOpening, ErrorsClosing, 10.5)
  connection (ErrorsClosing, ErrorsConnected)
  select_shape (ErrorsConnected, FinalErrors, 'area', 'and', 300, 1000000)
  count_obj (FinalErrors, NumErrors)
  if (NumErrors > 0)
    disp_message (WindowHandle, 'Mesh not OK', 'window', -1, -1, 'red', \
                  'true')
  else
    disp_message (WindowHandle, 'Mesh OK', 'window', -1, -1, \
                  'forest green', 'true')
  endif
endfor
```

At the end of the novelty detection the classifiers are cleared from memory.

```
clear_class_svm (SVMHandle)
clear_class_svm (SVMHandleReduced)
```

6.1.1.3 Novelty Detection with GMM or k-NN

The example program `hdevelop\Segmentation\Classification\novelty_detection_gmm.hdev` shows how to apply a novelty detection with GMM. Generally, the example does the same as `hdevelop\Segmentation\Classification\novelty_detection_svm.hdev` did. That is, the same images are used and the results are rather similar (see [figure 6.5](#)). The significant differences between novelty detection with GMM and with SVM concern the parameter settings when creating the classifier and the output returned when classifying an image. The novelty detection is presented here with the GMM approach. The operator names for the GMM and k-NN classification differ only in their ending. That is, if you want to apply

a k-NN classification for the novelty detection, you mainly have to replace 'gmm' with 'knn' in the specific operator names and adjust some parameters.

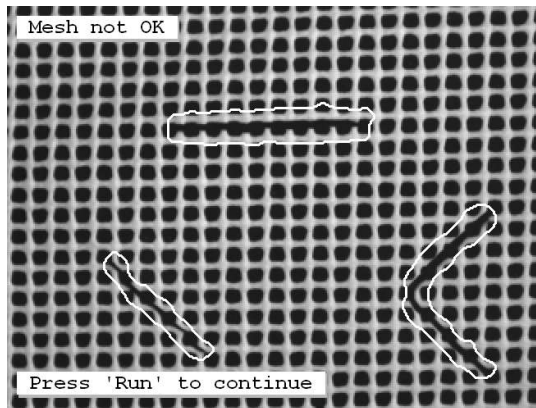
When creating the classifier for GMM, in contrast to SVM, no explicit parameter for novelty detection is needed. Here, simply a classifier for a single class (`NumClasses` set to 1) is created.

```
create_class_gmm (5, 1, [1,5], 'spherical', 'normalization', 5, 42, \
                  GMMHandle)
```

When classifying an image, the output parameter `ClassRegions` (here called `Correct`) of the operator `classify_image_class_gmm`, in contrast to the novelty detection with SVM, does not return a region built by erroneous pixels but a region that is built by pixels that belong to the trained texture class. To obtain the erroneous region, the difference between the input region and the returned region has to be calculated using `difference`.

```
classify_image_class_gmm (ImageTextureReduced, Correct, GMMHandle, \
                          0.001)
difference (Rectangle, Correct, Errors)
```

Novelty-Detection with SVM



Novelty-Detection with GMM

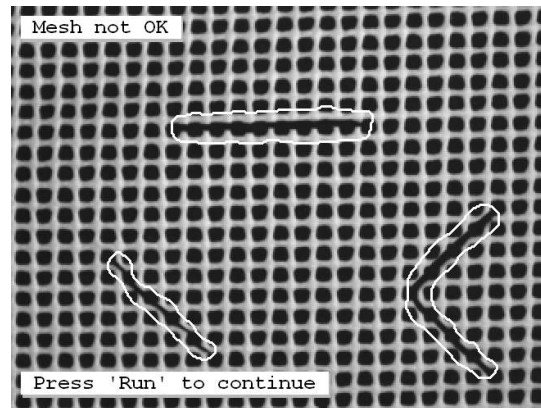


Figure 6.5: Novelty detection is used to extract parts of an image or region that do not fit to a trained pattern and can be applied with SVM or GMM.

Both significant differences occur because the GMM classifier by default returns only those regions that precisely belong to the trained classes (within a specified threshold) and thus automatically rejects all other pixels. For SVM, parts that do not belong to a class can only be determined for two-class problems, i.e., when explicitly setting the `Mode` to 'novelty-detection'. Otherwise, SVM assigns all pixels to the available classes, even if some pixels do not significantly match any of them. When explicitly setting a parameter for novelty detection, it is obvious that the returned region should show the requested novelties. For GMM, no specific parameter has to be set, i.e., the novelty detection is realized by applying a regular image segmentation. Thus, the returned region shows the parts of the image that match the trained class. Note that for the GMM classifier novelty detection is not restricted to a two-class problem and image segmentation, but can be applied also for multi-class problems and general classification (see [section 5.5.5](#) on page 60).

6.1.2 Involved Operators (Overview)

This section gives a brief overview on the operators that are provided for MLP, SVM, GMM, and k-NN classification for image segmentation. In particular, first the operators for the basic steps and then the advanced operators used for image segmentation are introduced.

6.1.2.1 Basic Operators

Summarizing the information obtained in [section 6.1.1](#) on page 68, the image segmentation consists of the following basic steps and operators, which are applied in the same order as listed here. Note that the steps are similar to the steps applied for a general classification (see [section 5.2.1](#) on page 37), mainly the step for adding the samples and the step for the actual classification vary.

1. Create a classifier. Here, some important properties of the classifier are defined. The returned handle is needed in all later classification steps. Each classification step modifies this handle. This step corresponds to the approach of the general classification.

- `create_class_mlp`
- `create_class_svm`
- `create_class_gmm`
- `create_class_knn`

2. Predefine the sequence in which the classes are defined and later accessed, i.e., define the correspondences between the class IDs and the class names, respectively define the colors that visualize the different classes. This step may as well be applied before the creation of the classifier.

3. Add samples, i.e., a region for each class to the classifier. In contrast to the general classification, a single operator call can be used to add all sample regions at once. The sequence of the added regions define the classes, i.e., the first region is class 0, the second is class 1 etc. Having several images for the training, the operator can be called multiple times, then the sample regions for the classes must be defined in the same sequence. If one of the classes is not represented in an image, an empty region has to be passed. This step significantly differs from the approach of the general classification.

- `add_samples_image_class_mlp`
- `add_samples_image_class_svm`
- `add_samples_image_class_gmm`
- `add_samples_image_class_knn`

4. Train the classifier, i.e., use the added samples to obtain the boundaries between the classes. This step corresponds to the approach of the general classification.

- `train_class_mlp`
- `train_class_svm`
- `train_class_gmm`

- `train_class_knn`
5. Store the used samples to file and access them in a later step (optionally). This step corresponds to the approach of the general classification.
 - `write_samples_class_mlp` and `read_samples_class_mlp`
 - `write_samples_class_svm` and `read_samples_class_svm`
 - `write_samples_class_gmm` and `read_samples_class_gmm`
 - Note that there are no operators for writing and reading the samples of a k-NN classifier separately because the samples are an intrinsic component of the k-NN classifier. Use `write_class_knn` and `read_class_knn` instead.
 6. Store the trained classifier to file and read it from file again or, if the offline and online part is not separated, clear the samples manually from memory. This step corresponds to the approach of the general classification.
 - `write_class_mlp` (default file extension: .gmc) and `read_class_mlp` or `clear_samples_class_mlp`
 - `write_class_svm` (default file extension: .gsc) and `read_class_svm` or `clear_samples_class_svm`
 - `write_class_gmm` (default file extension: .ggc) and `read_class_gmm` or `clear_samples_class_gmm`
 - `write_class_knn` (default file extension: .gnc) and `read_class_knn`
Note that the samples cannot be deleted from a k-NN classifier because they are an intrinsic component of this classifier.
 7. Segment the image by classification. That is, insert a new image and use one of the following operators to segment the image into regions of different classes. This step significantly differs from the approach of the general classification.
 - `classify_image_class_mlp`
 - `classify_image_class_svm`
 - `classify_image_class_gmm`
 - `classify_image_class_knn`
 8. Clear the classifier from memory. This step corresponds to the approach of the general classification.
 - `clear_class_mlp` or `clear_class_mlp`
 - `clear_class_svm` or `clear_class_svm`
 - `clear_class_gmm` or `clear_class_gmm`
 - `clear_class_knn` or `clear_class_knn`

Besides the basic steps of a classification, some additional steps and operators can be applied if suitable. These advanced operators are similar for image segmentation and general classification.

6.1.2.2 Advanced Operators

Especially if the training and classification do not lead to a satisfying result, it is helpful to access some information that is implicitly contained in the model. Available steps to query information are:

- Access an individual sample from the training data. This is needed, e.g., to check the correctness of its class assignment. The sample had to be stored previously by the operator `add_samples_image_class_mlp`, `add_samples_image_class_svm`, `add_samples_image_class_gmm`, or `add_samples_image_class_knn`, respectively.

- `get_sample_class_mlp`
 - `get_sample_class_svm`
 - `get_sample_class_gmm`
 - `get_sample_class_knn`

- Get the number of samples that are stored in the training data. The obtained number is needed, e.g., to access the individual samples or to know how much individual samples you can access.

- `get_sample_num_class_mlp`
 - `get_sample_num_class_svm`
 - `get_sample_num_class_gmm`
 - `get_sample_num_class_knn`

- Get information about the content of the preprocessed feature vectors. This information is reasonable, if the parameter Preprocessing was set to 'principal_components' or 'canonical_variates' during the creation of the classifier. Then, you can check if the information that is contained in the preprocessed feature vector still contains significant data or if a different preprocessing parameter, e.g., 'normalization', is to be preferred.

- `get_prep_info_class_mlp`
 - `get_prep_info_class_svm`
 - `get_prep_info_class_gmm`

- Note that this kind of operator is not available for k-NN classifiers, because they do not provide the above mentioned preprocessing options.

- Get the parameter values that were set during the creation of the classifier. This is needed if the offline training and the online classification are separated and the information about the training part is not available anymore.

- `get_params_class_mlp`
 - `get_params_class_svm`
 - `get_params_class_gmm`
 - `get_params_class_knn`

Furthermore, there are operators that are available only for specific classifiers. In particular,

- For SVM you can reduce the number of support vectors returned by the offline training to speed up the following online classification.
 - `reduce_class_svm`
- Additionally, for SVM the number or index of the support vectors can be determined after the training. This is suitable for the visualization of the support vectors and thus for diagnostic reasons.
 - `get_support_vector_num_class`
 - `get_support_vector_class`
- For k-NN classifiers, you can set various parameters with
 - `set_params_class_knn`.

See [section 5.6.4](#) on page 64 for a detailed descriptions of this operator.

If you want to speed up an image segmentation for images with a maximum of three image channels, you can apply a classification that is based on look-up tables (LUT, see also [section 6.1.7](#) on page 84). Then, the approach differs from the basic image segmentation as follows:

- After creating a classifier, adding samples to it and training it, the result of the training is stored in a LUT-accelerated classifier.
 - `create_class_lut_mlp`
 - `create_class_lut_svm`
 - `create_class_lut_gmm`
 - `create_class_lut_knn`
- For the actual image segmentation, instead of `classify_image_class_mlp`, `classify_image_class_svm`, `classify_image_class_gmm`, or `classify_image_class_knn`, respectively, the LUT-accelerated classifier is applied.
 - `classify_image_class_lut`
- At the end of the classification, besides the originally created and trained classifier also the LUT-accelerated classifier is destroyed.
 - `clear_class_lut`

6.1.3 Parameter Setting for MLP

Most rules for the parameter setting for an image segmentation using MLP classification correspond to the rules for the general classification with MLP (see [section 5.3](#) on page 40). As the most important operators and parameters to adjust are listed and described there, here only the parameter settings for the operators that are specific for image segmentation are described. These are the operators that add the training samples, i.e., sample regions, to the classifier and those that segment the unknown image.

6.1.3.1 Adjusting `add_samples_image_class_mlp`

For image segmentation with MLP, sample regions are added to the classifier with `add_samples_image_class_mlp`. In contrast to the samples used for a general classification, here, no feature vectors have to be generated explicitly but are implicitly given by the gray values of each pixel of the respective input region in all channels of the input image. The dimension of the feature vectors depends on the number of channels of the image containing the sample regions. The quality of the samples is very important for the quality of the classification. [Section 4.3](#) on page 32 provides hints how to select a set of suitable samples. For the operator `add_samples_image_class_mlp`, the following parameters have to be set:

- **Image**: The image that contains the sample regions
- **ClassRegions**: The tuple containing the training regions. Here, one region per class is defined. The number of classes corresponds to the number of regions, and thus, the label of an individual class corresponds to the position of the training region in the tuple, i.e., its index.
- **MLPHandle**: The handle of the classifier that was created with `create_class_gmm`

The operator returns the modified handle of the classifier (`MLPHandle`).

6.1.3.2 Adjusting `classify_image_class_mlp`

With the operator `classify_image_class_mlp` a new image is segmented into regions of the classes that were trained with `train_class_mlp` using the samples that were added with `add_samples_image_class_mlp`. The following parameters have to be set:

- **Image**: The image that has to be segmented into the classes that were trained with `train_class_gmm`.
- **MLPHandle**: The handle of the classifier that was created with `create_class_mlp`, to which samples were added with `add_samples_image_class_mlp`, and that was trained with `train_class_mlp`.
- **RejectionThreshold**: The threshold on the probability measure returned by the classification. All pixels having a probability below `RejectionThreshold` are not assigned to any class.

The operator returns a tuple of regions in `ClassRegions`. This tuple contains one region for each class. The sequence of the classes corresponds to the sequence used for the training regions that were added to the classifier with `add_samples_image_class_mlp`.

In contrast to the general classification using `classify_class_mlp` described in [section 5.3.5](#) on page 46, no confidence for the classification but a rejection class is returned. This rejection class depends on the selected rejection threshold. Note that the returned rejection class has not the same quality than the rejection class returned for a GMM classification, as the MLP classification is typically influenced by outliers (see [section 5.3.5](#) on page 47). Thus, for MLP the explicit training of a rejection class is recommended.

6.1.4 Parameter Setting for SVM

Most rules for the parameter setting for an image segmentation using SVM classification correspond to the rules for the general classification with SVM (see [section 5.4](#) on page 47). As the most important operators and parameters to adjust are listed and described there, here only the parameter settings for the operators that are specific for image segmentation are described. These are the operators that add the training samples, i.e., sample regions, to the classifier and those that segment the unknown image.

6.1.4.1 Adjusting `add_samples_image_class_svm`

For image segmentation with SVM, sample regions are added to the classifier with `add_samples_image_class_svm`. In contrast to the samples used for a general classification, here, no feature vectors have to be generated explicitly but are implicitly given by the gray values of each pixel of the respective input region in all channels of the input image. The dimension of the feature vectors depends on the number of channels of the image containing the sample regions. The quality of the samples is very important for the quality of the classification. [Section 4.3](#) on page 32 provides hints how to select a set of suitable samples. For the operator `add_samples_image_class_svm`, the following parameters have to be set:

- **Image:** The image that contains the sample regions
- **ClassRegions:** The tuple containing the training regions. Here, one region per class is defined. The number of classes corresponds to the number of regions, and thus, the label of an individual class corresponds to the position of the training region in the tuple, i.e., its index.
- **SVMHandle:** The handle of the classifier that was created with `create_class_svm`

The operator returns the modified handle of the classifier (`SVMHandle`).

6.1.4.2 Adjusting `classify_image_class_svm`

With the operator `classify_image_class_svm` a new image is segmented into regions of the classes that were trained with `train_class_svm` using the samples that were added with `add_samples_image_class_svm`. The following parameters have to be set:

- **Image:** The image that has to be segmented into the classes that were trained with `train_class_svm`.
- **SVMHandle:** The handle of the classifier that was created with `create_class_svm`, to which samples were added with `add_samples_image_class_svm`, and that was trained with `train_class_svm`.

The operator returns a tuple of regions in `ClassRegions`. This tuple contains one region for each class. The sequence of the classes corresponds to the sequence used for the training regions that were added to the classifier with `add_samples_image_class_svm`.

6.1.5 Parameter Setting for GMM

Most rules for the parameter setting for an image segmentation using GMM classification correspond to the rules for the general classification with GMM (see [section 5.5](#) on page 54). As the most important operators and parameters to adjust are listed and described there, here only the parameter settings for the operators that are specific for image segmentation are described. These are the operators that add the training samples, i.e., sample regions, to the classifier and those that segment the unknown image.

6.1.5.1 Adjusting `add_samples_image_class_gmm`

For image segmentation with GMM, sample regions are added to the classifier with `add_samples_image_class_gmm`. In contrast to the samples used for a general classification, here, no feature vectors have to be generated explicitly but are implicitly given by the gray values of each pixel of the respective input region in all channels of the input image. The dimension of the feature vectors depends on the number of channels of the image containing the sample regions. The quality of the samples is very important for the quality of the classification. [Section 4.3](#) on page 32 provides hints how to select a set of suitable samples. For the operator `add_samples_image_class_gmm`, the following parameters have to be set:

- **Image:** The image that contains the sample regions
- **ClassRegions:** The tuple containing the training regions. Here, one region per class is defined. The number of classes corresponds to the number of regions, and thus, the label of an individual class corresponds to the position of the training region in the tuple, i.e., its index.
- **GMMHandle:** The handle of the classifier that was created with `create_class_gmm`
- **Randomize:** The parameter that handles undesired effects that may occur for originally integer feature values (see also [section 5.5.2](#) on page 58).

The operator returns the modified handle of the classifier (`GMMHandle`).

6.1.5.2 Adjusting `classify_image_class_gmm`

With the operator `classify_image_class_gmm` a new image is segmented into regions of the classes that were trained with `train_class_gmm` using the samples that were added with `add_samples_image_class_gmm`. The following parameters have to be set:

- **Image:** The image that has to be segmented into the classes that were trained with `train_class_gmm`.
- **GMMHandle:** The handle of the classifier that was created with `create_class_gmm`, to which samples were added with `add_samples_image_class_gmm`, and that was trained with `train_class_gmm`.
- **RejectionThreshold:** The threshold on the K-sigma probability (KSigmaProb) measure returned by the classification (see also [section 5.5.5](#) on page 60). All pixels having a probability below `RejectionThreshold` are not assigned to any class.

The operator returns a tuple of regions in `ClassRegions`. This tuple contains one region for each class. The sequence of the classes corresponds to the sequence used for the training regions that were added to the classifier with `add_samples_image_class_gmm`.

In contrast to the general classification using `classify_class_gmm` described in [section 5.5.5](#) on page 60, no probabilities for the classes but a rejection class is returned. This rejection class depends on the selected rejection threshold.

6.1.6 Parameter Setting for k-NN

Most rules for the parameter setting for an image segmentation using k-NN classification correspond to the rules for the general classification with k-NN (see [section 5.6](#) on page 61). As the most important operators and parameters to adjust are listed and described there, here only the parameter settings for the operators that are specific for image segmentation are described. These are the operators that add the training samples, i.e., sample regions, to the classifier and those that segment the unknown image.

6.1.6.1 Adjusting `add_samples_image_class_knn`

For image segmentation with k-NN, sample regions are added to the classifier with `add_samples_image_class_knn`. In contrast to the samples used for a general classification, here, no feature vectors have to be generated explicitly but are implicitly given by the gray values of each pixel of the respective input region in all channels of the input image. The dimension of the feature vectors depends on the number of channels of the image containing the sample regions. The quality of the samples determines the quality of the classification. [Section 4.3](#) on page 32 provides hints how to select a set of suitable samples. For the operator `add_samples_image_class_knn`, the following parameters have to be set:

- **Image:** The image that contains the sample regions
- **ClassRegions:** The tuple containing the training regions. Here, one region per class is defined. The number of classes corresponds to the number of regions, and thus, the label of an individual class corresponds to the position of the training region in the tuple, i.e., its index.
- **KNNHandle:** The handle of the classifier that was created with `create_class_knn`

The operator returns the modified handle of the classifier (`KNNHandle`).

6.1.6.2 Adjusting `classify_image_class_knn`

With the operator `classify_image_class_knn` a new image is segmented into regions of the classes that were trained with `train_class_knn` using the samples that were added with `add_samples_image_class_knn`. The following parameters have to be set:

- **Image:** The image that has to be segmented into the classes that were trained with `train_class_knn`.

- **KNNHandle**: The handle of the classifier that was created with `create_class_knn`, to which samples were added with `add_samples_image_class_knn`, and that was trained with `train_class_knn`.
- **RejectionThreshold**: The threshold on the distance returned by the classification (see also [section 5.6.5](#) on page 65). All pixels having a distance above `RejectionThreshold` are not assigned to any class.

The operator returns a tuple of regions in `ClassRegions`. This tuple contains one region for each class. The sequence of the classes corresponds to the sequence used for the training regions that were added to the classifier with `add_samples_image_class_knn`.

The returned image `DistanceImage`, contains the distance of each pixel of the input image `Image` to its nearest neighbor.

6.1.7 Classification Based on Look-Up Tables

A significant speed-up for the image segmentation can be obtained by applying a classification that is based on look-up tables (LUT). That is, you store the content of a trained classifier into a LUT and use the LUT-accelerated classifier instead of the original classifier for the classification. The approach is as follows:

First, you create an MLP, SVM, GMM, or k-NN classifier, add samples to it, and apply the training as described for the basic image segmentation in the previous sections.

Then, the LUT-accelerated classifier is created using the operator `create_class_lut_mlp`, `create_class_lut_svm`, `create_class_lut_gmm`, or `create_class_lut_knn`, respectively. Here, you insert the handle of the trained classifier and you can adjust the following parameters.

- `'bit_depth'` (for all classifiers)
The parameter `'bit_depth'` describes the number of bits used from the pixels. It controls the storage requirement of the LUT-accelerated classifier and the runtime needed for the LUT-accelerated classification. A byte image has a bit depth of 8. If the bit depth is set to a value of 7 or 6, the storage requirement can be reduced. But note that a bit depth that is smaller than the bit depth of the image will usually lead to a lower accuracy of the classification.
- `'class_selection'` (for MLP, SVM, and GMM classifiers)
the parameter `'class_selection'` is used to control the accuracy and the runtime needed for the creation of the LUT-accelerated classifier. A higher accuracy slows down the runtime and a lower accuracy leads to a speed-up. The value of `'class_selection'` is ignored if the bit depth of the LUT is maximal.
- `'rejection_threshold'` (for MLP, GMM, and k-NN classifiers)
The parameter `'rejection_threshold'` corresponds to the rejection threshold that is described for the basic image segmentation in [section 6.1.3.2](#) for MLP, in [section 6.1.5.2](#) for GMM, and in [section 6.1.6.2](#) for k-NN.

For the actual image segmentation, the operator `classify_image_class_lut` is applied instead of the operator `classify_image_class_mlp`, `classify_image_class_svm`, `classify_image_class_gmm`, or `classify_image_class_knn`, respectively. Note that the number of channels of the image that has to be classified must correspond to the value specified for the dimension of the feature space when creating the original classifier, i.e., the value of `NumInput` in `create_class_mlp`, `NumFeatures` in `create_class_svm`, `NumDim` in `create_class_gmm`, or `NumDim` in `create_class_knn`.

As soon as a classifier is not needed anymore, it should be destroyed to free the memory. In most cases, the original trained classifier can be destroyed as soon as the LUT-accelerated classifier has been created. But note that if you need it for further applications, you should store it to file before destroying it (see [section 6.1.2.1](#) on page 76). To destroy the original trained classifier, you apply `clear_class_mlp`, `clear_class_svm`, `clear_class_gmm`, or `clear_class_knn`, respectively, as described for the basic image segmentation. The LUT-accelerated classifier cannot be stored to file, as it needs a lot of memory and thus, it is more suitable to create it again from the reused original classifier when starting a new application. When it is not needed anymore, it is destroyed using `clear_class_lut`.

The HDevelop example program `hdevelop\Applications\Color-Inspection\classify_fuses_gmm_based_lut.hdev` uses a LUT-accelerated classifier that is based on a trained GMM classifier to segment fuses of different color (see [figure 6.6](#)).



Figure 6.6: Fuses of different color are segmented using a LUT-accelerated GMM classifier.

First, the ROIs that serve as training samples for different color classes are selected and concatenated into the tuple `Classes`. Then, a GMM classifier is created, the training samples are added, and the classifier is trained. Until now, the approach is the same as for the image segmentation that was described in the previous sections.

```
create_class_gmm (3, 5, 1, 'full', 'none', 3, 42, GMMHandle)
add_samples_image_class_gmm (Image, Classes, GMMHandle, 0)
train_class_gmm (GMMHandle, 100, 0.001, 'training', 0.001, Centers, Iter)
```

In contrast to the basic image segmentation, the training result, i.e., the classifier, is then stored in a LUT-accelerated classifier using `create_class_lut_gmm`. The original classifier is not needed anymore and is therefore destroyed.

```
create_class_lut_gmm (GMMHandle, ['bit_depth','rejection_threshold'], [6, \
                                0.03], ClassLUTHandle)
clear_class_gmm (GMMHandle)
```

Now, for each image that has to be classified, the operator `classify_image_class_lut` is applied to segment the images based on the LUT of the new classifier. At the end of the program, the LUT-accelerated classifier is destroyed as well.

```
for Img := 0 to 3 by 1
    read_image (Image, ImageRootName + Img)
    classify_image_class_lut (Image, ClassRegions, ClassLUTHandle)
endfor
clear_class_lut (ClassLUTHandle)
```

The HDevelop example program `hdevelop\Segmentation\Classification\classify_image_class_lut.hdev` compares the runtime needed by MLP, SVM, GMM, and k-NN classification using the basic image segmentation on the one hand and the LUT-accelerated classification on the other hand. It exemplarily shows that the online part of the LUT-accelerated classification is significantly faster than that of the basic image segmentation. **But note that it needs also additional memory and the runtime for the offline part is increasing.** Because of that the LUT-accelerated classification is restricted to feature spaces with a maximum of three dimensions. Figure 6.7 shows the interdependencies between the number of classes, the bit depth, and the required memory for a three-channel image. Furthermore, depending on the selected bit depth of the look-up table, the accuracy of the classification may be decreased. Summarized, if a three-channel image has to be segmented, a speed-up of the online part is required, and the runtime for the offline part is not critical, LUT-accelerated classification is a good alternative to the basic image segmentation.

Number of classes	Bit depth	Needed memory
256	3 x 8 Bit	32 MB
1	3 x 8 Bit	2 MB
10	3 x 6 Bit	0,125 MB

Figure 6.7: Memory needed for a LUT-accelerated classifier for three-channel images with different numbers of classes and different bit depths.

6.2 Approach for a Two-Channel Image Segmentation

For two-channel images a simple and very fast pixel classification can be applied using the operator `class_2dim_sup`. As we already learned, a class is defined as a well-defined part of the feature space and the dimension of the feature space depends on the number of features used for the classification. In case of a two-channel image and a pure pixel based classification, the classification is based only on the two gray values that are assigned to each pixel position and thus the two-dimensional feature space can be visualized in a 2D graph or in a 2D image, respectively. There, for each position of the image or a specific image region the gray value of the first image `ImageCol` is used as column coordinate and the gray value of the second image `ImageRow` is used as row coordinate (see figure 6.8, left). A class is defined by the feature space of a manually specified image region.

The general approach using `class_2dim_sup` for a two-channel image segmentation is as follows: you first specify a class by a region in the two-channel image that is typical for the class. Then, you apply the operator `histo_2dim`, which needs the two channels and the specified image region as input and returns the two-dimensional histogram, i.e., an image in which the position of a pixel is built by the combination of the gray values of the two channels and its gray value is defined by the frequency of the specific gray value combination. To extract the essential region of the feature space, a threshold is applied. Now, the result can be preprocessed for generalization purposes (see figure 6.8, right), e.g., by a morphological operation like `closing_circle`. For the actual classification, the feature space region and the two channels of the image that has to be classified are used as input for the operator `class_2dim_sup`. The returned region `RegionClass2Dim` consists of all pixels in the classified two-channel image, for which the gray value distribution is similar to the gray value distribution of the training region, i.e., for which the position in the feature space lies inside the preprocessed feature space region that defines the class.

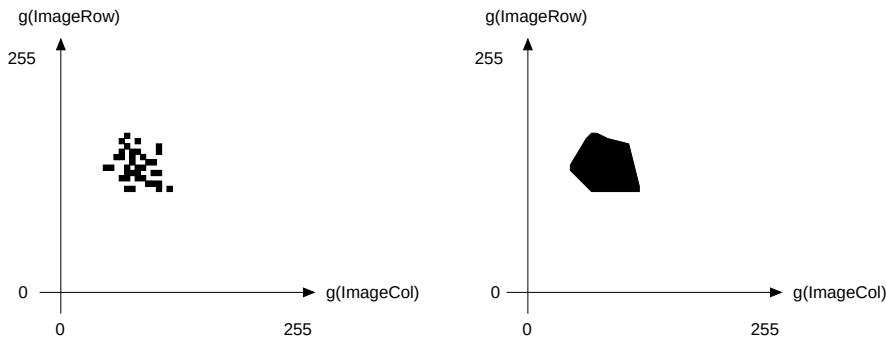


Figure 6.8: Positions of the 2D feature space for a supervised classification: (left) gray values of the two images in a 2D graph, (right) feature space region (class) after generalization.

The example `hdevelop\Segmentation\Classification\class_2dim_sup.hdev` shows the approach for the segmentation of a two-channel image that contains several capacitors. First the color image is decomposed into its three channels, so that two of them can be accessed for the classification. Then, a sample region for one of the capacitors is defined and used as input for `histo_2dim`, which together with `threshold` and `closing_circle` is used to derive a generalized feature space region. Finally, the two channels of the image and the trained feature space region are used by `class_2dim_sup` to get the region with all pixels that correspond to the trained feature space.

```
read_image (Image, 'ic')
decompose3 (Image, Red, Green, Blue)
gen_rectangle1 (Pattern, 362, 276, 371, 298)
histo_2dim (Pattern, Red, Blue, Histo2Dim)
threshold (Histo2Dim, Features, 1, 255)
closing_circle (Features, FeaturesClosed, 11.5)
class_2dim_sup (Red, Blue, FeaturesClosed, RegionClass2Dim)
```

This image segmentation approach is very fast. To select the two channels of a multi-channel image that should be used for the classification, different approaches exist. For color images, i.e., three-channel 'rgb' images, you can, e.g., apply a color transformation using `trans_from_rgb` to transform the 'rgb' image into a, e.g., 'hsi' image. This image contains one channel for the 'hue', one for the 'saturation', and one for the 'intensity' of the pixels. When using the 'hue' and 'saturation' channels for the classification, you obtain a classifier that is invariant to illumination changes (see also Solution Guide I, [chapter 13](#) on page 191 for color transformations). For arbitrary multi-channel images you can also transform your image by a principal component analysis using the operator `principal_comp`. Then, the first two channels of the returned image are the channels with the largest information content and thus are predestinated to be input to the two-channel image segmentation.

6.3 Approach for Euclidean and Hyperbox Classification

For the simple image segmentation of multi-channel images, two operators are available: `class_ndim_box` and `class_ndim_norm`. The first one is used for a hyperbox classification and the second one can be applied either using a hyperbox or an Euclidean metric (for hyperbox and Euclidean classification see [section 3.2](#) on page 19). Note that both operators can be applied following the general idea of hyperbox classification, but their implementations differ significantly.

From a user's point of view the key difference between `learn_ndim_box` and `learn_ndim_norm` is that for `learn_ndim_box` the rejection class affects the classification process itself. Here, a hyperplane is generated that separates the classes 'Foreground' and 'Background', so that no points in feature space are classified incorrectly. For `learn_ndim_norm`, however, an overlap between the classes 'Foreground' and 'Background' is allowed. This has its effect on the return value Quality. The larger the overlap, the smaller the value. Note that the operator `class_ndim_norm` is very efficient. Compared, e.g., to the classic image segmentation using GMM ([section 6.1.5](#) on page 82), it is significantly faster (approximately by factor 3). Compared to a LUT-accelerated classification it has the advantage that the storage requirements are low and the feature space can be easily visualized. Thus, if the classes are build by compact clusters, it is a good alternative.

6.3.0.1 Classification with `class_ndim_box`

The image segmentation using a hyperbox classification is applied as follows. Similar to the complex classification approaches using MLP, SVM, and GMM, you first create a classifier. For a hyperbox classification, it is created with `create_class_box`. Then, you specify a foreground and a background region to use them as input for the training with `learn_ndim_box`. The gray value combinations of each pixel of the region `Foreground` represent the pattern to be trained and those of the region `Background` define gray value combinations that have to be rejected.

Each pixel is trained once during the training process. For pixels of the region **Foreground** the class 0 is used, while for pixels of the region **Background** 1 is used. Pixels are trained by alternating pixels from Foreground with pixels from Background. If one region is smaller than the other, pixels are taken cyclically from the smaller region until the larger region is exhausted. The operator `learn_ndim_box` later accepts only pixels that can be classified into class 0. Note that all channels must be of the same type.

The actual classification of the image, i.e., the segmentation of the image into parts belonging to the class and parts to be rejected, is realized with `class_ndim_box`. At the end, you destroy the classifier with `close_class_box`.

No parameters need to be adjusted for this approach. The only influence you have on the classification process is a suitable selection of the training regions **Foreground** and **Background**.

The example `hdevelop\Segmentation\Classification\class_ndim_box.hdev` shows how to apply a hyperbox classification for image segmentation. The image is read, a classifier is created, the foreground and background regions are defined and used for a training, the image is segmented, and finally, the classifier is cleared from memory. The result of the image segmentation is shown in **figure 6.9**.

```
read_image (Image, 'ic')
create_class_box (ClassifHandle)
gen_rectangle1 (foreground, 360, 198, 369, 226)
gen_rectangle1 (reject, 84, 336, 337, 504)
learn_ndim_box (foreground, reject, Image, ClassifHandle)
class_ndim_box (Image, Regions, ClassifHandle)
close_class_box (ClassifHandle)
```

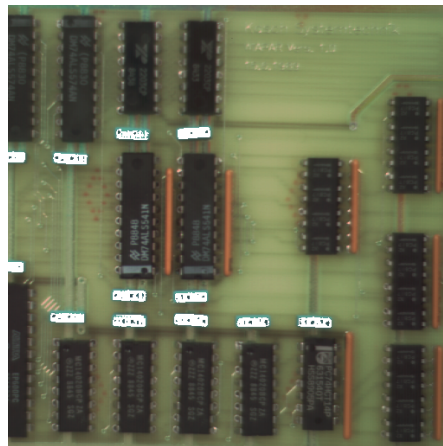


Figure 6.9: Result of image segmentation using `class_ndim_box` (returned regions marked in white).

6.3.0.2 Classification with `class_ndim_norm`

Opposite to the approach with `class_ndim_box`, when segmenting an image using `class_ndim_norm`, you do not explicitly create and destroy a classifier, but immediately apply the training using

`learn_ndim_norm`. Instead of storing the training results in a classifier and using the classifier as input for the classification, the training returns explicit information about the centers and radii of the clusters related to the trained patterns and this information is used as input for the classification, which is applied with `class_ndim_norm`. You can choose between a classification using hyperboxes and a classification using hyperspheres (Euclidean classification).

With `learn_ndim_norm` you generate the classification clusters from the region `Foreground`. The region `Background` can be used to define a rejection class, but in contrast to `learn_ndim_box` may also be empty (an empty region can be created by `gen_empty_region`). Note that the rejection class does not influence the clustering, but can be used to detect problems that might occur because of overlapping classes.

To choose between the two available clustering approaches, the parameter `Metric` is used. It can be either set to 'euclid', which uses a minimum distance algorithm (n-dimensional hyperspheres) or to 'maximum', which uses n-dimensional hyperboxes to build the clusters. `Metric` must be set to the same value for the training as well as for the classification. The Euclidean metric usually yields the better results but needs more run time.

The parameter `Distance` describes the minimum distance between two cluster centers and thus determines the maximum value allowed for the output parameter `Radius`. Note that the cluster centers depend on the sequence used to add the training samples (pixels). Thus, it is recommended to select a small value for `Distance`. Then, the (small) hyperboxes or hyperspheres can approximate the feature space well. But simultaneously, the runtime during classification increases.

The ratio of the number of pixels in a cluster to the total number of pixels (in percent) must be larger than the value of the parameter `MinNumberPercent`, otherwise the cluster is not returned. `MinNumberPercent` serves to eliminate outliers in the training set. If it is chosen too large many clusters are suppressed.

As result of the operator, the parameter `Radius` returns the minimum distance between two cluster centers, i.e., radii for hyperspheres or half edge lengths for hyperboxes, and `Center` returns the coordinates of the cluster centers. Furthermore, the parameter `Quality` returns the quality of the clustering, i.e., a measure of overlap between the rejection class and the classifier classes. Values larger than 0 denote the corresponding ratio of overlap. If no rejection region is given, its value is set to 1. The regions in `Background` do not influence the clustering. They are merely used to check the results that can be expected.

When classifying a multi-channel image with `class_ndim_norm`, you set the same metric (`Metric`) used also for the training and set the parameter `SingleMultiple` to 'single' if one region has to be generated or to 'multiple' if multiple regions have to be generated for each cluster. Additionally, `Radius` and `Center`, which were returned by `learn_ndim_norm`, are inserted. The result of `class_ndim_norm` is returned in `Regions`, which either contains a single region or a tuple of regions, depending on the value of `SingleMultiple`.

The example `hdevelop\Segmentation\Classification\class_ndim_norm.hdev` shows how to apply an image segmentation with `class_ndim_norm`. The image is read and within the image a region for the class to be trained and an empty region for the rejection class are generated and used as input for the training with `learn_ndim_norm`. The classification is then applied with `class_ndim_norm`. The result of the image segmentation is shown in [figure 6.10](#).

```
read_image (Image, 'ic')
gen_rectangle1 (Region, 360, 198, 369, 226)
gen_empty_region (EmptyRegion)
learn_ndim_norm (Region, EmptyRegion, Image, 'euclid', 10, 0.01, Radius, \
                Center, Quality)
class_ndim_norm (Image, Regions, 'euclid', 'multiple', Radius, Center)
```

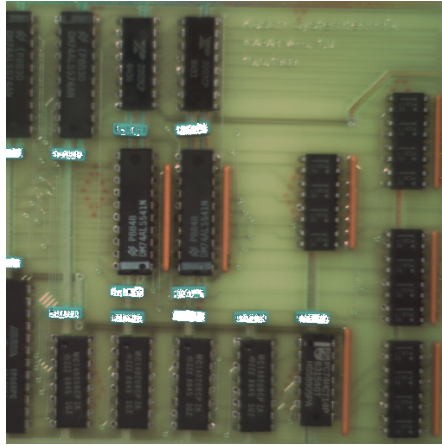


Figure 6.10: Result of image segmentation using class_ndim_norm (returned regions marked in white).

Chapter 7

Classification for Optical Character Recognition (OCR)

If classification is used for optical character recognition (OCR), individual regions are first extracted from the image by a segmentation and then, with the help of some region features, assigned to classes that typically (but not necessarily) represent individual characters or numbers. Approaches that are suitable for this feature-based OCR comprise the MLP, the SVM, and the k-NN classifiers. A hyperbox classifier is also provided, but is not recommended anymore.

In [section 7.1](#) the general approach for OCR is illustrated by an example that trains and reads the characters 'A' to 'G'. In [section 7.2](#) the steps of OCR and the involved operators are listed for a brief overview. The parameters used for the basic OCR operators are introduced in [section 7.3](#) for MLP, [section 7.4](#) for SVM, and [section 7.5](#) for k-NN. [Section 7.6](#) finally lists all features that are available for OCR.

7.1 General Approach

[Figure 7.1](#) shows the general approach for OCR. Typically, the approach is divided into an offline and an online process. The offline process comprises the training of the font, i.e., regions that represent characters or numbers (in the following just called 'characters') are extracted and stored together with the corresponding character names in training files. The content of a training file optionally can be accessed again. The access is needed for different reasons. First, they can be used to find errors that occurred during the training, which is needed on one hand for your general quality assurance and on the other hand for the correspondence with your HALCON support team (if needed), and second, you can reuse the contained information for the case that you want to apply a similar application in the future.

Now, the training files are used to train the font. To access the font in the later online process, the classifier is written into a font file before the classifier is cleared from memory.

If you want to read a font that is rather common and you want to use the MLP approach, you can also use one of the pretrained fonts provided by HALCON (see Solution Guide I, [chapter 12](#) on page 173 for illustrations of the provided fonts). The pretrained fonts are stored in the subdirectory ocr of the folder

where you installed HALCON. Then, you can skip the offline training process. For SVM and k-NN classifiers, no pretrained fonts are available.

In the online process, the font file is read so that the classifier can be accessed again. Then, the regions of unknown characters are extracted, most suitably by the same method that was used within the offline training process, and classified, i.e., the characters are read. At the end, the classifier is cleared from memory again.

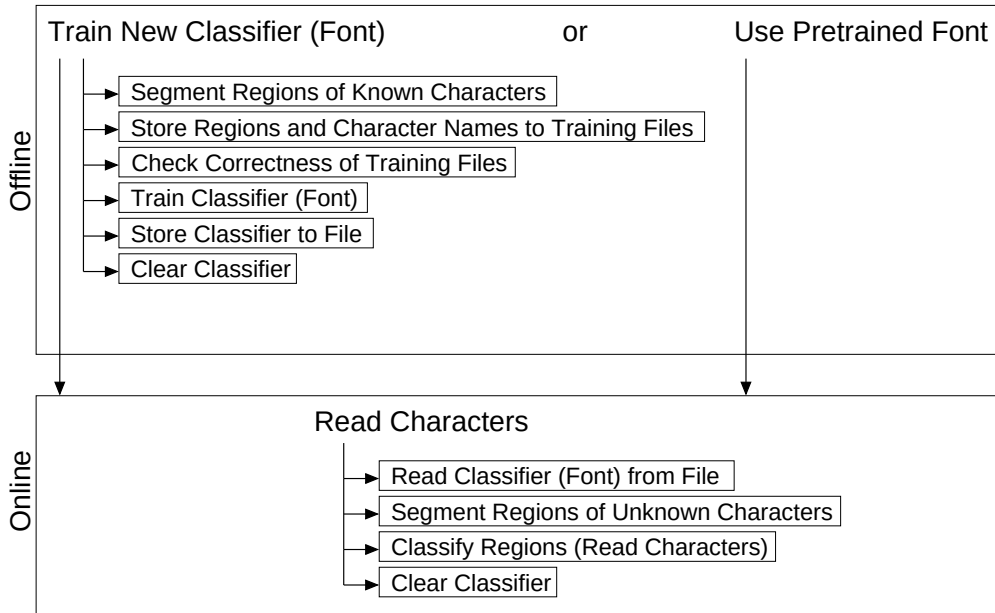


Figure 7.1: The basic steps of OCR.

In the following, we illustrate the general approach for OCR classification with the examples `solution_guide\classification\train_characters_ocr.hdev` and `solution_guide\classification\classify_characters_ocr.hdev`. These examples show how the characters 'A', 'B', 'C', 'D', 'E', 'F', and 'G' are first trained (see [figure 7.2](#)) and then read (see [figure 7.3](#)) with an SVM-based OCR classification. Note that the number of classes as well as the number of training samples is very small as the example is used only to demonstrate the general approach. Typically, a larger number of classes is trained with OCR and a lot of samples and probably a different set of features are needed to get a robust classification.

The examples use SVM-based OCR classification. For MLP and k-NN, the general approach and the operators are similar. Then, you mainly have to replace 'svm' by 'mlp' or 'knn', respectively in the specific operator names and adjust different parameters. The specific parameters are explained in more detail in [section 7.3](#) on page 100 for MLP, in [section 7.4](#) on page 104 for SVM, and in [section 7.5](#) on page 108 for k-NN.

The program `solution_guide\classification\train_characters_ocr.hdev` starts with the creation of an SVM-based OCR classifier using the operator `create_ocr_class_svm`. Here, the most important parameters are adjusted. The width and height of a normalized character is defined (the reason

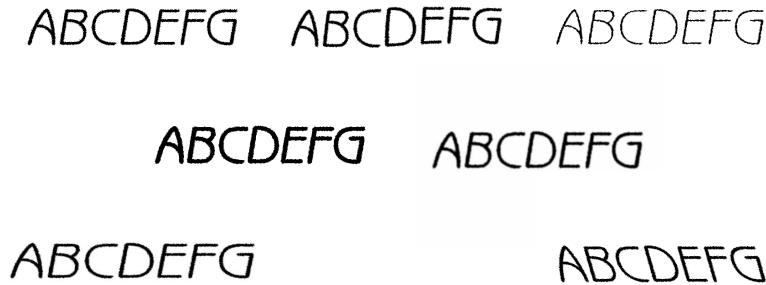


Figure 7.2: Training images for the characters 'A', 'B', 'C', 'D', 'E', 'F', and 'G'.

for this is explained in more detail in [section 7.3.1](#) on page 100) and the mode for the interpolation that is used to scale the characters to the average character size is set. Further, the features that should be calculated to get the feature vector are selected. OCR can be applied for a broad set of features, which is listed in [section 7.6](#) on page 111. The default features are 'ratio' and 'pixel_invar'. Here, the default does not lead to a satisfying result, so we use the features 'convexity', 'num_holes', 'projection_horizontal', and 'projection_vertical' instead. Now, the names of the available classes (the characters A to G) are assigned, which were previously stored in the tuple `ClassNames`. Furthermore, some SVM specific parameters are adjusted that are described in more detail for the general classification in [section 5.4](#) on page 47. The output of `create_ocr_class_svm` is the handle of the classifier (`OCRHandle`), which is needed for the following classification steps.

```
ClassNames := ['A','B','C','D','E','F','G']
create_ocr_class_svm (8, 10, 'constant', ['convexity','num_holes', \
    'projection_horizontal','projection_vertical'], \
    ClassNames, 'rbf', 0.02, 0.05, 'one-versus-one', \
    'normalization', 10, OCRHandle)
```

For the training of the characters, the training images are read and the regions of the characters are extracted via a blob analysis within the procedure `get_regions`. Alternatively you can use also a combination of the operators `segment_characters` and `select_characters` to extract regions.

In the program, the first region is added together with its class name (which is obtained from the tuple `ClassName`) to a new training file with `write_ocr_trainf`. All following regions and their corresponding class names are appended to this training file with `append_ocr_trainf`.

```

for I := 1 to 7 by 1
    read_image (Image, 'ocr/chars_training_' + I$.2d')
    get_regions (Image, SortedRegions)
    count_obj (SortedRegions, NumberObjects)
    for J := 1 to NumberObjects by 1
        select_obj (SortedRegions, ObjectSelected, J)
        if (I == 1 and J == 1)
            write_ocr_trainf (ObjectSelected, Image, ClassNames[J - 1], \
                              'train_characters_ocr.trf')
        else
            append_ocr_trainf (ObjectSelected, Image, ClassNames[J - 1], \
                               'train_characters_ocr.trf')
        endif
    endfor
endfor

```

After all samples were added to the training file, the operator `read_ocr_trainf` is applied to check if the training samples and the corresponding class names were correctly assigned within the training file. In a short for-loop, the individual characters and their corresponding class names are visualized. Note that the index for iconic objects (Characters) starts with 1 and that of numeric objects (CharacterNames) with 0.

```

read_ocr_trainf (Characters, 'train_characters_ocr.trf', CharacterNames)
count_obj (Characters, NumberCharacters)
for I := 1 to NumberCharacters by 1
    select_obj (Characters, CharacterSelected, I)
    dev_display (CharacterSelected)
    disp_message (WindowHandle, CharacterNames[I - 1], 'window', 10, 10, \
                  'black', 'true')
endfor

```

Then, the OCR classifier is trained with `trainf_ocr_class_svm`, which needs the training file as input. For SVM, the number of support vectors obtained from the training can be reduced to enhance the speed of the later classification. This is done with `reduce_ocr_class_svm`. The resulting handle is stored in a font file with `write_ocr_class_svm` for later access. For MLP the handle obtained directly by the training would be stored.

```

trainf_ocr_class_svm (OCRHandle, 'train_characters_ocr.trf', 0.001, \
                     'default')
reduce_ocr_class_svm (OCRHandle, 'bottom_up', 2, 0.001, OCRHandleReduced)
write_ocr_class_svm (OCRHandleReduced, 'font_characters_ocr')

```

At the end of the training program, both classifiers are cleared from memory using the operator `clear_ocr_class_svm`.

```

clear_ocr_class_svm (OCRHandle)
clear_ocr_class_svm (OCRHandleReduced)

```

Now, the example program `solution_guide\classification\classify_characters_ocr.hdev` is used to read unknown characters of the same font type used for the training.

A font is read from file with `read_ocr_class_svm`. Then, the images with unknown characters are read, and the regions that most probably represent characters are extracted. If possible, the method to extract the regions should be the same for the offline and online process. Of course this advice can only be followed if the methods used in the offline process are known, i.e., it can not be followed when using pretrained fonts.

The extracted regions are then classified, i.e., the characters are read. In the example, we read all regions simultaneously with `do_ocr_multi_class_svm`. Alternatively, you can also read the regions individually with `do_ocr_single_class_svm`. Then, not only the best class for each region is returned, but also the second best (and third best etc.) class can be obtained, which might be suitable when having overlapping classing. But if only the best class is of interest, `do_ocr_multi_class_svm` is faster and therefore recommended. Finally, the classifier is cleared from memory with `clear_ocr_class_svm`.

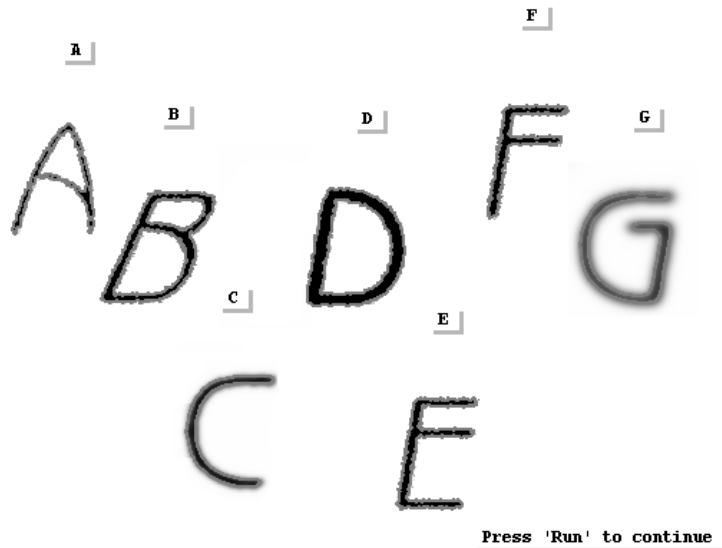


Figure 7.3: Classifying the characters 'A', 'B', 'C', 'D', 'E', 'F', and 'G' with OCR.

```

read_ocr_class_svm ('font_characters_ocr', OCRHandle)
for I := 1 to 3 by 1
    read_image (Image, 'ocr/chars_' + I$.2d')
    get_regions (Image, SortedRegions)
    do_ocr_multi_class_svm (SortedRegions, Image, OCRHandle, Classes)
    area_center (SortedRegions, AreaCenter, Row, Column)
    count_obj (SortedRegions, NumberObjects)
    disp_message (WindowHandle, Classes, 'window', Row - 100, Column, \
        'black', 'true')
    if (I < 3)
    endif
endfor
endfor
clear_ocr_class_svm (OCRHandle)

```

7.2 Involved Operators (Overview)

This section gives a brief overview on the operators that are provided for OCR. In particular, first the operators for the basic steps and then the advanced operators used for OCR are introduced.

7.2.0.3 Basic Operators

The basic steps apply the following operators in the following sequence.

1. Create an OCR classifier using `create_ocr_class_mlp`, `create_ocr_class_svm`, or `create_ocr_class_knn`.
2. Extract the regions that represent the characters that have to be trained.
3. Store the samples, i.e., the training regions and the corresponding class names to a training file. This can be done in different ways. Either
 - store all samples at once using `write_ocr_trainf`. Then the regions as well as the corresponding class names have to be available in a tuple. Or
 - successively add the individual regions (characters) and their corresponding class names to the training file using `append_ocr_trainf`.
 - Write characters into a training file with `write_ocr_trainf_image`. That is, regions, representing characters, including their gray values (region and pixel) and the corresponding class name are written into a file. An arbitrary number of regions within one image is supported. In contrast to `write_ocr_trainf` one image per character is passed. The domain of this image defines the pixels which belong to the character. The file format can be defined by the parameter 'ocr_trainf_version' of the operator `set_system`.

Additionally, several training files can be concatenated with `concat_ocr_trainf`.

4. Read the training characters from the training file and convert them into images with `read_ocr_trainf` to check the correctness of the training file content.
5. Train the OCR classifier with `trainf_ocr_class_mlp`, `trainf_ocr_class_svm`, or `trainf_ocr_class_knn`.
6. Write the OCR classifier to a font file with `write_ocr_class_mlp` (default file extension: `.omc`), `write_ocr_class_svm` (default file extension: `.osc`), or `write_ocr_class_knn` (default file extension: `.onc`).
7. Read the OCR classifier from the font file with `read_ocr_class_mlp`, `read_ocr_class_svm`, or `read_ocr_class_knn`.
8. Extract the regions of the characters that have to be classified according to the trained font.
9. Classify the regions of the characters to be classified. Here, you have different possibilities:
 - Classify multiple characters with an OCR classifier with `do_ocr_multi_class_mlp`, `do_ocr_multi_class_svm`, or `do_ocr_multi_class_knn`.
 - Classify a single character with an OCR classifier with `do_ocr_single_class_mlp`, `do_ocr_single_class_svm`, or `do_ocr_single_class_knn`.
10. Clear the specific OCR classifiers with `clear_ocr_class_mlp`, `clear_ocr_class_svm`, or `clear_ocr_class_knn`.

7.2.0.4 Advanced Operators

Besides the basic steps of an OCR classification, some additional steps and operators can be applied if suitable. In particular, you can

- compute the features of a character with `get_features_ocr_class_mlp`, `get_features_ocr_class_svm`, or `get_features_ocr_class_knn`,
- return the parameters of an OCR classifier with `get_params_ocr_class_mlp`, `get_params_ocr_class_svm`, or `get_params_ocr_class_knn`,
- compute the information content of the preprocessed feature vectors of an OCR classifier with `get_prep_info_ocr_class_mlp` or `get_prep_info_ocr_class_svm` (if Preprocessing was set to 'principal_components' or 'canonical_variates'; note that this kind of operator is not available for k-NN classifiers, because they do not provide the respective preprocessing options),
- query which characters are stored in a training file with `read_ocr_trainf_names`,
- read training specific characters from files and convert them to images with `read_ocr_trainf_select`, or
- classify a related group of characters with an OCR classifier with `do_ocr_word_mlp`, `do_ocr_word_svm`, or `do_ocr_word_knn`. This is an alternative to `do_ocr_multi_class_mlp`, `do_ocr_multi_class_svm`, or `do_ocr_multi_class_knn` and is suitable when searching for specific words or regular expressions that are specified in a lexicon that has been created with `create_lexicon` or imported with `import_lexicon`.

Besides these operators, some operators are provided that are available only for SVM:

- To enhance the speed, the trained SVM-based OCR classifier can be approximated with a reduced number of support vectors by applying `reduce_ocr_class_svm` after the training.
- The number of support vectors that are stored within the SVM-based OCR classifier is returned with `get_support_vector_num_ocr_class_svm`.
- The index of a support vector from a trained SVM-based OCR classifier is returned with `get_support_vector_ocr_class_svm`.

In the following, the parameters for the basic operators are introduced and tips for their adjustment are provided.

7.3 Parameter Setting for MLP

The following sections introduce you to the parameters that have to be set for the basic operators needed for an MLP-based classification for OCR.

7.3.1 Adjusting `create_ocr_class_mlp`

An MLP classifier for OCR is created using `create_ocr_class_mlp`. Here, most of the important parameters have to be set.

Parameter `WidthCharacter` / `HeightCharacter`

Like for the general classification described in [section 5](#) on page 33, OCR uses a set of features to classify regions into classes, which in this case correspond to specific characters and numbers. Some of the features that can be used for OCR are gray value features for which the number of returned features varies dependent on the region's size. As a classifier requires a constant number of features, i.e., the dimension of the feature vector has to be the same for all training samples and all regions to be classified, the region of a character has to be transformed (scaled) to a standard size. This size is determined by `WidthCharacter` and `HeightCharacter`. In most applications, sizes between 6x8 and 10x14 should be used. As a rule of thumb, the values may be small if only few characters have to be distinguished but large when classifying characters with complex shapes (e.g., Japanese signs).

Parameter `Interpolation`

The input parameter `Interpolation` is needed to control the transformation of the region to the size specified with `WidthCharacter` and `HeightCharacter`. Generally, when transforming a region, transformed points will lie between discrete pixel coordinates. To assign each point to its final pixel coordinate and additionally to avoid aliasing, which typically occurs for scaled regions, an appropriate interpolation scheme is needed. Three types of interpolation with different quality and speed properties are provided by HALCON and can be selected for the parameter `Interpolation`:

- `'nearest_neighbor'`

If `'nearest_neighbor'` is selected, a nearest-neighbor interpolation is applied. There, the gray value is determined from the nearest pixel's gray value. This interpolation scheme is very fast but may lead to a low interpolation quality.

- `'bilinear'`

If `'bilinear'` is selected, a bilinear interpolation is applied. There, the gray value is determined from the four nearest pixels through bilinear interpolation. This interpolation scheme is of medium speed and quality. Do not use it if the characters in the image appear larger than `WidthCharacter` times `HeightCharacter`. In this case, the interpolation method `'constant'` or `'weighted'` should be used.

- `'constant'`

If `'constant'` is selected, a bilinear interpolation is applied. There, the gray value is determined from the four nearest pixels through bilinear interpolation. If the transformation contains a scaling with a scale factor smaller than 1, a kind of mean filter is used to prevent aliasing effects. This interpolation scheme is of medium speed and quality.

- `'weighted'`

If `'weighted'` is selected, again a bilinear interpolation is applied, but now, aliasing effects for a scaling with a scale factor smaller than 1 are prevented by a kind of Gaussian filter instead of a mean filter. This interpolation scheme is slow but leads to the best quality.

The interpolation should be chosen such that no aliasing effects occur in the transformation. For most applications, `Interpolation` should be set to `'constant'`.

Parameter `Features`

The input parameter `Features` specifies the features that are used for the classification. `Features` can contain a tuple of several feature names. Each of these feature names results in one or more features to be calculated for the classifier. That is, the length of the tuple in `Features` is similar or smaller than the dimension of the final feature vector. In [section 7.6](#) on page 111 all features that are available for OCR are listed. To classify characters, in most cases the `'default'` setting can be used. Then, the features `'ratio'` and `'pixel_invar'` are selected. Note that the selection of the features significantly influences the quality of the classification.

Parameter `Characters`

The input parameter `Characters` contains a tuple with the names of the characters that will be trained. Each name must be passed as a string. The number of elements in the tuple determines the number of available classes.

Parameter `NumHidden`

The input parameter `NumHidden` follows the same rules as provided for the corresponding operator used to create an MLP classifier for a general classification (see [section 5.3.1](#) on page 41).

Parameters [Preprocessing](#) / [NumComponents](#)

The parameters [Preprocessing](#) and [NumComponents](#) follow the same rules as provided for the corresponding operator used to create an MLP classifier for a general classification (see [section 5.3.1](#) on page 41). The only exception is that for the OCR classification the features are already approximately normalized. Thus, [Preprocessing](#) can typically be set to 'none'.

If [Preprocessing](#) is set to 'principal_components' or 'canonical_variates' you can use the operator [get_prep_info_ocr_class_mlp](#) to determine the optimum number of components as described for the general classification in [section 5.3.1](#) on page 42.

Parameter [RandSeed](#)

The parameter [RandSeed](#) follows the same rules as provided for the corresponding operator used to create an MLP classifier for a general classification (see [section 5.3.1](#) on page 41).

Parameter [OCRHandle](#)

The output parameter [OCRHandle](#) is the handle of the classifier that is needed and modified throughout the following classification steps.

7.3.2 Adjusting [write_ocr_trainf](#) / [append_ocr_trainf](#)

After creating a classifier and segmenting the regions for the characters of known classes, i.e., character names, the samples must be stored to a training file. Here, the same operators are used for MLP and SVM classifiers.

Different operators are provided for storing training samples to file. You can either store all samples to file in one step by inserting a tuple containing all regions and a tuple containing all corresponding class names to the operator [write_ocr_trainf](#). Or you can successively append single training samples to the training file using [append_ocr_trainf](#). If you choose the latter, be aware that the training file is extended every time you run the program, i.e., it is not created anew. So, if you want to successively add samples, it is recommended to use [write_ocr_trainf](#) for the first sample and [append_ocr_trainf](#) for all following samples. The operators are applied as follows:

- Store training samples to a new training file:

When storing all training samples simultaneously into a file using [write_ocr_trainf](#), you have to assign a tuple of regions that represent characters to the parameter [Character](#). The image that contains the regions must be set in [Image](#) so that knowledge about the gray values within the regions is available. In [Class](#) a tuple of class names that correspond to the regions with the same tuple index must be inserted. Finally, you specify the name and path of the stored training file in [FileName](#).

- Append training samples to a training file:

When successively storing individual training samples into a file using [append_ocr_trainf](#), the same parameters as for [write_ocr_trainf](#) have to be set. But in contrast to the operator [write_ocr_trainf](#) the characters are appended to an existing file using the same training file format. If the file does not exist, a new file is generated.

If no file extension is specified in `FileName` the extension `'.trf'` is appended to the file name. The version of the file format used for writing data can be defined by the parameter `'ocr_trainf_version'` of the operator `set_system`.

If you have several training files that you want to combine, you can concatenate them with the operator `concat_ocr_trainf`.

7.3.3 Adjusting `trainf_ocr_class_mlp`

`trainf_ocr_class_mlp` trains the OCR classifier `OCRHandle` with the training characters stored in the OCR training file given by `TrainingFile`. The remaining parameters `MaxIterations`, `WeightTolerance`, `ErrorTolerance`, `Error`, and `ErrorLog` have the same meaning as introduced for the training of an MLP classifier for a general classification (see [section 5.3.3](#) on page 45).

7.3.4 Adjusting `do_ocr_multi_class_mlp`

With `do_ocr_multi_class_mlp` multiple characters can be classified in a single call. Typically, this is faster than successively applying `do_ocr_single_class_mlp`, which classifies single characters, in a loop. However, `do_ocr_multi_class_mlp` can only return the best class of each character. If the second best class is needed, e.g., because the classes significantly overlap (see [section 5.3.5](#) on page 47 for the possible outliers related to the confidence values of MLP classifications), `do_ocr_single_class_mlp` should be used instead. The following parameters have to be set for `do_ocr_multi_class_mlp`:

Parameter `Character`

The input parameter `Character` contains a tuple of regions that have to be classified.

Parameter `Image`

The input parameter `Image` contains the image that provides the gray value information for the regions that have to be classified.

Parameter `OCRHandle`

The input parameter `OCRHandle` is the handle of the classifier that was trained with `trainf_ocr_class_mlp`.

Parameter `Class`

The output parameter `Class` returns the result of the classification, i.e., a tuple of character names that correspond to the input regions that were given in the tuple `Character`.

Parameter `Confidence`

The output parameter `Confidence` returns the confidence value for the classification. Note, that for the confidence of MLP classifications, outliers are possible as described for the general classification in [section 5.3.5](#) on page 47.

7.3.5 Adjusting `do_ocr_single_class_mlp`

Instead of using `do_ocr_multi_class_mlp` to add all samples in a single call, `do_ocr_single_class_mlp` can be used to successively add samples. Then, besides the best class for a region, also the second best (and third best etc.) class can be obtained. This may be suitable, if the class membership of a region is uncertain because of, e.g., overlapping classes. If only the best class for each region is searched for, `do_ocr_multi_class_mlp` is faster and therefore recommended.

Parameter `Character`

The input parameter `Character` contains a single region that has to be classified.

Parameter `Image`

The input parameter `Image` contains the image that provides the gray value information for the region that has to be classified.

Parameter `OCRHandle`

The input parameter `OCRHandle` is the handle of the classifier that was trained with `trainf_ocr_class_mlp`.

Parameter `Num`

The input parameter `Num` specifies the number of best classes to be searched for. Generally, `Num` is set to 1 if only the class with the best probability is searched for, and to 2 if the second best class is also of interest, e.g., because the classes overlap.

Parameter `Class`

The output parameter `Class` returns the result of the classification, i.e., the `Num` best character names that correspond to the input region that was specified in `Character`.

Parameter `Confidence`

The output parameter `Confidence` returns the `Num` best confidence values for the classification. Note, that for the confidence of MLP classifications, outliers are possible as described for the general classification in [section 5.3.5](#) on page 47.

7.3.6 Adjusting `clear_ocr_class_mlp`

To destroy the classifier, the operator `clear_ocr_class_mlp` is applied only with the input parameter `OCRHandle`.

7.4 Parameter Setting for SVM

The following sections introduce you to the parameters that have to be set for the basic operators needed for an SVM-based classification for OCR.

7.4.1 Adjusting `create_ocr_class_svm`

An SVM classifier for OCR is created using `create_ocr_class_svm`. Here, most of the important parameters have to be set.

Parameters `WidthCharacter` / `HeightCharacter`

Like for the general classification described in [section 5](#) on page 33, OCR uses a set of features to classify regions into classes, which in this case correspond to specific characters and numbers. Some of the features that can be used for OCR are gray value features for which the number of returned features varies dependent on the region's size. As a classifier requires a constant number of features, i.e., the dimension of the feature vector has to be the same for all training samples and all regions to be classified, the region of a character has to be transformed (scaled) to a standard size. This size is determined by `WidthCharacter` and `HeightCharacter`. In most applications, sizes between 6x8 and 10x14 should be used.

Parameter `Interpolation`

The input parameter `Interpolation` is needed to control the transformation of the region to the size specified with `WidthCharacter` and `HeightCharacter`. Generally, when transforming a region, transformed points will lie between discrete pixel coordinates. To assign each point to its final pixel coordinate and additionally to avoid aliasing, which typically occurs for scaled regions, an appropriate interpolation scheme is needed. The four types of interpolation that are provided by HALCON are 'nearest_neighbor', 'bilinear', 'constant', and 'weighted'. The properties of the individual interpolation schemes were already introduced for the creation of an MLP-based OCR classifier in [section 7.3.1](#) on page 100. For most applications, `Interpolation` should be set to 'constant'.

Parameter `Features`

The input parameter `Features` specifies the features that are used for the classification. `Features` can contain a tuple of several feature names. Each of these feature names results in one or more features to be calculated for the classifier. That is, the length of the tuple in `Features` is similar or smaller than the dimension of the final feature vector. In [section 7.6](#) on page 111 all features that are available for OCR are listed. To classify characters, in most cases the 'default' setting can be used. Then, the features 'ratio' and 'pixel_invar' are selected. Note that the selection of the features significantly influences the quality of the classification.

Parameter `Characters`

The input parameter `Characters` contains a tuple with the names of the characters that will be trained. Each name must be passed as a string. The number of elements in the tuple determines the number of available classes.

Parameters `KernelType`, `KernelParam`

The input parameters `KernelType` and `KernelParam` follow the same rules as provided for the corresponding operator used to create an SVM classifier for a general classification (see [section 5.4.1](#) on page 48).

Parameter Nu

The input parameter Nu follows the same rules as provided for the corresponding operator used to create an SVM classifier for a general classification (see [section 5.4.1](#) on page 48).

Parameter Mode

The input parameter Mode follows the same rules as provided for the corresponding operator used to create an SVM classifier for a general classification (see [section 5.4.1](#) on page 48).

Parameters Preprocessing / NumComponents

The parameters Preprocessing and NumComponents follow the same rules as provided for the corresponding operator used to create a classifier for a general classification (see [section 5.3.1](#) on page 41). For the sake of numerical stability, Preprocessing can typically be set to 'normalization'. In order to speed up classification time, 'principal_components' or 'canonical_variates' can be used, as the number of input features can be significantly reduced without deterioration of the recognition rate.

If Preprocessing is set to 'principal_components' or 'canonical_variates' you can use the operator [get_prep_info_ocr_class_svm](#) to determine the optimum number of components as described for the general classification in [section 5.3.1](#) on page 42.

Parameter OCRHandle

The output parameter OCRHandle is the handle of the classifier that is needed and modified throughout the following classification steps.

7.4.2 Adjusting write_ocr_trainf / append_ocr_trainf

The approach to store the training samples into a training file is the same for MLP-based and SVM-based OCR classification. See [section 7.3.2](#) on page 102 for details.

7.4.3 Adjusting trainf_ocr_class_svm

[trainf_ocr_class_svm](#) trains the OCR classifier OCRHandle with the training characters stored in the OCR training file given by TrainingFile. The remaining parameters Epsilon and TrainMode have the same meaning as introduced for the training of an SVM classifier for a general classification (see [section 5.4.3](#) on page 52).

7.4.4 Adjusting do_ocr_multi_class_svm

With [do_ocr_multi_class_svm](#) multiple characters can be classified in a single call. Typically, this is faster than successively applying [do_ocr_single_class_svm](#), which classifies single characters, in a loop. However, [do_ocr_multi_class_svm](#) can only return the best class of each character. If the second best class is of interest, [do_ocr_single_class_mlp](#) should be used instead. The following parameters have to be set for [do_ocr_multi_class_svm](#):

Parameter Character

The input parameter `Character` contains a tuple of regions that have to be classified.

Parameter Image

The input parameter `Image` contains the image that provides the gray value information for the regions that have to be classified.

Parameter OCRHandle

The input parameter `OCRHandle` is the handle of the classifier that was trained with `trainf_ocr_class_svm`.

Parameter Class

The output parameter `Class` returns the result of the classification, i.e., a tuple of character names that correspond to the input regions that were given in the tuple `Character`.

7.4.5 Adjusting `do_ocr_single_class_svm`

Instead of using `do_ocr_multi_class_svm` to add all samples in a single call, `do_ocr_single_class_svm` can be used to successively add samples. Then, besides the best class for a region, also the second best (and third best etc.) class can be obtained. If only the best class for each region is searched for, `do_ocr_multi_class_mlp` is faster and therefore recommended.

Parameter Character

The input parameter `Character` contains a single region that has to be classified.

Parameter Image

The input parameter `Image` contains the image that provides the gray value information for the region that has to be classified.

Parameter OCRHandle

The input parameter `OCRHandle` is the handle of the classifier that was trained with `trainf_ocr_class_svm`.

Parameter Num

The input parameter `Num` specifies the number of best classes to be searched for. Generally, `Num` is set to 1 if only the class with the best probability is searched for, and to 2 if the second best class is also of interest.

Parameter `Class`

The output parameter `Class` returns the result of the classification, i.e., the `Num` best character names that correspond to the input region that was specified in `Character`.

7.4.6 Adjusting `clear_ocr_class_svm`

To destroy the classifier, the operator `clear_ocr_class_svm` is applied only with the input parameter `OCRHandle`.

7.5 Parameter Setting for k-NN

The following sections introduce you to the parameters that have to be set for the basic operators needed for an k-NN-based classification for OCR.

7.5.1 Adjusting `create_ocr_class_knn`

A k-NN classifier for OCR is created using `create_ocr_class_knn`.

Parameters `WidthCharacter` / `HeightCharacter`

Like for the general classification described in [section 5](#) on page 33, OCR uses a set of features to classify regions into classes, which in this case correspond to specific characters and numbers. Some of the features that can be used for OCR are gray value features for which the number of returned features varies dependent on the region's size. As a classifier requires a constant number of features, i.e., the dimension of the feature vector has to be constant for all training samples and all regions to be classified, the region of a character has to be transformed (scaled) to a standard size. This size is determined by `WidthCharacter` and `HeightCharacter`. In most applications, sizes between 6x8 and 10x14 should be used.

Parameter `Interpolation`

The input parameter `Interpolation` is needed to control the transformation of the region to the size specified with `WidthCharacter` and `HeightCharacter`. Generally, when transforming a region, transformed points will lie between discrete pixel coordinates. To assign each point to its final pixel coordinate and additionally to avoid aliasing, which typically occurs for scaled regions, an appropriate interpolation scheme is needed. The four types of interpolation that are provided by HALCON are 'nearest_neighbor', 'bilinear', 'constant', and 'weighted'. The properties of the individual interpolation schemes were already introduced for the creation of an MLP-based OCR classifier in [section 7.3.1](#) on page 100. For most applications, `Interpolation` should be set to 'constant'.

Parameter Features

The input parameter `Features` specifies the features that are used for the classification. `Features` can contain a tuple of several feature names. Each of these feature names results in one or more features to be calculated for the classifier. That is, the length of the tuple in `Features` is identical or smaller than the dimension of the final feature vector. In [section 7.6](#) on page 111 all features that are available for OCR are listed. To classify characters, in most cases the `'default'` setting can be used. Then, the features `'ratio'` and `'pixel_invar'` are selected. Note that the selection of the features significantly influences the quality of the classification.

Parameter Characters

The input parameter `Characters` contains a tuple with the names of the characters that will be trained. Each name must be passed as a string. The number of elements in the tuple determines the number of classes.

Generic parameters

The pair of input parameters `GenParamNames` and `GenParamValues` is provided for future use only.

Parameter OCRHandle

The output parameter `OCRHandle` is the handle of the classifier that is needed and modified throughout the following classification steps.

7.5.2 Adjusting `write_ocr_trainf` / `append_ocr_trainf`

The approach to store the training samples into a training file is the same for MLP-based and k-NN-based OCR classification. See [section 7.3.2](#) on page 102 for details.

7.5.3 Adjusting `trainf_ocr_class_knn`

`trainf_ocr_class_knn` trains the OCR classifier `OCRHandle` with the training characters stored in the OCR training file given by `TrainingFile`. The generic parameters `'num_trees'` and `'normalization'` can be set with `GenParamNames` and `GenParamValues`. They have the same meaning as introduced for the training of an k-NN classifier for a general classification (see [section 5.6.3](#) on page 63).

7.5.4 Adjusting `do_ocr_multi_class_knn`

With `do_ocr_multi_class_knn` multiple characters can be classified in a single call. Typically, this is faster than successively applying `do_ocr_single_class_knn`, which classifies single characters, in a loop. However, `do_ocr_multi_class_knn` can only return the best class of each character. If the second best class is of interest, as well, `do_ocr_single_class_knn` should be used instead. The following parameters have to be set for `do_ocr_multi_class_knn`:

Parameter `Character`

The input parameter `Character` contains a tuple of regions that have to be classified.

Parameter `Image`

The input parameter `Image` contains the image that provides the gray value information for the regions that have to be classified.

Parameter `OCRHandle`

The input parameter `OCRHandle` is the handle of the classifier that was trained with `trainf_ocr_class_knn`.

Parameter `Class`

The output parameter `Class` returns the result of the classification, i.e., a tuple of character names that correspond to the input regions that were given in the tuple `Character`.

Parameter `Confidence`

The output parameter `Confidence` returns the confidence value for the classification.

7.5.5 Adjusting `do_ocr_single_class_knn`

Instead of using `do_ocr_multi_class_knn` to classify all samples in a single call, `do_ocr_single_class_svm` can be used to successively classify samples. Then, besides the best class for a given region, also the second best (and third best etc.) class can be obtained. If only the best class for each region is searched for, `do_ocr_multi_class_knn` will be faster and is therefore recommended.

Parameter `Character`

The input parameter `Character` contains a single region that has to be classified.

Parameter `Image`

The input parameter `Image` contains the image that provides the gray value information for the region that has to be classified.

Parameter `OCRHandle`

The input parameter `OCRHandle` is the handle of the classifier that has been trained with `trainf_ocr_class_knn`.

Parameter NumClasses

The input parameter `NumClasses` specifies the maximum number of best classes to be returned. For example, `NumClasses` is set to 1 if only the class with the best probability is searched for, and to 2 if the second best class is also of interest. Note that less than `NumClasses` are returned, if the nearest `NumNeighbors` do not contain enough different classes.

Parameter NumNeighbors

The parameter `NumNeighbors` defines the number of nearest neighbors that are determined during the classification. The selection of a suitable value for `NumNeighbors` depends heavily on the particular application. Generally, larger values of `NumNeighbors` lead to higher robustness against noise, smooth the boundaries between the classes, and lead to longer runtimes during the classification.

In practice, the best way of finding a suitable value for `NumNeighbors` is indeed to try different values and to select the value for `NumNeighbors` that yields the best classification results under the constraint of an acceptable runtime.

Parameter Class

The output parameter `Class` returns the result of the classification, i.e., the maximally `NumClasses` best character names that correspond to the input region that was specified in `Character`.

7.5.6 Adjusting `clear_ocr_class_knn`

To destroy the classifier, the operator `clear_ocr_class_knn` is applied only with the input parameter `OCRHandle`.

7.6 OCR Features

The features that determine the feature vector for an OCR specific classification are selected via the parameter `Feature` in the operator `create_ocr_class_mlp` or `create_ocr_class_svm`, respectively. Note that some of the features lead to more than one feature value, i.e., the dimension of the feature vector can be larger than the number of selected feature types. The following feature types can be set individually or in combinations:

Feature 'anisometry'

Anisometry of the character. If R_a and R_b are the two radii of an ellipse that has the “same orientation” and the “same side relation” as the input region, the anisometry is defined as:

$$\text{anisometry} = \frac{R_a}{R_b}$$

Feature 'chord_histo'

Frequency of the runs per row. The number of returned features depends on the height of the pattern.

Feature 'compactness'

Compactness of the character. If L is the length of the contour and F the area of the region, the compactness is defined as:

$$\text{OCR Feature compactness} = \frac{L^2}{4\pi F}$$

The compactness of a circle is 1. If the region is long or has holes, the compactness is larger than 1. The compactness responds to the run of the contour (roughness) and to holes.

Feature 'convexity'

Convexity of the character. If F_c is the area of the convex hull and F_o the original area of the region, the convexity is defined as:

$$\text{convexity} = \frac{F_o}{F_c}$$

The convexity is 1 if the region is convex (e.g., rectangle, circle etc.). If there are indentations or holes, the convexity is smaller than 1.

Feature 'cooc'

Values of the binary co-occurrence matrices. A binary co-occurrence matrix describes how often the values 0 (outside the region) and 1 (inside the region) are located next to each other in a certain direction (0, 45, 90, 135 degrees). These numbers are stored in the co-occurrence matrix at the locations (0,0), (0,1), (1,0), and (1,1). Due to the symmetric nature of the co-occurrence matrix, each matrix contains two independent entries, e.g., (0,0) and (0,1). These two entries are taken from each of the four matrices. The feature type 'cooc' returns eight features.

Feature 'foreground'

Fraction of pixels in the foreground.

Feature 'foreground_grid_16'

Fraction of pixels in the foreground in a 4x4 grid within the smallest enclosing rectangle of the character. The feature type 'foreground_grid_16' returns 16 features.

Feature 'foreground_grid_9'

Fraction of pixels in the foreground in a 3x3 grid within the smallest enclosing rectangle of the character. The feature type 'foreground_grid_9' returns nine features.

Feature 'gradient_8dir'

Gradients are computed on the character image. The gradient directions are discretized into 8 directions. The amplitude image is decomposed into 8 channels according to these discretized directions. 25 samples on a 5x5 grid are extracted from each channel. These samples are used as features (200 features).

Feature 'height'

Height of the character before scaling the character to the standard size (not scale-invariant).

Feature 'moments_central'

Normalized central moments of the character. The feature type 'moments_central' is invariant under other affine transformations, e.g., rotation or stretching, and returns the four features `psi1`, `psi2`, `psi3`, and `psi4`.

Feature 'moments_gray_plane'

Normalized gray value moments and the angle of the gray value plane. This incorporates the gray value center of gravity (${}^g\bar{r}; {}^g\bar{c}$) together with the parameters α and β , which describe the orientation of the plane which approximates the gray values. The feature type 'moments_gray_plane' returns four features.

Feature 'moments_region_2nd_invar'

Normalized 2nd moments of the character. The feature type 'moments_region_2nd_invar' returns the three features μ_{11} , μ_{20} , and μ_{02} .

Feature 'moments_region_2nd_rel_invar'

Normalized 2nd relative moments of the character. The feature type 'moments_region_2nd_rel_invar' returns the two features `phi1` and `phi2`.

Feature 'moments_region_3rd_invar'

Normalized 3rd moments of the character. The feature type 'moments_region_3rd_invar' returns the four features μ_{21} , μ_{12} , μ_{03} , and μ_{30} .

Feature 'num_connect'

Number of connected components.

Feature 'num_holes'

Number of holes.

Feature 'num_runs'

Number of runs in the region normalized by the area.

Feature 'phi'

Sine and cosine of the orientation of an ellipse that has the “same orientation” and the “same side relation” as the input region. The feature type 'phi' returns two features.

Feature 'pixel'

Gray values of the character. The number of returned features depends on the height and width of the pattern.

Feature 'pixel_binary'

Region of the character as a binary image. The number of returned features depends on the height and width of the pattern.

Feature 'pixel_invar'

Gray values of the character with maximum scaling of the gray values. The number of returned features depends on the height and width of the pattern.

Feature 'projection_horizontal'

Horizontal projection of the gray values, i.e., the mean values in the horizontal direction of the gray values of the input image. The number of returned features depends on the height of the pattern.

Feature 'projection_horizontal_invar'

Maximally scaled horizontal projection of the gray values. The number of returned features depends on the height of the pattern.

Feature 'projection_vertical'

Vertical projection of the gray values, i.e., the mean values in the vertical direction of the gray values of the input image. The number of returned features depends on the width of the pattern.

Feature 'projection_vertical_invar'

Maximally scaled vertical projection of the gray values. The number of returned features depends on the width of the pattern.

Feature 'ratio'

Aspect ratio of the character.

Feature 'width'

Width of the character before scaling the character to the standard size (not scale-invariant).

Feature 'zoom_factor'

Difference in size between the character and the values of PatternWidth and PatternHeight (not scale-invariant).

Further information about the individual features and their calculation can be accessed via the Reference Manual entries for [create_ocr_class_mlp](#) or [create_ocr_class_svm](#), respectively.

Chapter 8

General Tips

This section provides you with some additional tips that may help you to optimize your classification application. In particular, a method for optimizing the most critical parameters is introduced in [section 8.1](#), the classification of general region features with the OCR specific classification operators is described in [section 8.2](#), and means to visualize the feature space for low dimensional feature vectors (2D and 3D) are given in [section 8.3](#).

8.1 Optimize Critical Parameters with a Test Application

To optimize the most critical parameters for a classification, different parameter values should be tested with the available training data. To optimize the generalization ability of a classifier, the parameter optimization should be combined with a cross validation. There, the training data is divided into typically five sub sets and the training is performed rotative with four of the five sub sets and tested with the fifth sub set (see [figure 8.1](#)). Take care, that the training data is uniformly distributed in the sub sets. That is, if for one class only five samples are available, each sub set should contain one of it, and if for another class hundred samples are available, each sub set should contain twenty of them. Note that a cross validation needs a lot of time as it is reasonable mainly for a very large set of training data, i.e., for applications that are challenging because of the many variations inside the classes and the overlaps between the classes.

The actual test application can be applied as follows:

- You first split up the training data into five uniformly distributed data sets.
- Then, you create a loop over the different parameter values that are to be tested, e.g., over different values for `NumHidden` in case of an MLP classification. When adjusting two parameters simultaneously, e.g., the `Nu-KernelParam` pair for SVM, you have to nest two loops into each other.
- Within the (inner) loop, the cross validation is applied, i.e., each sub set of the training data is once classified with a classifier that is trained by the other four sub sets using the tested parameters. The sum of the correctly classified samples of the test data set is stored so that later the sum of correct classifications can be assigned to the corresponding tested parameter values.



Figure 8.1: Cross validation: The training data is divided into 5 sub sets. Each set is used once as test data (black) that is classified by a classifier trained by the training data of the other 4 sub sets (gray).

- After testing all parameter values, you select the best result, i.e., the parameter values that led to the largest number of correctly classified test samples within the test application are used for the actual classification application.

For the cross validation, a number of five sub sets is sufficient. When increasing this number, no advantage is obtained, but the training is slowed down significantly. The parameters for which such a test application is reasonable mainly comprise [NumCenters](#) for GMM (then, the parameter [CovarType](#) should be set to 'full'), [NumHidden](#) for MLP, and the [Nu-KernelParam](#) pair for SVM.

8.2 Classify General Regions using OCR

Sometimes it may be convenient to use the operators provided for OCR also for the classification of general objects. This is possible as long as the objects can be described by the features that are provided for OCR (see [section 7.6](#) on page 111). Note that many of the provided features are not rotation invariant. That is, if your objects have different orientations in the images, you have to apply an alignment before applying the classification. The example `solution_guide\classification\classify_metal_parts_ocr.hdev` shows how to use OCR to classify the metal parts that were already classified with a general classification in the example program `solution_guide\classification\classify_metal_parts.hdev` in [section 2](#) on page 13.

The program starts with the creation of an OCR classifier using `create_ocr_class_mlp`. There, the approximated dimensions of the regions that represent the objects are specified by the parameters `WidthCharacter` and `HeightCharacter`. The parameter `Features` is set to 'moments_central'. In contrast to the general classification, no feature vectors have to be explicitly calculated and stored. This may enhance the speed of the training as well as of the actual classification, and by the way needs less programming effort. The parameter `Characters` contains a tuple of strings that defines the available class names, in this case the classes 'circle', 'hexagon', and 'polygon' are available. In

`solution_guide\classification\classify_metal_parts.hdev` the classes were addressed simply by their index, i.e., 0, 1, and 2. There, the assignment of names for each class would have been possible, too, but then an additional tuple with names must have been assigned and the correspondence between the class index and the class name must have been made explicit.

```
create_ocr_class_mlp (110, 110, 'constant', 'moments_central', ['circle', \
    'hexagon','polygon'], 10, 'normalization', 10, 42, \
    OCRHandle)
```

Now, the input images, which are the same as already illustrated in [figure 2.1](#) on page 14, and the class names for the objects of each image are defined (`FileNames` and `ClassNamesImage`).

```
FileNames := ['nuts_01','nuts_02','nuts_03','washers_01','washers_02', \
    'washers_03','retainers_01','retainers_02','retainers_03']
ClassNamesImage := ['hexagon','hexagon','hexagon','circle','circle', \
    'circle','polygon','polygon','polygon']
```

Then, the individual training regions of the objects are extracted from the training images. The procedure to segment the regions is the same as used for `solution_guide\classification\classify_metal_parts.hdev` in [section 2](#) on page 13. The first region and its corresponding class name is stored into an OCR training file using `write_ocr_trainf`. All following regions and their class names are stored into the same training file by appending them via `append_ocr_trainf`.

```
for J := 0 to |FileNames| - 1 by 1
    read_image (Image, 'rings/' + FileNames[J])
    segment (Image, Objects)
    count_obj (Objects, NumberObjects)
    for k := 1 to NumberObjects by 1
        select_obj (Objects, ObjectSelected, k)
        if (J == 0 and k == 1)
            write_ocr_trainf (ObjectSelected, Image, ClassNamesImage[J], \
                'train_metal_parts_ocr.trf')
        else
            append_ocr_trainf (ObjectSelected, Image, ClassNamesImage[J], \
                'train_metal_parts_ocr.trf')
        endif
    endfor
endfor
```

After adding all training samples to the training file, the training file is used by `trainf_ocr_class_mlp` to train the 'font', which here consists of three different shapes.

```
trainf_ocr_class_mlp (OCRHandle, 'train_metal_parts_ocr.trf', 200, 1, 0.01, \
    Error1, ErrorLog1)
```

The images with the objects to classify are read in a loop and for each image the regions that represent the objects are extracted using the same procedure that was used for the training. Now, each region is classified using `do_ocr_single_class_mlp`. Dependent on the classification result, the regions are visualized by different colors (see [figure 8.2](#)).

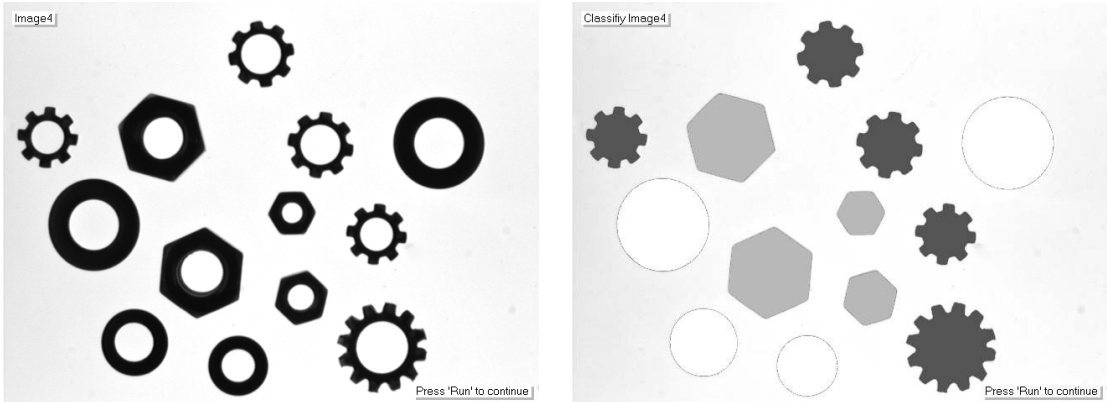


Figure 8.2: Classifying metal parts because of their shape using the OCR specific classification operators: (left) image with metal parts, (right) metal parts classified into three classes (illustrated by different gray values).

```
for J := 1 to 4 by 1
  read_image (Image, 'rings/mixed_' + J$'02d')
  segment (Image, Objects)
  for k := 1 to NumberObjects by 1
    select_obj (Objects, ObjectSelected, k)
    do_ocr_single_class_mlp (ObjectSelected, Image, OCRHandle, 1, Class, \
                           Confidence)

    if (Class == 'circle')
      dev_set_color ('blue')
    endif
    if (Class == 'hexagon')
      dev_set_color ('coral')
    endif
    if (Class == 'polygon')
      dev_set_color ('green')
    endif
    dev_display (ObjectSelected)
  endfor
endfor
```

At the end of the program, the classifier is cleared from memory using [clear_ocr_class_mlp](#).

```
clear_ocr_class_mlp (OCRHandle)
```

8.3 Visualize the Feature Space (2D and 3D)

Sometimes, it may be suitable to have a look at the feature space, e.g., to check if the selected features build clearly separable clusters. If not, another set of features should be preferred or further features

should be added. A reasonable visualization is possible only for the 2D ([section 8.3.1](#)) and 3D feature space ([section 8.3.2](#)), i.e., feature vectors or parts of feature vectors that contain only two to three features.

8.3.1 Visualize the 2D Feature Space

In [section 3](#) on page [17](#), the example `solution_guide\classification\classify_citrus_fruits.hdev` was coarsely introduced to explain what a feature space is. The example classifies citrus fruits into the classes 'oranges' and 'lemons' and visualizes the 2D feature space for the training samples. This feature space is built by the two shape features 'area' and 'circularity'. In the following, we summarize the steps of the example with the focus on how to visualize the 2D feature space.

At the beginning of the program, the names of the classes are defined and a GMM classifier is created. Then, inside a for-loop the training images are read, the regions of the contained fruits are segmented from the red channel of the color image (inside the procedure `get_regions`) and the features 'area' and 'circularity' are calculated for each region (inside the procedure `get_features`). The values for the area of the regions are integer values. As the feature vector has to consist of real values, the feature vector is converted into a tuple of real values before it is added to the classifier together with the corresponding known class ID.

```

ClassName := ['orange','lemon']
create_class_gmm (2, 2, 1, 'spherical', 'normalization', 10, 42, GMMHandle)
for I := 1 to 4 by 1
  read_image (Image, 'color/citrus_fruits_' + I$.2d')
  get_regions (Image, SelectedRegions)
  count_obj (SelectedRegions, NumberObjects)
  for J := 1 to NumberObjects by 1
    select_obj (SelectedRegions, ObjectSelected, J)
    get_features (ObjectSelected, WindowHandle, Circularity, Area, \
      RowRegionCenter, ColumnRegionCenter)
    FeaturesArea := [FeaturesArea,Area]
    FeaturesCircularity := [FeaturesCircularity,Circularity]
    FeatureVector := real([Circularity,Area])
    if (I <= 2)
      add_sample_class_gmm (GMMHandle, FeatureVector, 0, 0)
    else
      add_sample_class_gmm (GMMHandle, FeatureVector, 1, 0)
    endif
  endfor
endfor
endfor

```

Now, the feature space for the oranges (dim gray) and lemons (light gray) of the training samples is visualized by the procedure `visualize_2D_feature_space` (see [figure 8.3](#)).

```

visualize_2D_feature_space (Cross, Height, Width, WindowHandle, \
                           FeaturesArea[0:5], FeaturesCircularity[0:5], \
                           'dim gray', 18)
visualize_2D_feature_space (Cross, Height, Width, WindowHandle, \
                           FeaturesArea[6:11], FeaturesCircularity[6:11], \
                           'light gray', 18)

```

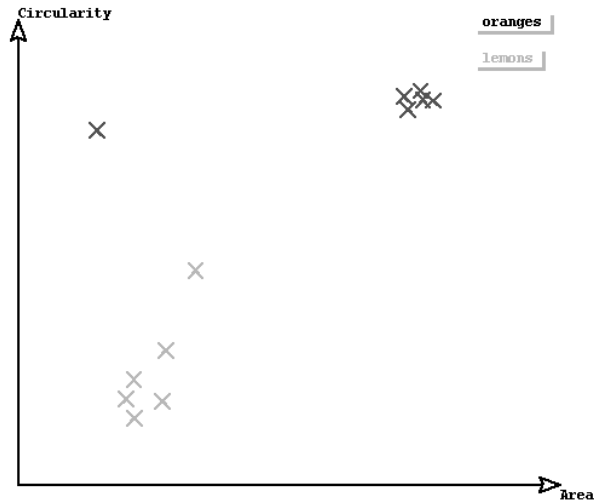


Figure 8.3: The feature space for the oranges (black) and lemons (gray) of the training samples.

Inside the procedure, first a 2D graph is created, i.e., depending on the width and height of the window, the origin of the 2D graph is defined in image coordinates (`OriginOfGraph`), each axis of the graph is visualized by an arrow (`disp_arrow`), and each axis is labeled with the name of the corresponding feature (`set_tposition`, `write_string`).

```

procedure visualize_2D_feature_space (Cross, Height, Width, WindowID,
                                     FeaturesA, FeaturesC,
                                     ColorFeatureVector, CrossSize)::
dev_set_color ('black')
OriginOfGraph := [Height - 0.1 * Height, 0.1 * Width]
disp_arrow (WindowID, OriginOfGraph[0], OriginOfGraph[1], OriginOfGraph[0], \
           Width - 0.2 * Width, 2)
disp_arrow (WindowID, OriginOfGraph[0], OriginOfGraph[1], 0.1 * Height, \
           OriginOfGraph[1], 2)
set_tposition (WindowID, OriginOfGraph[0], Width - 0.2 * Width)
write_string (WindowID, 'Area')
set_tposition (WindowID, 0.07 * Height, OriginOfGraph[1])
write_string (WindowID, 'Circularity')

```


Then, the procedure determines the relations between the image coordinates and the feature values. For that, the extent of the graph is defined on one hand in pixels for the image coordinate system (`ExtentOfGraph`) and on the other hand in feature value units (`RangeC`, `RangeA`). Inside the image coordinate system, the extent is the same for both axes and depends on the window height. For the feature values, the extent is defined for each feature axis individually so that it covers the whole range of the corresponding feature values that is expected for the given set of feature vectors. That is, for each feature, the extent corresponds to the approximated difference between the expected maximum and minimum feature value. Having the extent of the graph in image coordinates as well as the individual value ranges for the features, the scaling factor for each axis between feature values and the image coordinate system is known (`ScaleC`, `ScaleA`).

```
ExtentOfGraph := Height - 0.3 * Height
RangeC := 0.5
RangeA := 24000
ScaleC := ExtentOfGraph / RangeC
ScaleA := ExtentOfGraph / RangeA
```

In addition to the scaling, a translation of the feature vectors is needed. Otherwise, the points representing the feature vectors would be outside of the window. Here, the feature vectors are moved such that the position that is built by the expected minimum feature values corresponds to the origin of the 2D graph in image coordinates. The feature values at the origin are then described by `MinC` and `MinA`.

```
MinC := 0.5
MinA := 20000
```

In [figure 8.4](#) the relations between the image coordinates and the feature values are illustrated.

Knowing the relations between the feature values and the image coordinate system, the procedure calculates the image coordinates for each individual feature vector (`RowFeature`, `ColumnFeature`). For that, the distance of each feature value to the origin of the 2D graph is calculated (in feature value units) and multiplied with the scaling factor. The obtained distance in pixels (`DiffC`, `DiffA`) then simply is subtracted from respectively added to the corresponding image coordinates of the graph's origin (`OriginOfGraph[0]`, `OriginOfGraph[1]`). The resulting image coordinates are visualized by a cross contour that is created with the operator `gen_cross_contour_xld` and displayed with `dev_display`.

```
NumberFeatureVectors := |FeaturesA|
for I := 0 to NumberFeatureVectors - 1 by 1
    DiffC := ScaleC * (FeaturesC[I] - MinC)
    DiffA := ScaleA * (FeaturesA[I] - MinA)
    RowFeature := OriginOfGraph[0] - DiffC
    ColumnFeature := OriginOfGraph[1] + DiffA
    gen_cross_contour_xld (Cross, RowFeature, ColumnFeature, CrossSize, \
                          0.785398)
    dev_display (Cross)
endfor
return ()
```

After visualizing the feature space for the training samples with the procedure `visualize_2D_feature_space`, the training and classification is applied by the approach described in more detail in the sections of [section 5](#) on page 33.

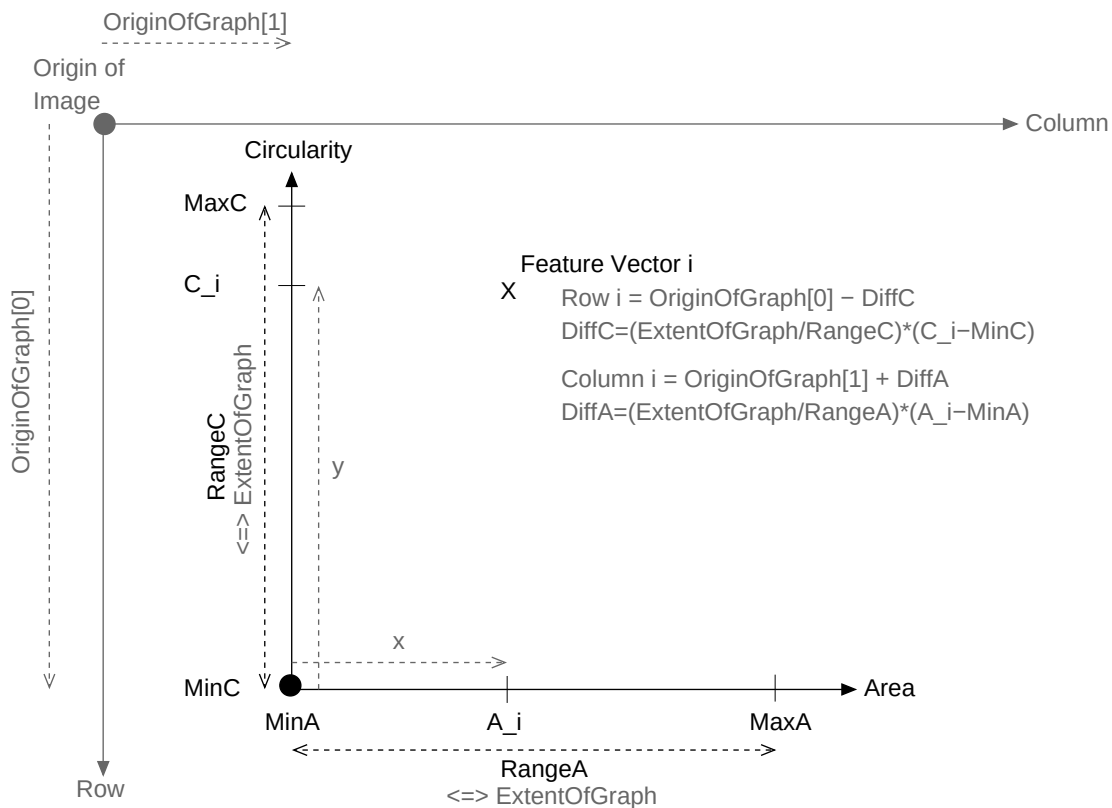


Figure 8.4: Relations between image coordinates (gray) and feature values (black).

```

train_class_gmm (GMMHandle, 100, 0.001, 'training', 0.0001, Centers, Iter)
for I := 1 to 15 by 1
  read_image (Image, 'color/citrus_fruits_' + I$.2d')
  get_regions (Image, SelectedRegions)
  count_obj (SelectedRegions, NumberObjects)
  for J := 1 to NumberObjects by 1
    select_obj (SelectedRegions, ObjectSelected, J)
    get_features (ObjectSelected, WindowHandle, Circularity, Area, \
      RowRegionCenter, ColumnRegionCenter)
    FeaturesArea := [FeaturesArea, Area]
    FeaturesCircularity := [FeaturesCircularity, Circularity]
    FeatureVector := real([Circularity, Area])
    classify_class_gmm (GMMHandle, FeatureVector, 1, ClassID, ClassProb, \
      Density, KSigmaProb)
  endfor
endfor
clear_class_gmm (GMMHandle)

```

8.3.2 Visualize the 3D Feature Space

The example `solution_guide\classification\visualize_3d_feature_space.hdev` shows how to visualize a 3D feature space for the pixels of two regions that contain differently textured patterns. The feature vector for each pixel is built by three gray values.

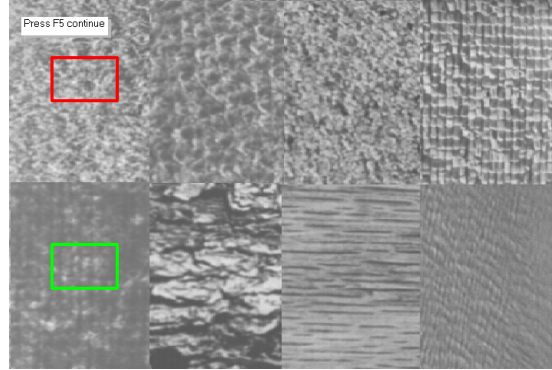


Figure 8.5: The two texture classes that have to be classified are marked by rectangles.

First, the feature vectors, i.e., the three gray values for each pixel have to be derived. For that, a texture image is created by applying different texture filters ([texture_laws](#)), which are combined with a linear smoothing ([mean_image](#)), to the original image. As we do not exactly know which laws filters are suited best to separate the specific texture classes from each other, we construct six differently filtered images and combine them to a six channel image ([compose6](#)).

```
set_system ('clip_region', 'false')
read_image (Image, 'combine')
get_part (WindowHandle, Row1, Column1, Row2, Column2)
texture_laws (Image, ImageTexture1, 'ee', 5, 7)
texture_laws (Image, ImageTexture2, 'ss', 2, 7)
texture_laws (Image, ImageTexture3, 'rr', 0, 7)
texture_laws (Image, ImageTexture4, 'ww', 0, 7)
texture_laws (Image, ImageTexture5, 'le', 7, 7)
texture_laws (Image, ImageTexture6, 'el', 7, 7)
mean_image (ImageTexture1, ImageMean1, 41, 41)
mean_image (ImageTexture2, ImageMean2, 41, 41)
mean_image (ImageTexture3, ImageMean3, 41, 41)
mean_image (ImageTexture4, ImageMean4, 41, 41)
mean_image (ImageTexture5, ImageMean5, 41, 41)
mean_image (ImageTexture6, ImageMean6, 41, 41)
compose6 (ImageMean1, ImageMean2, ImageMean3, ImageMean4, ImageMean5, \
          ImageMean6, TextureImage)
```

To get uncorrelated images, i.e., to discard data with little information, and to save storage, the six-channel image is transformed by a principal component analysis. The resulting transformed image is then input to the procedure `gen_sample_tuples`.

```
principal_comp (TextureImage, PCAImage, InfoPerComp)
gen_sample_tuples (PCAImage, Rectangles, Sample1, Sample2, Sample3)
```

Within the procedure, the first three images of the transformed texture image, i.e, the three channels with the largest information content, are accessed via [access_channel](#). Then, inside the image, for the two texture classes rectangles are generated (see [figure 8.5](#) on page 123) and all pixel coordinates within these rectangles are determined and stored in the tuples RowsSample and ColsSample. For each pixel the gray values of the first three channels of the transformed texture image are determined and stored in the tuples Sample1, Sample2, and Sample3.

```
procedure gen_sample_tuples (PCAImage, Rectangles, Sample1, Sample2,
                             Sample3)::
  gen_empty_obj (ClassSamples)
  Sample1 := []
  Sample2 := []
  Sample3 := []
  gen_empty_obj (Rectangles)
  access_channel (PCAImage, Image1, 1)
  access_channel (PCAImage, Image2, 2)
  access_channel (PCAImage, Image3, 3)
  ClassNum := 0
  I := 0
  for Row := 80 to 340 by 260
    for Col := 40 to 460 by 460
      gen_rectangle1 (ClassSample, Row, Col, Row + 60, Col + 60)
      concat_obj (Rectangles, ClassSample, Rectangles)
      RowsSample := []
      ColsSample := []
      for RSample := Row to Row + 60 by 1
        for CSample := Col to Col + 60 by 1
          RowsSample := [RowsSample, RSample]
          ColsSample := [ColsSample, CSample]
        endfor
      endfor
      get_grayval (Image1, RowsSample, ColsSample, Grayvals1)
      get_grayval (Image2, RowsSample, ColsSample, Grayvals2)
      get_grayval (Image3, RowsSample, ColsSample, Grayvals3)
      Sample1 := [Grayvals1, Sample1]
      Sample2 := [Grayvals2, Sample2]
      Sample3 := [Grayvals3, Sample3]
    endfor
  endfor
  return ()
```

The feature vectors that are built by the gray values of the three channels are now displayed by the procedure `visualize_3d`. To show the feature space from different views, it is by default rotated in discrete steps around the y axis (RotY). Furthermore, the view can be changed by dragging the mouse. Then, dependent on the position of the mouse pointer in the graphics window, the feature space is additionally rotated around the x and z axes.

```

for j := 0 to 360 by 1
    dev_set_check ('~give_error')
    get_mposition (WindowHandle, Row, Column, Button)
    dev_set_check ('give_error')
    if (Button != [])
        RotX := fmod(Row,360)
        RotZ := fmod(Column,360)
    else
        RotX := 75
        RotZ := 45
    endif
    RotY := j
    visualize_3d (WindowHandle, Sample1, Sample2, Sample3, RotX, RotY, \
                  RotZ)
endfor

```

Within the procedure `visualize_3d`, similar to the visualization of 2D feature vectors described in [section 8.3.1](#) on page 119, the minimum and maximum values for the three feature axes are determined. Then, the maximum value range of the features is determined and is used to define the scale factor for the visualization. In contrast to the example used for the visualization of 2D feature vectors, the same scale factor is used here for all feature axes. This is because all features are of the same type (gray values), and thus the ranges are in the same order of magnitude.

```

Min1 := min(Sample1)
Max1 := max(Sample1)
Min2 := min(Sample2)
Max2 := max(Sample2)
Min3 := min(Sample3)
Max3 := max(Sample3)
MaxFeatureRange := max([Max1 - Min1, Max2 - Min2, Max3 - Min3])
Scale := 1. / MaxFeatureRange

```

After defining a value for the virtual z axis, a homogeneous transformation matrix is generated and transformed so that the feature space of interest fits completely into the image and can be visualized under the view specified before calling the procedure. The homogeneous transformation matrix is built using the operators `hom_mat3d_translate`, `hom_mat3d_scale`, and `hom_mat3d_rotate`. The actual transformation of the feature vectors with the created transformation matrix is applied with `affine_trans_point_3d`. To project the 3D points into the 2D image, the operator `project_3d_point` is used. Here, camera parameters are needed. These are defined as follows: the focal length is set to 0.1 to simulate a candid camera. The distortion coefficient κ is set to 0, because no distortions caused by the lens have to be modeled. The two scale factors correspond to the horizontal and vertical distance between two cells of the sensor, and the image center point as well as the width and height of the image are derived from the image size.

```

DistZ := 7
hom_mat3d_identity (HomMat3DIdentity)
hom_mat3d_translate (HomMat3DIdentity, -(Min1 + Max1) / 2, \
                    -(Min2 + Max2) / 2, -(Min3 + Max3) / 2 + DistZ, \
                    HomMat3DTranslate)
hom_mat3d_scale (HomMat3DTranslate, Scale, Scale, Scale, 0, 0, DistZ, \
                HomMat3DScale)
hom_mat3d_rotate (HomMat3DScale, rad(RotX), 'x', 0, 0, DistZ, \
                HomMat3DRotateX)
hom_mat3d_rotate (HomMat3DRotateX, rad(RotY), 'y', 0, 0, DistZ, \
                HomMat3DRotateY)
hom_mat3d_rotate (HomMat3DRotateY, rad(RotZ), 'z', 0, 0, DistZ, \
                HomMat3DRotateZ)
affine_trans_point_3d (HomMat3DRotateZ, Sample1, Sample2, Sample3, Qx, Qy, \
                    Qz)
CamParam := [0.1,0,0.00005,0.00005,360,240,720,480]
project_3d_point (Qx, Qy, Qz, CamParam, Row, Column)

```

The result of the projection is a row and column coordinate for each feature vector. At this position, a region point is generated and displayed (see [figure 8.6](#)).

```

gen_region_points (Region, Row, Column)
set_part (WindowHandle, 0, 0, 479, 719)
set_system ('flush_graphic', 'false')
clear_window (WindowHandle)
disp_obj (Region, WindowHandle)
set_system ('flush_graphic', 'true')

```

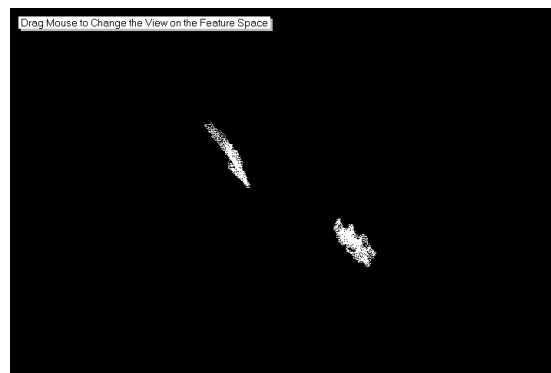


Figure 8.6: The feature space shows two clearly separated clusters for the two texture classes.

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