HALCON

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Solution Guide III-B

2D Measuring



HALCON 21.05 *Progress*

MVTec Software GmbH

Building Vision for Business

How to measure in 2D with high accuracy, Version 21.05.0.0

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About This Manual

In a broad range of applications, 2D measuring is applied to get spatial information about planar objects or object parts that are extracted from images. This Solution Guide leads you through a variety of approaches suited to measure in 2D with HALCON.

Section 1 on page 7 gives a short introduction to the general topic. Then, a first example is presented that gives an impression on the variety of methods usable for 2D measuring tasks.

In section 2 on page 11, the different HALCON methods that can be used to extract objects and their features are introduced. The methods comprise

- region processing (see section 2.1 on page 11),
- contour processing (see section 2.2 on page 14),
- 2D metrology (see section 2.3 on page 21), and
- simple geometric operations (see section 2.4 on page 25).

Section 3 on page 27 provides you with practical tips for the tool selection. In particular, section 3.1 on page 27 guides you from the features to extract to the methods to choose and section 3.2 on page 31 compares the two most common and competing approaches, region processing and contour processing. Both can be used for similar goals but are differently suited depending on the required precision and the appearance of the object in the image.

Practical guidance is given by a comprehensive collection of HDevelop examples in section 4 on page 35. The HDevelop example programs that are presented in this Solution Guide can be found in the specified subdirectories of the directory `%HALCONEXAMPLES%`.

Additional aspects that may be of interest are discussed in section 5. In particular, the identification of corresponding object parts in different images (see section 5.1 on page 63) and means to measure in world coordinates (see section 5.2 on page 68) are discussed.

Contents

1 Introduction **7**

2 Basic Tools **11**
2.1 Region Processing . . . 11
2.1.1 Preprocess Image or Region . . . 12
2.1.2 Segment the Image into Regions . . . 12
2.1.3 Select and Modify Regions . . . 12
2.1.4 Extract Features . . . 14
2.2 Contour Processing . . . 14
2.2.1 Create Contours . . . 15
2.2.2 Get Relevant Contours . . . 16
2.2.3 Segment Contours . . . 18
2.2.4 Extract Features of Contour Segments by Approximating them by known Shapes . . . 19
2.2.5 Extract Features of Contours Without Knowing Their Shapes . . . 20
2.3 2D Metrology . . . 21
2.3.1 Aligning the Metrology Model based on different methods . . . 23
2.3.2 Querying Results . . . 24
2.4 Geometric Operations . . . 25

3 Tool Selection **27**
3.1 From the Feature to the Tool . . . 27
3.1.1 Area . . . 29
3.1.2 Orientation and Angle . . . 29
3.1.3 Position . . . 30
3.1.4 Dimension and Distance . . . 30
3.1.5 Number of Objects . . . 31
3.2 Region Processing vs. Contour Processing . . . 31

4 Examples for Practical Guidance **35**
4.1 Rotate Image and Region (2D Transformation) . . . 35
4.2 Get Width of Screw Thread . . . 36
4.3 Get Deviation of a Contour from a Straight Line . . . 37
4.4 Get the Distance between Straight Parallel Contours . . . 41
4.5 Get Width of Linear Structures . . . 43
4.6 Get Lines and Junctions of a Grid . . . 44
4.7 Get Positions of Corner Points . . . 47
4.8 Get Angle between Adjacent Lines . . . 49
4.9 Get Positions, Orientations, and Extents of Rectangles . . . 49
4.10 Get Radii of Circles and Circular Arcs . . . 52
4.11 Get Deviation of a Contour from a Circle . . . 54
4.12 Inspect Ball Grid Array (BGA) . . . 56
4.13 Extract Contours from Color Images . . . 60

5 Miscellaneous **63**
5.1 Identify Corresponding Object Parts . . . 63
5.2 Measure in World Coordinates . . . 68

Index **73**

Chapter 1

Introduction

HALCON provides various methods that are suited for a broad range of different 2D measurement tasks. Measuring in images consists of the extraction of specific features of objects. 2D features that are often extracted comprise

- the area of an object, i.e., the number of pixels representing the object,
- the orientation of the object,
- the angle between objects or segments of objects,
- the position of an object,
- the dimension of an object, i.e., its diameter, width, height, or the distance between objects or parts of objects, and
- the number of objects.

To extract the features, several tools are available. Which tool to choose depends on the goal of the measuring task, the required accuracy, and the way the object is represented in the image. This Solution Guide leads you through the alternative approaches of common 2D measuring applications.

This chapter shows a first example for a 2D measuring application that uses different basic measuring tools. To follow the example actively, start the HDevelop program `%HALCONEXAMPLES%\solution_guide\2d_measuring\measure_metal_part_first_example.hdev`, which extracts several features from a flat metal part; the steps described below start after the initialization of the application (press `Run` once to reach this point).

Step 1: Create regions and extract basic features

```
threshold (Image, Region, 100, 255)
```

In a first step, region processing is used to extract some basic features. The image is segmented by a simple `threshold` operator. The result of the operator is a single region that can consist of several connected components. If more than one connected component is returned, the components can be separated by the operator `connection`, which is recommended for most applications. Here, the returned region consists of only one connected component, so no separation is necessary.

For the obtained region representing the metal part, the operators `area_center` and `orientation_region` calculate the area, position, and orientation (see figure 1.1).

```
area_center (Region, AreaRegion, RowCenterRegion, ColumnCenterRegion)
orientation_region (Region, OrientationRegion)
dev_display (Region)
```

A more advanced task is the extraction of features using the object's outline, e.g., if you want to extract the radii of the circular contour segments:

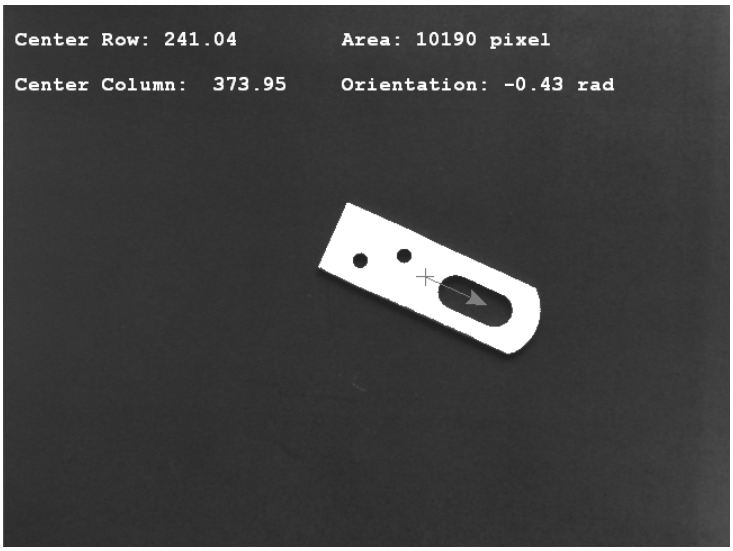

Figure 1.1: Region obtained by a threshold and display of extracted features.

Step 2: Extract contours

```
edges_sub_pix (Image, Edges, 'canny', 0.6, 30, 70)
```

Here, instead of a region the contours of the object are used to get information about the object. The edges of the metal part are extracted as subpixel-precise XLD contours (see Quick Guide, section 2.1.1 on page 10 for XLDs) using the edge extractor `edges_sub_pix`. Figure 1.2 shows the metal part overlaid with the extracted edges.

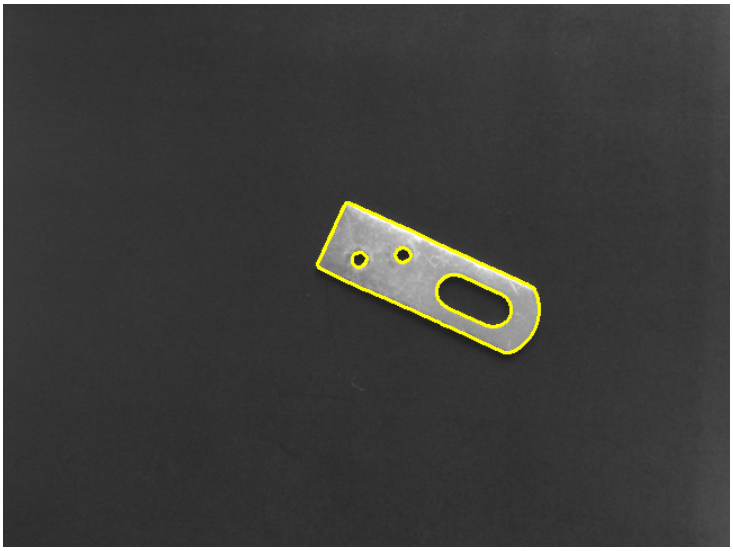

Figure 1.2: XLD contours obtained by a subpixel-precise edge extraction.

Step 3: Segment contours

```
segment_contours_xld (Edges, ContoursSplit, 'lines_circles', 6, 4, 4)
```

The operator `segment_contours_xld` segments the contours into linear and circular segments using the parameter `'lines_circles'`. Alternative parameter values are `'lines'` to segment only into lines and `'lines_ellipses'` to segment into lines and ellipses. Figure 1.3 shows the line and circle segments for the metal part in different colors.

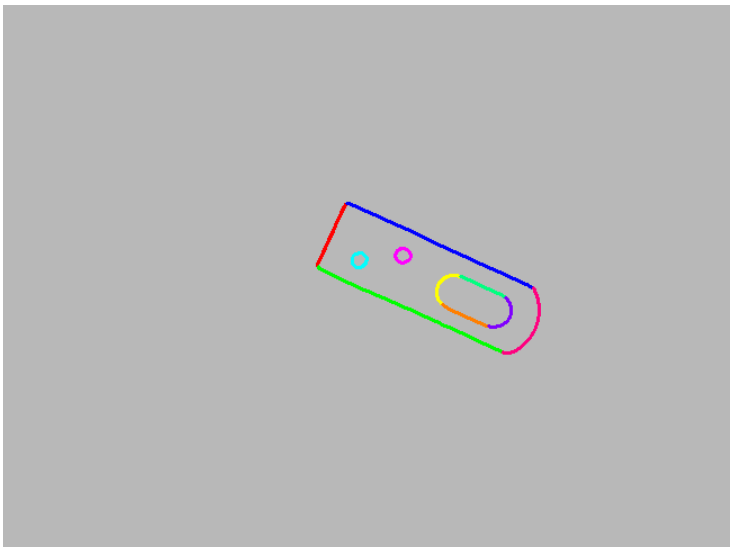

Figure 1.3: Individual segments of the contours.

Step 4: Divide contour segments into linear and circular segments

Now, the circular segments are selected from the list of contour segments. To achieve this, the operator segment_contours_xld sets the global contour attribute 'cont_approx' for each segment. The value of this variable can be queried by the operator get_contour_global_attrib_xld. It determines, whether the segment represents a line ('cont_approx' =-1), an elliptic arc ('cont_approx' =0), or a circular arc ('cont_approx' =1). As we selected the parameter 'lines_circles' inside segment_contours_xld, 'cont_approx' can be -1 or 1. Depending on this value, each contour can be approximated either by a circle or a line.

```
select_obj (ContoursSplit, SingleSegment, i)
get_contour_global_attrib_xld (SingleSegment, 'cont_approx', Attrib)
```

Step 5: Extract radii of circular contour segments

```
if (Attrib == 1)
    fit_circle_contour_xld (SingleSegment, 'atukey', -1, 2, 0, 5, 2, \
                            Row, Column, Radius, StartPhi, EndPhi, \
                            PointOrder)
    gen_circle_contour_xld (ContCircle, Row, Column, Radius, 0, \
                            rad(360), 'positive', 1)
    RowsCenterCircle := [RowsCenterCircle,Row]
    ColumnsCenterCircle := [ColumnsCenterCircle,Column]
endif
```

The operator fit_circle_contour_xld approximates segments with the value 1 by circles, i.e., it determines the parameters describing the circle that can be fitted best into the selected contour segment. The parameters 'StartPhi' and 'EndPhi' determine the part of the circle belonging to the actual contour segment. The parameters 'Radius', 'Row', and 'Column' describe the radius and the position of the circle and are used as input for the operator gen_circle_contour_xld that generates the corresponding circles. These are then displayed.

Step 6: Extract distance between circle centers

```
distance_pp (RowsCenterCircle[1], ColumnsCenterCircle[1], \
             RowsCenterCircle[2], ColumnsCenterCircle[2], Distance_2_3)
distance_pp (RowsCenterCircle[0], ColumnsCenterCircle[0], \
             RowsCenterCircle[2], ColumnsCenterCircle[2], Distance_1_3)
distance_pp (RowsCenterCircle[3], ColumnsCenterCircle[3], \
             RowsCenterCircle[4], ColumnsCenterCircle[4], Distance_4_5)
```

Finally, distance_pp, a simple geometric operation, uses the obtained positions of the circles to compute the distance between selected circle centers, in particular between the circles C2 and C3, C1 and C3, as well as C4 and

C5. Figure 1.4 shows the metal part, the approximated circles, the lines between the selected circle centers for which the distance was computed, as well as the numerical results of the measurement.

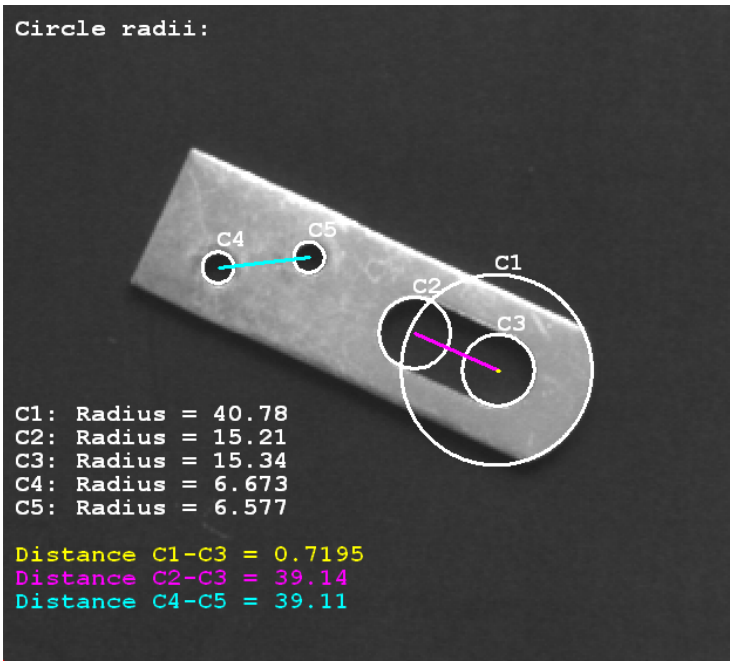

Figure 1.4: Visualization of the fitted circles, selected distances, and numerical results.

Chapter 2

Basic Tools

In our first example the measuring task started with the creation of regions or contours extracted from an image. In general, the extraction of elements from an image is preceded by another step: the image acquisition. A good measurement result highly depends on the quality of the image. Thus, we recommend to read the Solution Guide II-A, appendix C on page 49, which discusses **how to obtain a good quality image.**

Having a suitable image at hand, the appropriate tool to extract the object feature of interest must be chosen. Here, we shortly introduce the available basic tools, before section 3 on page 27 shows how to select the tools suited best for specific applications. The basic tools partially correspond to the HALCON methods described in the Solution Guide I. In particular, the basic tools comprise

- region processing (see section 2.1), which corresponds mainly to the method blob analysis (Solution Guide I, chapter 4 on page 35),
- contour processing (see section 2.2), which here comprises the methods edge filtering (Solution Guide I, chapter 6.1 on page 59), edge and line extraction (Solution Guide I, chapter 7 on page 69) as well as contour processing (Solution Guide I, chapter 9 on page 87),
- 2D metrology (see section 2.3), which is an easy to use method to measure simple shapes for which the parameters are approximately known, and
- geometric operations (see section 2.4).

2.1 Region Processing

For objects or object parts that are represented by regions of similar gray value, color, or texture, blob analysis is a fast and simple way to extract objects and their features. Here, the image is segmented into so-called blobs, which are regions in the image that comprise a specific range or behavior of pixel values (see Solution Guide I, chapter 4 on page 35). The blob analysis consists of different essential steps, in particular

- the preprocessing (see section 2.1.1),
- the segmentation of the image into regions (see section 2.1.2),
- the modification of the regions (see section 2.1.3), and
- the extraction of the region features that are searched for (see section 2.1.4).

The steps are not necessarily applied in that order. Especially the segmentation and the modification of regions are often applied with changing sequence.

The following descriptions introduce several operators. Details about them can be found in the corresponding parts of the Reference Manual (just follow the links) or in the Solution Guide I. Practical examples are provided in section 4 on page 35. Here, a short overview about the general proceeding is given.

2.1.1 Preprocess Image or Region

A preprocessing is recommended if the conditions during the image acquisition are not ideal, e.g., the image is noisy, cluttered, or the object is disturbed or overlapped by objects of small extent so that small spots or thin lines prevent the actual object of interest from being described by a homogeneous region.

Often applied preprocessing steps comprise the elimination of noise using `mean_image` or `binomial_filter` and the suppression of small spots or thin lines with `median_image`. Further operators common to preprocess the whole image comprise, e.g., `gray_opening_shape` and `gray_closing_shape`. A smoothing of the image can be realized with `smooth_image`. If you want to smooth the image but you want to preserve edges, you can apply `anisotropic_diffusion` instead.

For regions, holes can be filled up using `fill_up` or a morphological operator. Morphological operators modify regions to suppress small areas, regions of a given orientation, or regions that are close to other regions. For example, `opening_circle` and `opening_rectangle1` suppress noise, whereas `closing_circle` and `closing_rectangle1` fill gaps.

When having an inhomogeneous background, a shading correction is suitable to compensate the influence of the background. There, a reference image of the background without the object to measure is taken and subtracted from the images containing the object (using, e.g., the operator `sub_image`).

2.1.2 Segment the Image into Regions

After the preprocessing the image must be segmented into suitable regions that represent the objects of interest. Several kinds of threshold operators are available that segment a gray-value image or a single channel of a multichannel image according to its gray value distribution. Common threshold operators are `threshold`, `binary_threshold`, `auto_threshold`, `dyn_threshold`, `fast_threshold`, and `local_threshold`.

When choosing a threshold manually, it may be helpful to get information about the gray value distribution of the image. Suitable operators are, e.g., `gray_histo`, `histo_to_thresh`, and `intensity`. Additionally, you can use the online `Gray Histogram` inspection in HDevelop with `Display` set to `'threshold'` to interactively search for a suitable threshold.

After segmenting the image with a threshold operator, the image parts of interest are available as one region. To split this region into several regions, i.e., one region for every connected component, the operator `connection` must be applied.

For objects with a honeycomb structure, `watershed` operators are better suited than a threshold operator, as they segment the image based on the topology instead of the distribution of the gray values. If you want to obtain regions having the same intensity, apply `regiongrowing`. For both operators a preprocessing using a low pass filter like `binomial_filter` is recommended.

2.1.3 Select and Modify Regions

After segmenting the image into a set of regions, regions having specific features can be selected using operators like `select_shape` or `select_gray`. Common features are, e.g., a specific area range, a certain shape, or a specific gray value. For the list of all features that can be used for the selection, see, e.g., the entry in the Reference Manual for `select_shape`.

In many cases, a modification of the regions is necessary. For example, small gaps or small connections can be eliminated by a morphological operator like `opening_circle` or `dilation_rectangle`. Furthermore, different regions can be combined by the set-theoretical operators shown in figure 2.1. There,

- `union1` or `union2` merge regions,
- `intersection` returns the intersection of regions,
- `difference` subtracts the overlapping part of two regions from the first region, and
- `complement` obtains the complement of a region.

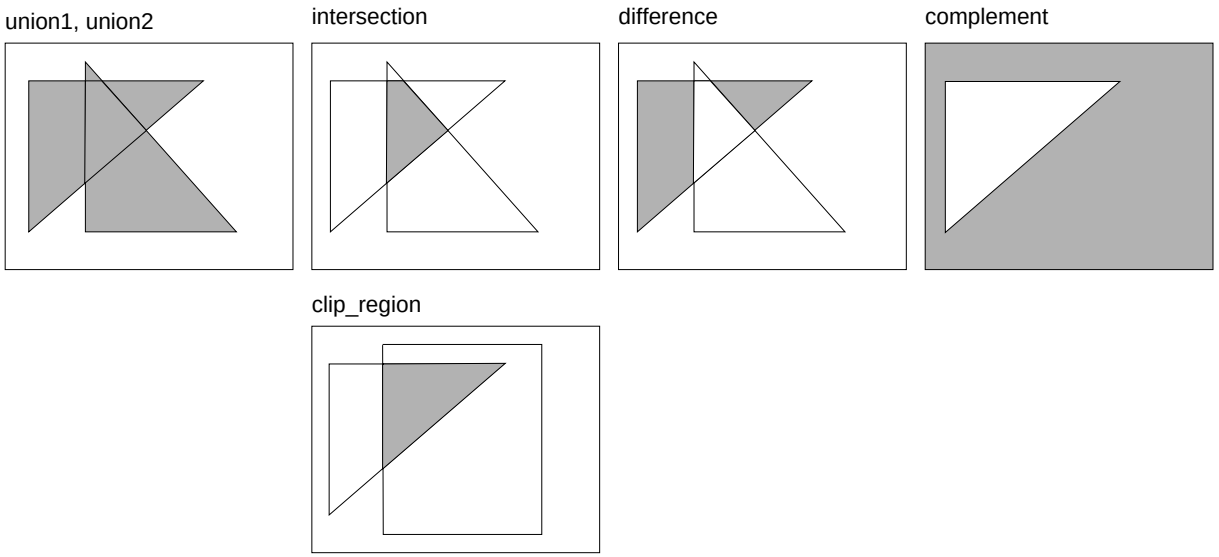

Figure 2.1: Common set-theoretical operations to combine regions.

If you need the intersection of regions with a rectangle, e.g., created by `gen_rectangle1`, you should use `clip_region`. It works similar to `intersection` but is more efficient.

Another way of modifying a region is to transform it, in particular to approximate it by a specific shape using the operator `shape_trans`. This approach is suited if the features of the approximating shape describe the features you try to obtain. For example, if you search for the maximum width of an object, you can approximate the shape by its smallest enclosing rectangle or circle and extract its width or radius. A set of common shapes is illustrated in figure 2.2. The possible shapes comprise

- the convex hull (`'convex'`),
- the smallest enclosing circle (`'outer_circle'`),
- the largest circle fitting into the region (`'inner_circle'`),
- the smallest enclosing rectangle parallel to the coordinate axis (`'rectangle1'`),
- the smallest enclosing rectangle with arbitrary orientation (`'rectangle2'`),
- the largest rectangle parallel to the coordinate axis that fits completely into the region (`'inner_rectangle1'`),
- the ellipse with the same moments as the input region (`'ellipse'`), and
- the point on the skeleton of the input region having the smallest distance to the center of gravity of the input region (`'inner_center'`).

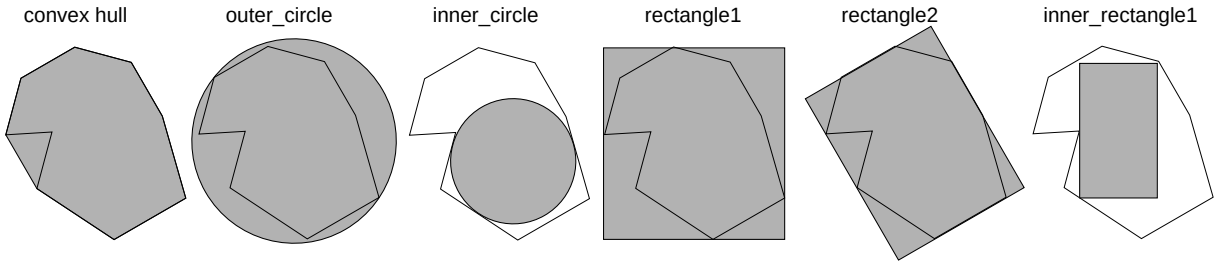

Figure 2.2: Common shapes to approximate a region.

A skeleton describes the medial axis of an input region and can be obtained by the operator `skeleton`. Furthermore, the regions can be processed by the operators `sort_region`, `partition_dynamic`, and `rank_region`.

2.1.4 Extract Features

Having obtained the region that represents the object to measure, the features of the object, i.e., the actual measurement results, can be extracted.

Several operators are provided to compute features like the area, position, orientation, or dimension of a region. Some of them can be used as alternatives to the shape transformations described in the preceding section. Common operators are, e.g.:

- `area_center` computes the area and the position of the center of an arbitrarily shaped region,
- `smallest_rectangle1` and `smallest_rectangle2` compute the smallest enclosing rectangle. In particular, `smallest_rectangle1` computes the corner coordinates for the smallest surrounding rectangle being parallel to the image coordinate axes, and `smallest_rectangle2` computes the radii (half lengths), position, and orientation of the smallest enclosing rectangle with arbitrary orientation.
- `inner_rectangle1` computes the corner coordinates for the largest rectangle parallel to the coordinate axes that fits completely into the region,
- `inner_circle` determines the radius and position of the largest circle fitting into the region,
- `diameter_region` obtains the maximum distance between two boundary points of a region, and
- `orientation_region` is used to get the orientation of a region.

Note that `orientation_region` and `smallest_rectangle2` both compute the orientation of the object, but the results of both can differ, depending on the shape of the object (see section 3.1.2 on page 29).

If you prefer to work with contour processing instead of region processing, and a pixel-precise measuring is sufficient, you can also start with region processing and at any time convert the regions into contours with `gen_contour_region_xld`. The contours then can be used for measuring purposes as described in the following section. A conversion may be necessary, e.g., if an object describes a simple shape but has large deformations, so that the contour processing approach described in section 2.2.4 on page 19 is better suited. For the advantages of contour processing see section 3.2 on page 31.

2.2 Contour Processing

Contour processing is suitable for high precision measuring, for objects that are not represented as homogeneous regions in the image but by clear gray value or color transitions (edges), or for object parts that are not bordered by a closed contour. The first steps of a contour processing consist of

- the creation of contours (see section 2.2.1), and
- the selection of relevant contours (see section 2.2.2).

Then, the evaluation of the contours follows. For this, HALCON provides different approaches. If you know the shape of the object parts you want to measure, a common approach is

- the segmentation of complex contours into contour segments of predefined shapes (section 2.2.3) and
- the extraction of the parameters of shape primitives that approximate the contours or contour segments (section 2.2.4).

If you have no knowledge about the object's shape or the shapes cannot be approximated by a simple shape like a line, circle, ellipse, or rectangle without loosing essential information, HALCON provides operators similar to the ones introduced for the region processing, i.e., operators for

- the extraction of general contour features like the diameter, length, or orientation of contours of unknown shape (section 2.2.5).

In some cases, contour processing is needed not for precision requirements but for one of its other advantages, which are introduced in section 3.2 on page 31. If a pixel-precise measuring is sufficient and the contour processing is needed only for a part of the measuring process, you can afterwards switch to the faster region processing. To do so, you can transform the contours into regions using the operator `gen_region_contour_xld`.

2.2.1 Create Contours

Contour processing starts with the creation of contours. The common way to obtain contours is to extract edges. Edges are transitions between dark and light areas in an image and can be mathematically determined by computing the image gradient, which can also be represented as edge amplitude and edge direction. By selecting pixels with a high edge amplitude or a specific edge direction, contours between areas can be extracted. This can be done in various ways and with varying precision.

2.2.1.1 Pixel-Precise Edges and Lines

If a pixel-precise edge extraction is sufficient, an edge filter can be applied (see also Solution Guide I, chapter 6.1 on page 59). It leads to one or two edge images, for which the edge regions can be extracted by selecting the pixels with a given minimum edge amplitude using a threshold operator. To get edges with a thickness of one pixel, the obtained regions have to be thinned, e.g., by using the operator `skeleton`. Common pixel-precise edge filters are the operator `sobel_amp`, which is fast, and `edges_image`, which is not that fast but already includes a hysteresis threshold and a thinning and leads to more accurate results than `sobel_amp`. `edges_image` and also its equivalent for color images, `edges_color`, can also be applied with the parameter `Filter` set to `'sobel_fast'`. Then, it is fast as well, but this parameter is recommended only for images with little noise or texture and sharp edges.

Besides edges, you can extract also lines that are built by thin structures on a contrasting background. In contrast to edges or the XLD lines that are obtained by a line fitting as described in section 2.2.4 on page 19, they have a certain (not necessarily constant) width. A common filter for these lines is `bandpass_image`, which is again applied in combination with a threshold and a thinning.

For edge filters, after applying the filter, threshold, and thinning, the result typically is transformed into XLD contours. With this approach, a broad range of further processing methods is available. For the transformation of the thinned edge regions into contours, e.g., the operator `gen_contours_skeleton_xld` is provided. Figure 2.3 (left) shows a pixel-precise edge obtained with `edges_image`.

2.2.1.2 Subpixel-Precise Edges and Lines

If a pixel-precise extraction is not sufficient, operators for the subpixel-precise edge and line extraction can be applied (see Solution Guide I, chapter 7 on page 69). These immediately return XLD contours. Common operators to extract subpixel-precise edges are `edges_sub_pix` for the general edge extraction, `edges_color_sub_pix` for extracting edges in color images, and `zero_crossing_sub_pix` for extracting zero crossings in an image, or respectively, to extract edges in Laplace-filtered images. Common operators for the extraction of subpixel-precise lines, i.e., thin linear structures with a certain (not necessarily constant) width, are `lines_gauss` for the general line extraction, `lines_facet` for extracting lines using a facet model, and `lines_color` for extracting lines in color images. Figure 2.3 (right) shows a subpixel-precise edge obtained with `edges_sub_pix`.



pixel precise edges subpixel precise edges

Figure 2.3: Edge extracted: (left) pixel-precise, (right) subpixel-precise.

2.2.1.3 Speed up the Contour Extraction

The subpixel-precise approaches are often slower than the pixel-precise approaches. To speed up the subpixel-precise edge extraction, it is recommended to apply it only to a small region of interest (ROI). To obtain a suitable ROI you can, e.g., determine the region enclosed by the contour with a thresholding (e.g., using `fast_threshold`). The returned region then must be reduced to its boundary by the operator `boundary` and possibly clipped by `clip_region_rel`. With a morphological operator, e.g., `dilation_circle`, the region is expanded by a small amount, the image is reduced to the returned region by `reduce_domain`, and the reduced image is used as an ROI. The ROI builds the search space for the subpixel-precise edge extraction (see figure 2.4). One of the various HDevelop examples illustrating this proceeding is described in section 4.3 on page 37.

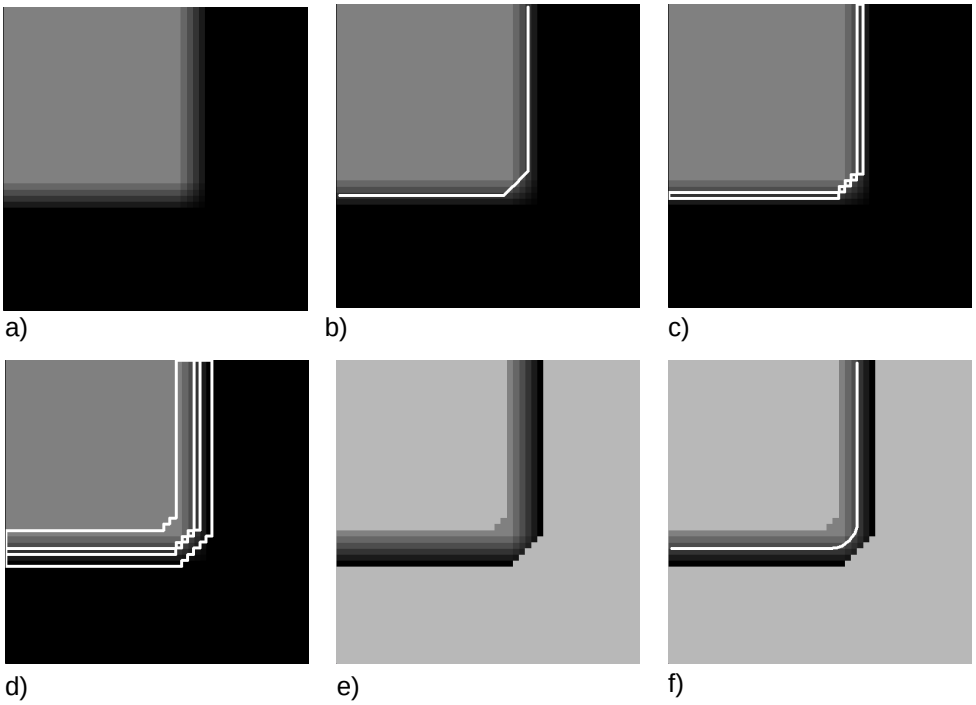

Figure 2.4: Creation of ROI for subpixel-precise edge extraction: a) original image, b) pixel-precise edge extraction, c) boundary for the edge region, d) dilation of the region, e) reduced domain (ROI), f) subpixel-precise edge extraction within the ROI.

2.2.1.4 Subpixel-Precise Thresholding

Another fast way to extract contours is provided by the subpixel-precise thresholding using the operator `threshold_sub_pix`, which can be applied in real time to a whole image. It is a thresholding operator similar to the ones used for the region processing (see section 2.1.2 on page 12), but in contrast to them it does not result in a closed region but in subpixel-precise contours describing the border or parts of a border of the region. Thus, in contrast to the threshold operators introduced for the region processing the returned contours need not be closed, multiple contours can be obtained for the same region, and junctions between contours are possible (see image figure 2.5). Like for the thresholding operators used for a region processing, you can search for a suitable threshold using, e.g., the online `Gray Histogram` inspection in HDevelop (with `Display` set to `'threshold'`), or obtain information about the gray value distribution of the image by the operators `gray_histo`, `histo_to_thresh`, and `intensity`.

2.2.2 Get Relevant Contours

If the creation of the contours led to more contours than needed for the further processing, there are means to reduce the set of extracted contours to a set of contours relevant for the specific measuring task.

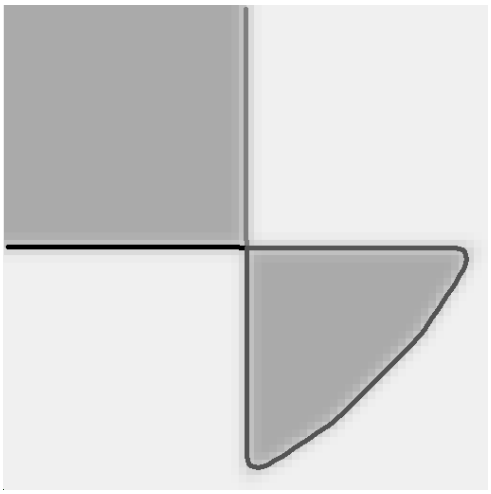

Figure 2.5: Contours obtained by threshold_sub_pix. The border of a region consists of different, not necessarily closed contours. Junctions are possible.

2.2.2.1 Suppress Irrelevant Contours

You can, e.g., suppress irrelevant contours by selecting only those contours fulfilling specific constraints. For example, the operator select_shape_xld can be used to select closed contours with a specific shape feature concerning, e.g., the contour's convexity, circularity, or area. Almost 30 different shape features are available, which are listed in the corresponding part of the Reference Manual. A similar operator for the selection of specific contours is select_contours_xld. It can be used to select open and closed contours according to typical line features like length, curvature, or direction. The operator select_xld_point can be used in combination with mouse functions to interactively select contours. One of the various examples how to select significant features is given in section 4.11 on page 54.

2.2.2.2 Combine Contours

When having several contours that approximate the same object part, the number of segments can further be reduced by a contour merging. Suitable operators are provided for the case that the contours

- lie approximately on the same line (union_collinear_contours_xld),
- on the same circle (union_cocircular_contours_xld, see figure 2.6),
- are adjacent (union_adjacent_contours_xld), or
- are cotangential (union_cotangential_contours_xld).

One of the examples applying a contour merging is described in section 4.9 on page 49.

For closed contours or polygons, you can also use set-theoretical operators to combine the enclosed regions of different closed contours or polygons. This is similar to the approach described for the region processing in section 2.1.3 on page 12. Available operators are

- intersection_closed_contours_xld and intersection_closed_polygons_xld for the calculation of the intersection of regions that are enclosed by closed contours or polygons,
- difference_closed_contours_xld and difference_closed_polygons_xld for the calculation of the difference between regions that are enclosed by closed contours or polygons,
- symm_difference_closed_contours_xld and symm_difference_closed_polygons_xld for the calculation of the symmetric difference between regions that are enclosed by closed contours or polygons, and
- union2_closed_contours_xld and union2_closed_polygons_xld for merging regions that are enclosed by closed contours or polygons.

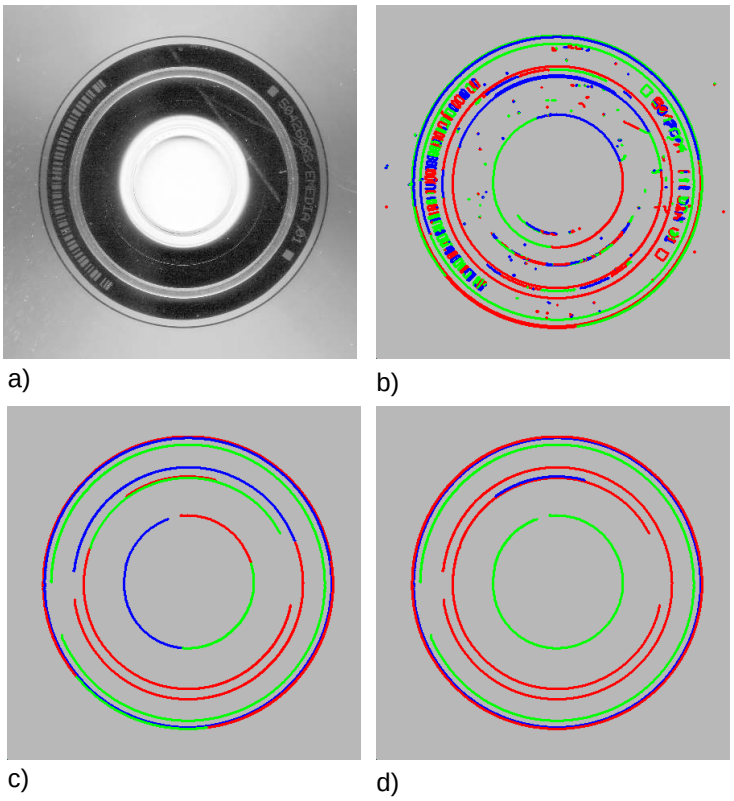

Figure 2.6: Get relevant contours: a) original image, b) subpixel-precise edges, c) selected contours with minimum length, d) cocircular contours merged.

2.2.2.3 Simplify Contours

Further, you can simplify contours by directly transforming them into shape primitives, which is similar to the approach described for the region processing in section 2.1.3 on page 12, but now works on contours instead of regions. With `shape_trans_xld` you can transform a contour into

- the smallest enclosing circle,
- the ellipse having the same moments,
- the convex hull,
- or the smallest enclosing rectangle (either parallel to the coordinate axis or with arbitrary orientation) (see figure 2.7).

2.2.3 Segment Contours

The obtained contours typically have more or less complex shapes. If a contour consists of elements of known shape, e.g., straight lines or circular arcs, a segmentation of the contour into these less complex contours helps to make the investigation of the object easier, as now each segment can be measured individually. For the measuring, primitive shapes like lines or circles are fitted to the segments and their parameters, e.g., the diameter of a circle or the length of a line, can be obtained (see next section). Available shape primitives for a shape fitting comprise lines, circles, ellipses, and rectangles.

For the contour segmentation the operator `segment_contours_xld` can be applied. Dependent on the parameters you choose, a contour can be segmented into linear segments (see figure 2.8), linear and circular segments, or linear and elliptic segments. The information by which shape each individual segment is approximated is stored in the attribute `'cont_approx'`. If you need only straight line segments, you can alternatively use the operator `gen_polygons_xld` instead. To get the individual line segments of the polygon, apply the operator `split_contours_xld`.

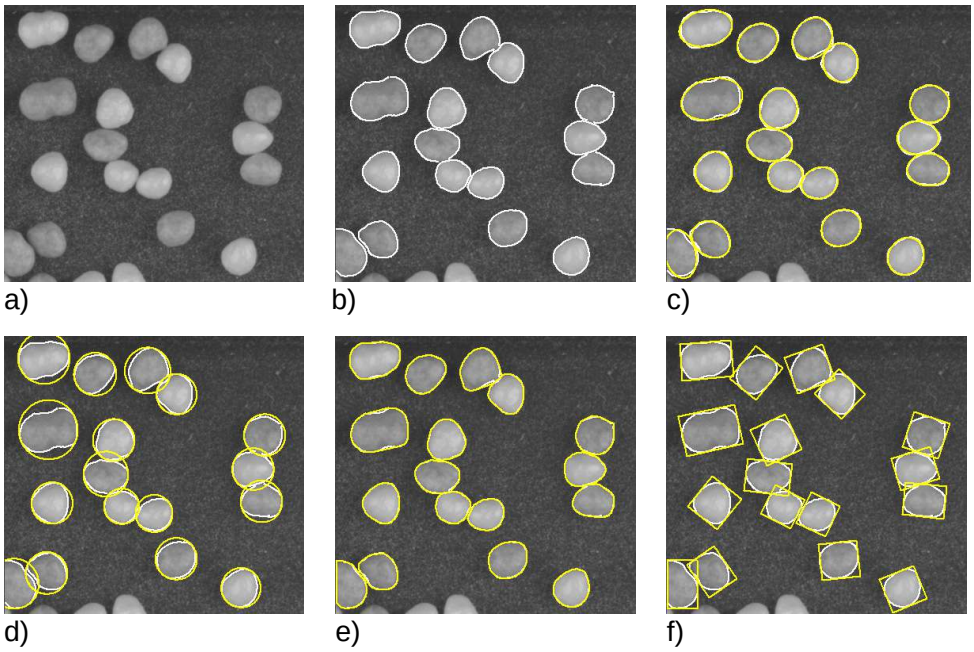

Figure 2.7: Contours transformed into approximating shapes: a) original image, b) extracted contours after suppression of irrelevant contours, c) contours transformed into ellipses with the same moments, d) contours transformed into their smallest enclosing circles, e) contours transformed into their convex hulls, and f) contours transformed into their smallest enclosing rectangles with arbitrary orientation.

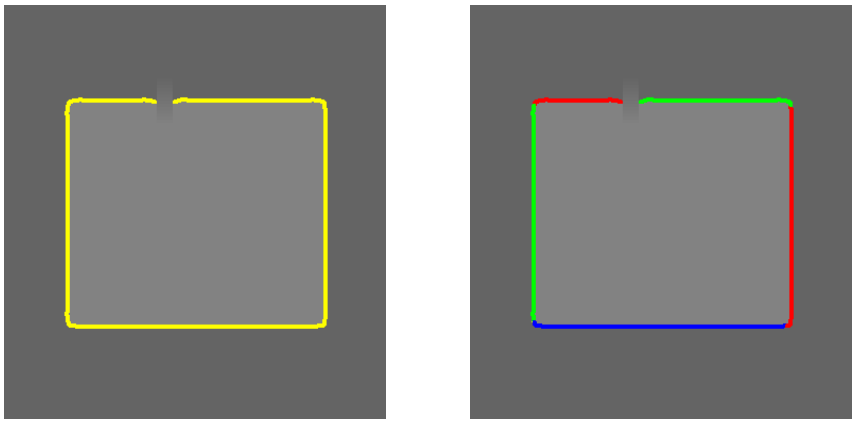

Figure 2.8: Segment a contour: (left) original image with edges, (right) segmented contour.

2.2.4 Extract Features of Contour Segments by Approximating them by known Shapes

The common step after the selection and possibly a segmentation is to fit shape primitives to the contours or contour segments to get their specific shape parameters. The available shape primitives are lines, circles, ellipses, and rectangles. The obtained features may be, e.g., the end points of the lines or the centers and radii of the circles.

If you have applied a segmentation in a preceding step, for each segment the value of `'cont_approx'`, i.e., the shape of the segment, can be queried with the operator `get_contour_global_attrib_xld`. Depending on its value, the best-suited shape primitive can be fitted into the contour segment using the corresponding fitting approach:

- For linear segments (`'cont_approx'` = -1), `fit_line_contour_xld` gets the parameters of each line segment, e.g., the coordinates for both end points.
- For circular arcs (`'cont_approx'` = 1), `fit_circle_contour_xld` and

- for elliptic arcs (`'cont_approx' = 0`), `fit_ellipse_contour_xld` are used to compute the center positions, the radii, and the parts of the circles or ellipses that are covered by the contour segments (determined by the angles of the start and end points).
- Rectangles consist either of a pure (unsegmented) contour or of linear contours that have been merged, e.g., by `union_adjacent_contours_xld`. For them, the operator `fit_rectangle2_contour_xld` is provided.

Examples for the application of the fitting operators are described, e.g., in section 4.6 on page 44 for lines, section 4.10 on page 52 for circles, and section 4.9 on page 49 for rectangles.

With the obtained parameters the corresponding contour can be generated for a visualization or a further processing. Lines can be generated with `gen_contour_polygon_xld`, circles with `gen_circle_contour_xld`, ellipses with `gen_ellipse_contour_xld`, and rectangles with `gen_rectangle2_contour_xld`. For the visualization, common visualization operators like `dev_display` are used. Figure 2.9 shows an example for fitting circles into circular contours and displaying their parameters.

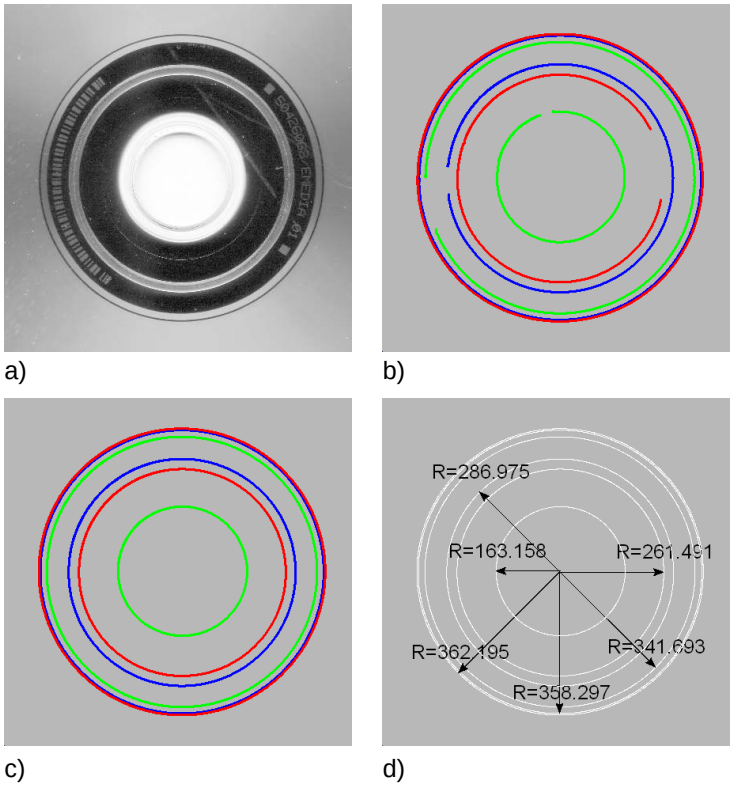

Figure 2.9: Fit circles to circular contours: a) original image, b) contours after suppression of irrelevant contours c) circles fitted into the contours d) visualization of radius R for each circle.

2.2.5 Extract Features of Contours Without Knowing Their Shapes

If the object to investigate cannot be described by a predefined shape primitive, HALCON provides several operators that compute general features of contours. Similar to the operators used for the feature extraction within a region processing (see section 2.1.4 on page 14), features like orientation or area can be queried. Common operators used for 2D measuring with contours are:

- `area_center_xld`: area and center of gravity for the region enclosed by the contour or polygon, and the order of the points along the boundary.
- `diameter_xld`: the coordinates of the two extreme points of the contour having the maximum distance, and the distance between them.

- elliptic_axis_xld: the two radii and the orientation of the ellipse having the same orientation and aspect ratio as the contour.
- length_xld: length of the contour or polygon.
- orientation_xld: orientation of the contour.
- smallest_circle_xld: center position and radius of the smallest enclosing circle.
- smallest_rectangle1_xld: coordinates of the corners describing the smallest enclosing rectangle that is parallel to the coordinate axis.
- smallest_rectangle2_xld: center position, orientation, and the two radii (half lengths) of the smallest enclosing rectangle with arbitrary orientation.

Some of the operators only work on contours that have no self intersections. Self intersections are not always obvious as they can occur due to internal calculations of an operator, e.g., if an open contour is closed for the needed operation (see figure 2.10). To check if a contour intersects itself you can apply the operator test_self_intersection_xld. If you face problems because of self intersections, you can also use the corresponding point-based operators. The available operators are area_center_points_xld, moments_points_xld, orientation_points_xld, elliptic_axis_points_xld, eccentricity_points_xld, and moments_any_points_xld.

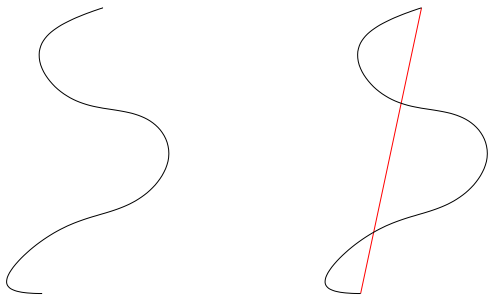

Figure 2.10: Self intersection: (left) curved contour, (right) self intersections occur because the contour is closed for internal calculations of an operator.

2.3 2D Metrology

If you want to measure objects that are represented by simple shapes like circles, ellipses, rectangles, or lines, and you have approximate knowledge about their positions, orientations, and dimensions, you can use 2D metrology to determine the exact shape parameters.

In particular, the values of the initial shape parameters are refined by a measurement that is based on the exact location of edges within so-called measure regions. These are rectangular regions that are evenly distributed along the boundaries of the approximately known shapes. As shown in figure 2.11, for a single initial shape also more than one refined instance may be returned.

The HDevelop example program %HALCONEXAMPLES%\hdevelop\2D-Metrology\apply_metrology_model.hdev shows the basic steps of 2D metrology. First, a metrology model must be created using create_metrology_model. In this model, all needed information related to the objects to measure will be stored. To enable an efficient measurement, the size of the image in which the measurements will be performed should be added to the model using the operator set_metrology_model_image_size.

```
read_image (Image, 'pads')
get_image_size (Image, Width, Height)
create_metrology_model (MetrologyHandle)
set_metrology_model_image_size (MetrologyHandle, Width, Height)
```

Then, the approximate values for the shapes of the objects in the image and some parameters that control the measurement must be added. For each shape, depending on its geometric type, the following operators are used:

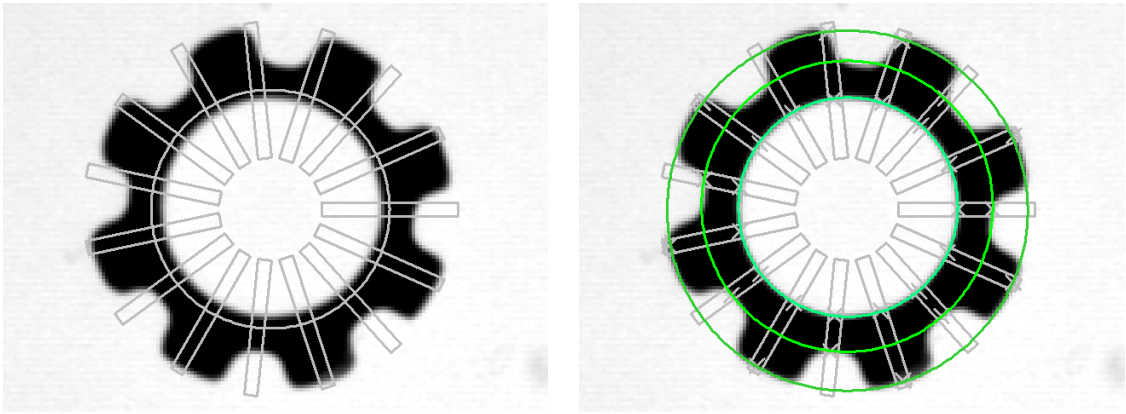

Figure 2.11: Applying 2D metrology: (left) initial circle and measure regions; (right) three circle instances returned by the measurement.

- add_metrology_object_circle_measure adds parameters of one or more circle(s), i.e., the coordinates of the center point and the radius.
- add_metrology_object_ellipse_measure adds parameters of one or more ellipse(s), i.e., the coordinates of the center point, the orientation of the main axis, and the size of the smaller and the larger half axis.
- add_metrology_object_line_measure adds parameters of one or more line(s), i.e., the coordinates of the start and end point.
- add_metrology_object_rectangle2_measure adds parameters of one or more rectangle(s), i.e., the coordinates of the center point, the orientation of the main axis, and the size of the smaller and the larger half axis.
- add_metrology_object_generic adds parameters of circles, ellipses, lines, and/or rectangles.

Note that you can change several parameters that control the measurement with the operator set_metrology_object_param.

In the example program, values for a rectangular and a circular object are added.

```
add_metrology_object_rectangle2_measure (MetrologyHandle, RectangleInitRow, \
                                         RectangleInitColumn, \
                                         RectangleInitPhi, \
                                         RectangleInitLength1, \
                                         RectangleInitLength2, \
                                         RectangleTolerance, 5, .5, 1, [], \
                                         [], MetrologyRectangleIndices)
add_metrology_object_circle_measure (MetrologyHandle, CircleInitRow, \
                                     CircleInitColumn, CircleInitRadius, \
                                     CircleRadiusTolerance, 5, 1.5, 2, [], \
                                     [], MetrologyCircleIndices)
```

The actual measurement in the image is performed with the operator apply_metrology_model. The refined shape parameters that result from the measurement can be accessed from the metrology model with the operator get_metrology_object_result.

```
apply_metrology_model (Image, MetrologyHandle)
get_metrology_object_result (MetrologyHandle, MetrologyRectangleIndices, \
                             'all', 'result_type', 'all_param', \
                             RectangleParameter)
get_metrology_object_result (MetrologyHandle, MetrologyCircleIndices, 'all', \
                             'result_type', 'all_param', CircleParameter)
```

To inspect the contours that have been added to the metrology model, use get_metrology_object_model_contour. To access the measure regions, which may be helpful when adjusting the parameters that control the measurement, you can call the operator get_metrology_object_measures.

Besides the basic steps, several other steps may be performed. For details about 2D metrology, see the entry in the Reference Manual for create_metrology_model.

2.3.1 Aligning the Metrology Model based on different methods

The HDevelop example program hdevelop/Applications/Measuring-2D/measure_stamping_part.hdev shows how the metrology model can be aligned, e.g., if the object's position varies from image to image.

It shows three different alignment methods:

- Using shape-based matching (see section 2.3.1.1)
- Using region processing (see section 2.3.1.2)
- Using a rigid transformation determined from point correspondences (see section 2.3.1.3)

The example allows you to select an alignment method by activating the desired line in the example code. As a default, shape-based matching is selected.

```
AlignmentMode := 'shape-based matching'
* AlignmentMode := 'region processing'
* AlignmentMode := 'rigid transformation'
```

2.3.1.1 Shape-based matching

To find the objects to be measured in a new image, create a shape model of the object first.

```
create_shape_model (ImageReduced, 6, 0, rad(360), 'auto', 'auto', \
                    'use_polarity', 'auto', 20, ShapeModelID)
```

Now, set the reference coordinate system to the origin of the shape model region with set_metrology_model_param. The origin of the shape model is the center of the input region used in create_shape_model and can be determined with area_center. By this, you are able to directly use the results of find_shape_model to align the metrology model.

```
area_center (ModelRegion, Area, RowModel, ColumnModel)
set_metrology_model_param (MetrologyHandle, 'reference_system', [RowModel, \
                           ColumnModel,0])
```

To inspect the contours that have been added to the metrology model, use get_metrology_object_model_contour. Note, that they now match the shape model contours returned by get_shape_model_contours.

In the online phase, the metrology model can be aligned with align_metrology_model. This operator aligns the metrology model using the positions and rotation angles obtained by an operator like find_shape_model (see Solution Guide II-B, section 2.4.3.2 on page 34 for further information about alignment).

```
find_shape_model (CurrentImage, ShapeModelID, 0, rad(360), 0.5, 1, 0, \
                  'least_squares', 5, 0.9, RowAlign, ColumnAlign, \
                  AngleAlign, Score)
align_metrology_model (MetrologyHandle, RowAlign, ColumnAlign, AngleAlign)
```

Finally, you can perform the actual measurement with apply_metrology_model.

```
apply_metrology_model (CurrentImage, MetrologyHandle)
```

2.3.1.2 Region processing

The alignment can also be performed via region processing. In this case, we use area_center and orientation_region to determine the reference position of the segmented reference object.

```
area_center (OriginalRegion, Area, RowOrig, ColumnOrig)
orientation_region (OriginalRegion, AngleOrig)
set_metrology_model_param (MetrologyHandle, 'reference_system', [RowOrig, \
                           ColumnOrig,AngleOrig])
```

In the online phase, first segment the object the same way as in the reference image and determine its position and orientation. If the reference system of the metrology model has been set, the result can directly be used for the alignment with align_metrology_model.

```
area_center (CurrentRegion, Area, RowAlign, ColumnAlign)
orientation_region (CurrentRegion, AngleAlign)
align_metrology_model (MetrologyHandle, RowAlign, ColumnAlign, AngleAlign)
```

Finally, you can perform the actual measurement with apply_metrology_model.

```
apply_metrology_model (CurrentImage, MetrologyHandle)
```

2.3.1.3 Rigid transformation from point correspondences

If it is possible to robustly detect correlated reference points in the reference image as well as in the online images, it is possible to calculate a rigid transformation from these point correspondences and use it for alignment.

First, extract the reference points for the alignment. In the example, the procedure extract_reference_points is used for this purpose.

```
extract_reference_points (Image, RowReference, ColumnReference)
```

In this case, no reference system has to be set.

In the online phase, extract the reference points and determine the rigid transformation parameters using the operators vector_to_rigid and hom_mat2d_to_affine_par. Note that you have to take care that corresponding points have the same indices in RowReference, ColumnReference, RowExtracted, and ColumnExtracted. The results are then used for the alignment with align_metrology_model.

```
extract_reference_points (CurrentImage, RowExtracted, ColumnExtracted)
vector_to_rigid (RowReference, ColumnReference, RowExtracted, \
                 ColumnExtracted, HomMat2D)
hom_mat2d_to_affine_par (HomMat2D, Sx, Sy, AngleAlign, Theta, RowAlign, \
                         ColumnAlign)
align_metrology_model (MetrologyHandle, RowAlign, ColumnAlign, AngleAlign)
```

Finally, you can perform the actual measurement with apply_metrology_model.

```
apply_metrology_model (CurrentImage, MetrologyHandle)
```

2.3.2 Querying Results

The HDevelop example program hdevelop/Applications/Measuring-2D/measure_stamping_part.hdev also shows how to query results.

The edge points that were actually used to fit the geometric forms can be visualized with get_metrology_object_result.

```
get_metrology_object_result (MetrologyHandle, 'all', 'all', 'used_edges', \
                             'row', UsedRow)
get_metrology_object_result (MetrologyHandle, 'all', 'all', 'used_edges', \
                             'column', UsedColumn)
gen_cross_contour_xld (UsedEdges, UsedRow, UsedColumn, 10, rad(45))
```

2.4 Geometric Operations

HALCON provides a selection of operators for geometric operations to calculate the relation between elements like points, lines, line segments, contours, or regions. Points can be determined by several point operators, e.g., points_foerstner, or by the intersection of lines. Lines, line segments, contours, and regions can be obtained as described in section 2.1 on page 11 and section 2.2 on page 14. The relations between the individual elements can be calculated by several operators. Most of the operators are constructed to calculate the distance relation between the elements. The operators for the distance relations are summarized in the following list:

	Point	Line	Line Segment	Contour
Point	distance_pp	distance_pl	distance_ps	distance_pc
Line	distance_pl	–	distance_sl	distance_lc
Line Segment	distance_ps	distance_sl	distance_ss	distance_sc
Contour	distance_pc	distance_lc	distance_sc	distance_cc distance_cc_min
Region	distance_pr	distance_lr	distance_sr	–

	Region
Point	distance_pr
Line	distance_lr
Line Segment	distance_sr
Contour	–
Region	distance_rr_min distance_rr_min_dil

Further operators for geometric operations are provided, which can be used to calculate, e.g.,

- the angle between two lines: angle_ll,
- the angle between a line and the vertical axis: angle_lx,
- a point on an ellipse corresponding to a specific angle: get_points_ellipse,
- the intersection of two lines: intersection_lines, and
- the projection of a point onto a line: projection_pl.

Chapter 3

Tool Selection

Because many tools are available, it is not obvious which tool to use in which situation. Section 3.1 guides you from the feature you want to extract and the object's appearance in the image to the appropriate tool to use. In section 3.2, additionally the two most important tools, region processing and contour processing, are compared. Practical guidance is provided in section 4 by a selection of HDevelop example programs that solve common measuring tasks.

3.1 From the Feature to the Tool

If you have no special requirements like precision or speed, often several measuring approaches are available to obtain the same feature as result. The graph in figure 3.1 leads you from a single feature you want to measure and the appearance of the object in the image to the part of section 2 that describes the basic tools suited best for your task. If you have specific requirements like precision or speed, you should additionally consider the different characteristics of region processing and contour processing discussed in section 3.2 on page 31.

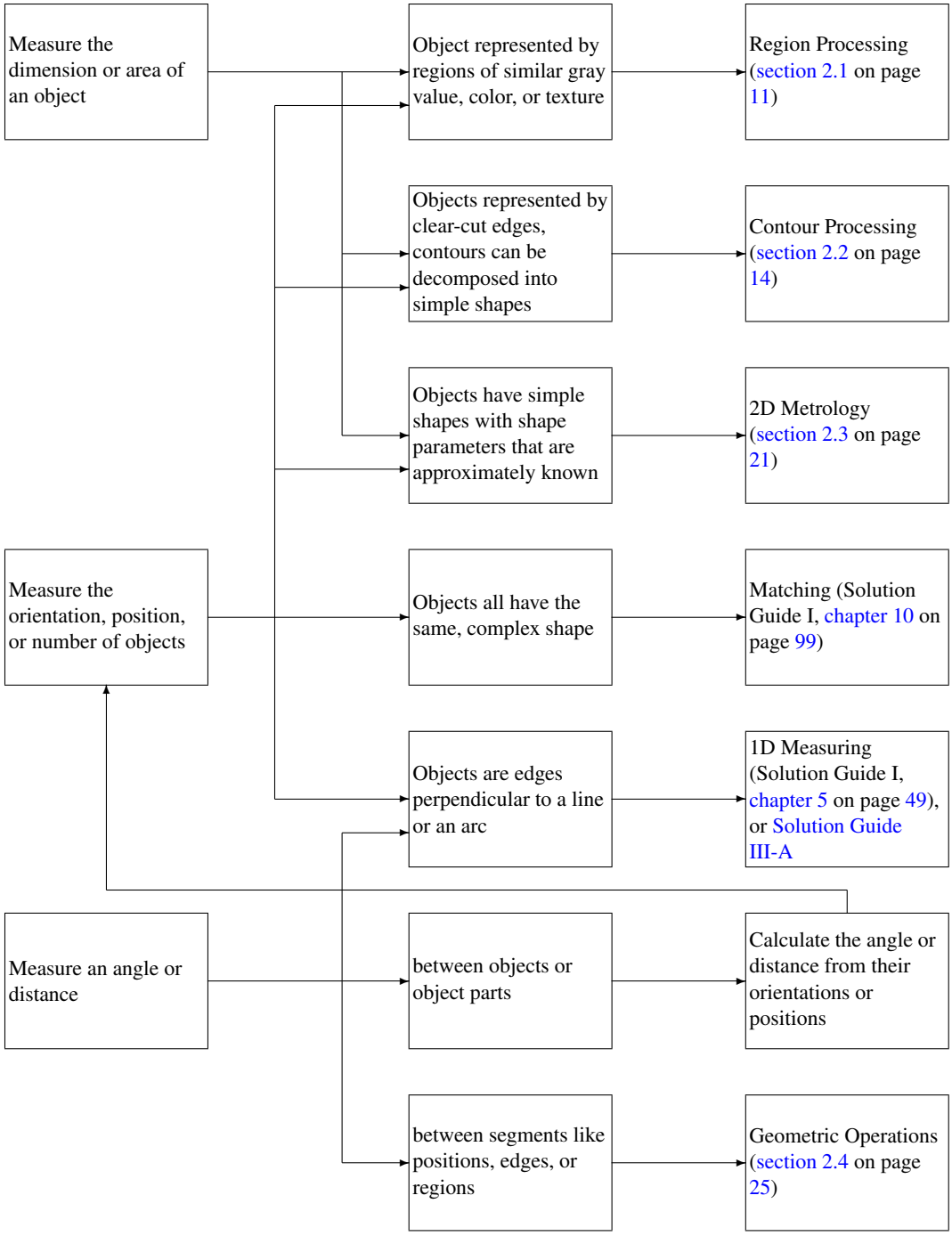

Figure 3.1: From the feature to measure to the corresponding basics section.

In most applications, it is not sufficient to obtain a single feature from an image since many features are needed to obtain the final feature that is searched for. Thus, dependent on the specific task and the characteristics of the object the basic tools are combined in different ways. The decision which tool to use does not only depend on the appearance of the object and the special requirements concerning precision or speed, but also on the interdependencies of the several tasks of an application and therefore also on the features you have already obtained during a preceding step of your program. Because there is a huge amount of influences, this guide can not be all-embracing, but hopefully conveys to you a feeling for the available tools.

Therefore, we shortly summarize which tools or approaches are common to obtain the different object features. Most of the corresponding examples, which can be used as practical guidance, are provided in section 4 on page 35.

3.1.1 Area

The area of an object is in most cases obtained by the operator `area_center`, i.e., via a region processing (see, e.g., the example in section 4.1 on page 35).

If a subpixel-precise measuring requires contour processing, you can use the corresponding operator `area_center_xld` or `area_center_points_xld` (see example in section 5.2 on page 68) instead.

Be aware that when computing the area of a region, possible holes in the region are considered, whereas when computing the area of a contour, the whole area enclosed by the contour is obtained. In the latter case, you therefore have to extract also the contours of the holes, get their areas, and subtract them from the area enclosed by the outer contour.

The mentioned operators were introduced in section 2.1.4 on page 14 for regions and in section 2.2.5 on page 20 for contours.

In addition, the operator `area_holes` calculates the area of the holes in the input regions.

3.1.2 Orientation and Angle

For the orientation of an arbitrary object, typically the operator `orientation_region` (see, e.g., the example in section 4.1 on page 35) is used and can be replaced for contours by the corresponding operator `orientation_xld` (see example in section 4.4 on page 41).

The operators `elliptic_axis` and `elliptic_axis_xld` compute the orientation and radii of the ellipse having the same moments as the input region or contour, respectively.

For very small symmetric objects, the operator `elliptic_axis_gray` is recommended (see example in section 4.12 on page 56).

If you want to obtain the orientation and extents of the smallest enclosing rectangle of an object, you can determine them via `smallest_rectangle2` for regions (see also example in section 4.12 on page 56) and `smallest_rectangle2_xld` for contours.

The mentioned operators were introduced in section 2.1.4 on page 14 for regions and in section 2.2.5 on page 20 for contours.

Note that `orientation_region` and `smallest_rectangle2` both determine the orientation of the object but use different approaches. `orientation_region` is based on `elliptic_axis` and computes the orientation of the ellipse that is equivalent to the object, whereas `smallest_rectangle2` computes the orientation of the smallest enclosing rectangle. Depending on the object's shape, one of the operators may be more suitable than the other. Figure 3.2 shows the character `'L'` for which the orientation is determined by the equivalent ellipse and by the smallest enclosing rectangle.



Figure 3.2: Orientation of (left) the equivalent ellipse or (right) the smallest enclosing rectangle.

Besides the different values for the orientation, the range of the returned values differs. `orientation_region` returns the orientation in a range of -180° to 180°, whereas for `smallest_rectangle2` the orientation is returned in a range of -90° to 90°. Be aware, that the 360° range of `orientation_region` is reliable only for unambiguous objects. For symmetric objects, the returned orientation may flip by 180°.

If you fit a primitive shape to a contour or contour segment as described in section 2.2.4 on page 19, for elliptic and rectangular contours also the orientation of the contour is returned by the corresponding fitting operator. An example for obtaining the orientations of rectangles is shown in section 4.9 on page 49.

If you have a rather complex, but rigid shape, which you like to find in different images, template matching is recommended to get the orientation of the object in each image. For further information about template matching, read the Solution Guide I, chapter 10 on page 99.

If the angle between two objects is needed, you can obtain the orientation of both objects as described before and compute the difference between them. If the angle between two lines or a line and the vertical axis is needed, the operators introduced in section 2.4 on page 25, `angle_ll` and `angle_lx`, are suited (see example in section 4.8 on page 49).

3.1.3 Position

To get the position of an object, an extensive selection of possible approaches is available.

The center position of an arbitrary object can be obtained by region processing (see section 2.1.4 on page 14) using `area_center` (see, e.g., the example in section 4.1 on page 35) or by contour processing (see section 2.2.5 on page 20) using the corresponding operator `area_center_xld` or `area_center_points_xld` (see example in section 5.2 on page 68).

For very small symmetric objects, the operator `area_center_gray` is recommended (see example in section 4.12 on page 56).

If the objects can be split into primitive shapes like lines, circles, ellipses, or rectangles, and these primitives are the objects of interest for the further investigation, fitting primitive shapes to the contours (see section 2.2.4 on page 19) leads to the positions of their center points or, in case of a line fitting, their end points. In section 4.9 on page 49, e.g., the fitting of rectangles to contours is described to obtain the position and orientation of rectangular objects. The examples in section 4.10 on page 52 and section 4.11 on page 54 show the corresponding process for fitting circles to circular contour segments.

If you have a rather complex, but rigid shape, which you like to find in different images, template matching is recommended to get the position of the object in each image. For further information about template matching, read the Solution Guide I, chapter 10 on page 99.

How to measure the positions of edges and the distances between them along a line or an arc that is approximately perpendicular to them is briefly described in the Solution Guide I, chapter 5 on page 49. Details can be found in the Solution Guide III-A.

If the position of a corner point of a contour is searched for, either point operators can be used (see section 2.4 on page 25), or lines, obtained by line fitting (see section 2.2.4 on page 19), are intersected using `intersection_lines`. Both approaches are used by the example in section 4.7 on page 47.

The intersection of lines can be applied also to get, e.g., the junction points of a grid (see example in section 4.6 on page 44). Additionally, contours or also regions can be intersected with other contours or regions to get the positions of points of intersection.

3.1.4 Dimension and Distance

The dimension of objects can be obtained by a large variety of approaches, depending primarily on the shape of the object.

For circular or elliptic contours or contour segments the radii and positions are usually obtained by fitting circles or ellipses to the contours (see section 2.2.4 on page 19). Examples are shown in section 4.10 on page 52 and section 4.11 on page 54.

If full circles and not only circular contour segments are given, you can also determine the radius and position of the largest circle fitting into a region using `inner_circle` (see section 2.1.4 on page 14) or the smallest circle enclosing a contour using `smallest_circle` or `smallest_circle_xld`, respectively (see section 2.2.5 on page 20). Note that, however, the results are much more influenced by small distortions than the result obtained by circle or ellipse fitting (see section 3.2).

For rectangles, you can obtain the extents and positions either via rectangle fitting as introduced in section 2.2.4 on page 19 (an example is described in section 4.9 on page 49), or you determine the smallest enclosing rectangles via `smallest_rectangle2` for regions (see section 2.1.4 on page 14) or `smallest_rectangle2_xld` for contours (see section 2.2.5 on page 20). The example in section 4.12 on page 56 shows how to determine the smallest enclosing rectangle for the region of a ball grid array (BGA). The obtained half lengths of the rectangle are used then to normalize the distances between the balls in the grid. Note that similar to the approaches for circular or elliptic objects, the results for the smallest enclosing rectangles are more influenced by outliers than the result of a rectangle fitting.

Many applications that aim to get the distance between objects or object parts extract suitable positions, e.g., the intersection points of two intersecting lines, and use them to measure distances between them and another point, line, line segment, contour, or region by a geometric operation (see section 2.4 on page 25). The example in section 4.6 on page 44, e.g., intersects the lines of a grid to calculate the positions of its junctions, which then could be used, e.g., to get the extent of the grid. Another example (section 4.7 on page 47) intersects lines to get the positions of the corner points of a metal plate and afterwards calculates the distance between them and the positions of the same points obtained by a point operator (for point operators see section 2.4 on page 25). The maximum distance between a contour and its approximating line (regression line) is determined in the example in section 4.3 on page 37.

How to measure the positions of edges and the distances between them along a line or an arc that is approximately perpendicular to them is briefly described in the Solution Guide I, chapter 5 on page 49. Details can be found in the Solution Guide III-A.

The width of an object can be obtained by different means, depending on the object. For example, the width of thin lines like cables, rivers, or arteries are often obtained by `lines_gauss` as described in section 4.5 on page 43, whereas the width of a strictly polygonal object is better obtained by calculating the distance between individual lines or points via geometric operations, which are possibly applied after checking the lines for parallelism (see example in section 4.4 on page 41). The width of an object may be also obtained via region processing, e.g., by using the smallest enclosing rectangle or, if the object consists of jagged lines, orient the object and its region parallel to the vertical axis and calculate the difference between the column coordinates of the region's border in each row to get the mean, minimum, and maximum width (see example in section 4.2 on page 36).

For objects with an arbitrary shape, region-based feature extraction, as described in section 2.1.4 on page 14, or the corresponding contour-based operators introduced in section 2.2.5 on page 20 can be used to get some general features of their region or contour. The example in section 5.2 on page 68, e.g., uses the operator `length_xld` to compute the length of a contour representing a scratch in an anodized aluminum surface.

3.1.5 Number of Objects

To get the number of objects, the common method is to work with tuples and to count their elements. In HDevelop, if a tuple contains iconic data, e.g., regions or contours, you can query the number of elements using the operator `count_obj`. If the tuple contains control data, e.g., the numeric results obtained for the rows or columns of a set of positions, you can query the number of elements via the corresponding HDevelop operation (|tuple|) inside the operator `assign`. Note also that the indices of numerical tuples do not correspond to the indices of the iconic tuples. Numerical tuples start with `0` and iconic tuples start with `1`. For more information about the HDevelop syntax related to tuples, see the HDevelop User's Guide, section 8.5.3 on page 289.

The next section goes deeper into the main differences between region processing and contour processing.

3.2 Region Processing vs. Contour Processing

The basic tools needed for 2D measuring are region processing and contour processing. Both can be used to get the area, orientation, position, dimension, or number of objects. This section helps you decide which approach is suited best for your task. For this, the appearance of the object in the image is taken into account. The following table summarizes the main differences between both tools. Afterwards, the individual topics are explained in more detail.

	Region Processing	Contour Processing
a)	pixel-precise	pixel- or subpixel-precise
b)	fast	not as fast as region processing
c)	works on closed contours	works on open and closed contours
d)	outliers strongly influence the result of a shape approximation	outliers can be compensated
e)	gray-value behavior of object may not change	gray-value behavior of object may change
f)	not sensitive to bad contrast	sensitive to bad contrast

a) The methods belonging to region processing can be applied only with pixel precision. Therefore, the methods are rather fast and easy to apply. For contour processing both pixel- as well as subpixel-precise methods are provided. The speed of an application varies depending on the used operators.

b) Region processing is not as precise, but in most cases significantly faster than contour processing. The HDevelop program `%HALCONEXAMPLES%\solution_guide\2d_measuring\measure_metal_part_extended.hdev` extracts an object and its area, center position, and orientation using region processing on one hand and contour processing on the other hand. For the region processing, the operators `threshold`, `area_center` and `orientation_region` are applied. The contour processing is preceded by the creation of an ROI to speed up the edge extraction. For this, the operators `threshold`, `boundary`, and `reduce_domain` are used. The actual contour processing then consists of the operators `edges_sub_pix`, `area_center_xld` and `orientation_xld`. For the contour processing, the areas of the holes of the metal plate have to be subtracted to get the actual area of the plate. Figure 3.3 shows the run time needed for both approaches. The region processing is significantly faster.

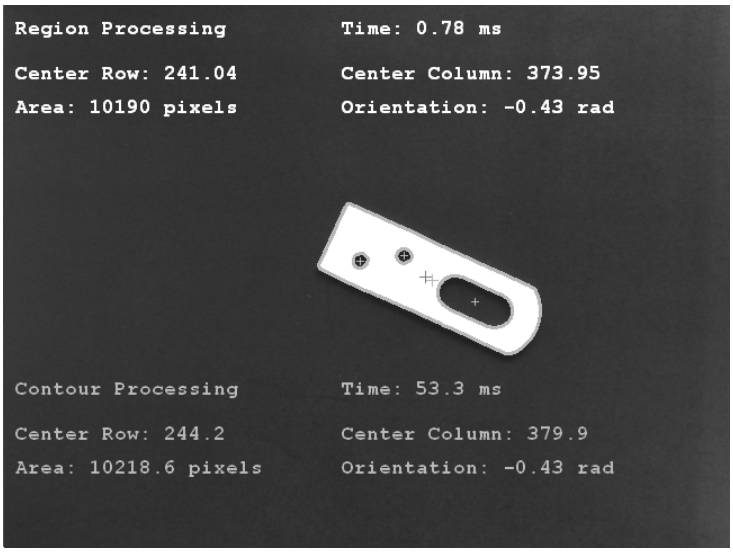

Figure 3.3: With region processing the extraction of area, center, and orientation is significantly faster than with contour processing.

c) Region processing only works for closed areas. For open contours, e.g., if only parts of the border of an object are visible or only a segment of an object is subject to the further investigation, contour processing is needed (see figure 3.4).

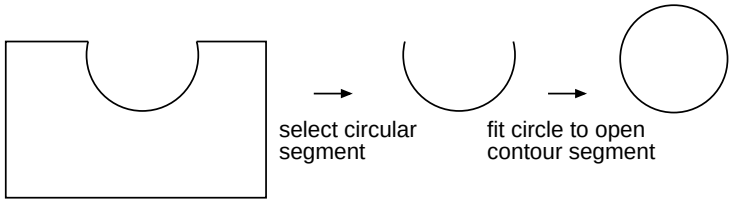

Figure 3.4: Open contours, including single segments of an object's border, can only be handled by contour processing.

d) Fitting a primitive shape to a region, e.g., its enclosing circle, is far more influenced by outliers of the object's

contour than the corresponding contour processing. In many cases, for region processing small gaps or thin protrusions can be eliminated by the right preprocessing steps, e.g., using an opening or closing. But large gaps or protrusions are kept and therefore influence and maybe falsify the feature extraction as illustrated in figure 3.5. There, the result of a shape approximation via region processing deviates strongly from the best fitting circle that can be obtained by a contour processing.

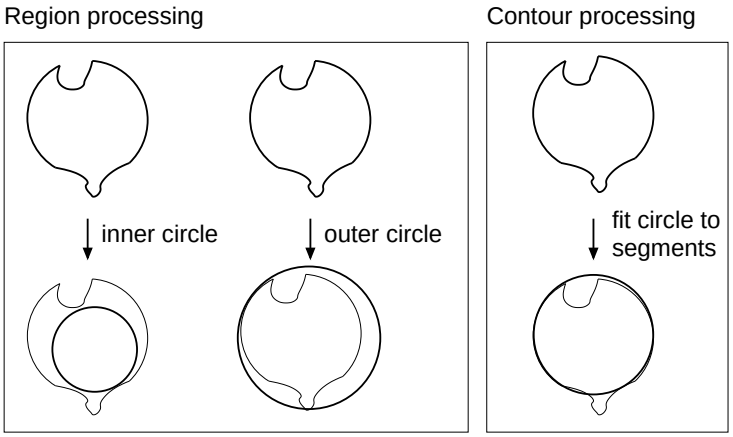

Figure 3.5: A circle fitting via contour processing is better suited to compensate outliers of the object's border than a circle approximation via region processing.

e) With region processing, regions are extracted as regions of similar gray value, color, or texture. A region can be defined, e.g., as a connected region of gray values that are brighter than a specified threshold. Thus, for region processing the object to measure must consist of a region that fulfills the constraint within its entire area. In some cases, there are means to adapt to changing gray values, e.g., by a gray-value scaling. Here, the image is scaled to another gray-value range so that, e.g., differences to a reference region are minimized. For contour processing only the edges, i.e., the transitions between light and dark, are needed to extract an object. As long as the discrete transition is visible, it does not matter whether the gray-value or color behavior changes inside the object.

f) Region processing is more robust to bad contrast than a contour processing, because small gray value differences can nevertheless be separated by a suitable threshold, whereas a reliable edge extraction needs clear transitions between areas of different gray value or color.

The following section provides you with a comprehensive collection of example applications that solve different tasks and can be used as a guide for your applications.

Chapter 4

Examples for Practical Guidance

The previous sections described theoretically how to use several tools provided by HALCON. Since every measuring task is unique, different influences must be considered for each special case. The pure theory may not be sufficient to get a feeling for choosing the right tool for a specific task. To give you also practical guidance, the following sections describe a collection of examples solving common measuring tasks.

4.1 Rotate Image and Region (2D Transformation)

For many measuring tasks, it is useful to align the object of interest parallel to the coordinate axis of the image. If the object cannot be aligned already at the image acquisition, the image or the extracted regions must be rotated by image processing. A rotation as well as a translation or a scaling can be realized by an affine 2D transformation, which is easily applied with HALCON.

The HDevelop program `%HALCONEXAMPLES%\solution_guide\2d_measuring\measure_screw.hdev` measures different dimension-related features of a screw. The image of the screw is acquired using a back light to get a good contrast between fore- and background. For the approach described in section 4.2, piecewise distance measuring is needed to obtain the minimum, maximum, and mean width of the screw. If the screw is vertical, the measuring can be applied easily row by row. Otherwise, the calculations become more complex. Thus, the first task of the program is to rotate the region of the screw so that it becomes vertical.

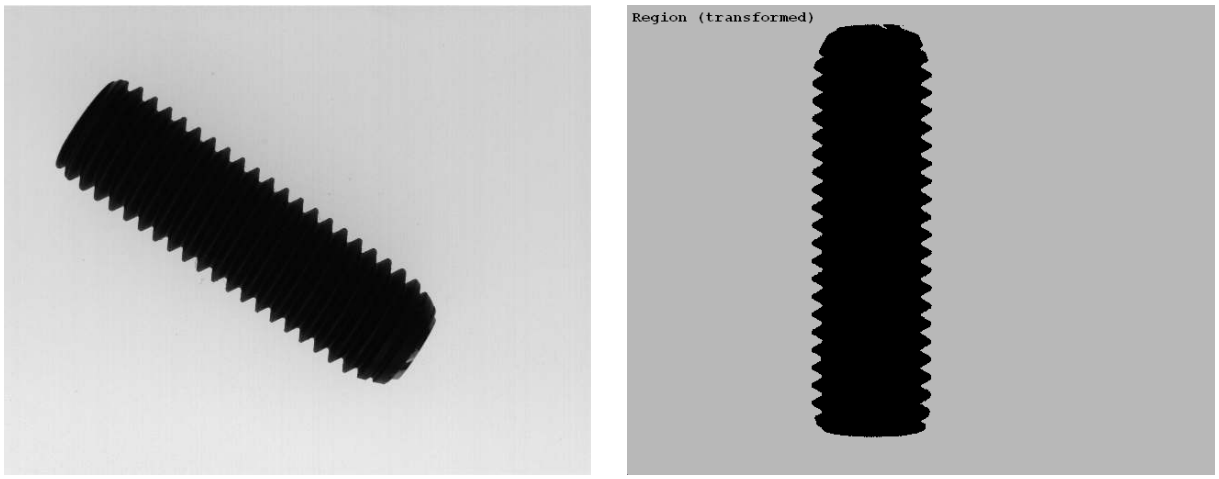

Figure 4.1: Affine 2D transformation: (left) original image, (right) rotated region.

The necessary steps for the rotation comprise

- the determination of the parameters for the rotation,
- the creation of a homogeneous transformation matrix, and

- the transformation of the region.

Step 1: Determine parameters for the rotation

```
threshold (Image, Region, 0, 100)
orientation_region (Region, OrientationRegion)
area_center (Region, Area, RowCenter, ColumnCenter)
```

Before applying a 2D transformation, the parameters for the transformation must be determined. Here, the region of the object is extracted using threshold and the orientation of the region is determined via orientation_region. The orientation intended for the following measuring is 90°. As center for the rotation we choose the center position of the region, which we obtain with area_center. Note that because of the approximately symmetrical shape of the screw, the screw can be twisted by 180°, but for the described task it is not important at which side of the screw we start to measure.

Step 2: Create the homogeneous transformation matrix

```
vector_angle_to_rigid (RowCenter, ColumnCenter, OrientationRegion, \
                       RowCenter, ColumnCenter, rad(90), HomMat2DRotate)
```

Now, vector_angle_to_rigid is applied. The operator creates a homogeneous transformation matrix for a simultaneous rotation and translation. Here, only a rotation is applied, i.e., the center point is the same for the original and the transformed region and only the angle is changing from the original orientation to the vertical direction. An additional translation is recommended, e.g., if similar objects in several images have to be placed in the same position so that a direct comparison between them is possible. Another need for a translation occurs if the object or parts of it moved out of the image because of the rotation. Alternatively to vector_angle_to_rigid, you can also create a homogeneous transformation matrix for the identical 2D transformation by hom_mat2d_identity and add a rotation and a translation to it by hom_mat2d_rotate and hom_mat2d_translate, respectively. Furthermore, if needed, also a scaling can be added to the homogeneous transformation matrix by hom_mat2d_scale, but you have to consider carefully that a scaling significantly influences the absolute values obtained by the measuring. To compensate this, you can afterwards transform the measurement results back to the original dimension by applying the inverse transformation matrix to them.

Step 3: Transform region

```
affine_trans_region (Region, RegionAffineTrans, HomMat2DRotate, \
                     'nearest_neighbor')
```

The actual transformation of the region is realized by the operator affine_trans_region (see figure 4.1). The rotated region is now used for the measuring task described in the next section.

4.2 Get Width of Screw Thread

The first measuring approach of the HDevelop program %HALCONEXAMPLES%\solution_guide\2d_measuring\measure_screw.hdev measures the minimum, maximum, and mean width of a screw thread. For this, we use the vertical region of the screw obtained in section 4.1 and measure the difference between the column coordinates of the region's border in each row.

The general steps for this task comprise

- the extraction of the width of the object in each row and
- the calculation of the mean, minimum, and maximum width.

Step 1: Get object width for each row

```
closing_circle (RegionAffineTrans, RegionToProcess, 4.5)
get_region_runs (RegionToProcess, RowRegionRuns, ColumnBegin, ColumnEnd)
NumberLines := |RowRegionRuns|
ColumnBeginSelected := ColumnBegin[90:NumberLines - 90]
ColumnEndSelected := ColumnEnd[90:NumberLines - 90]
Diameter := ColumnEndSelected - ColumnBeginSelected + 1
```

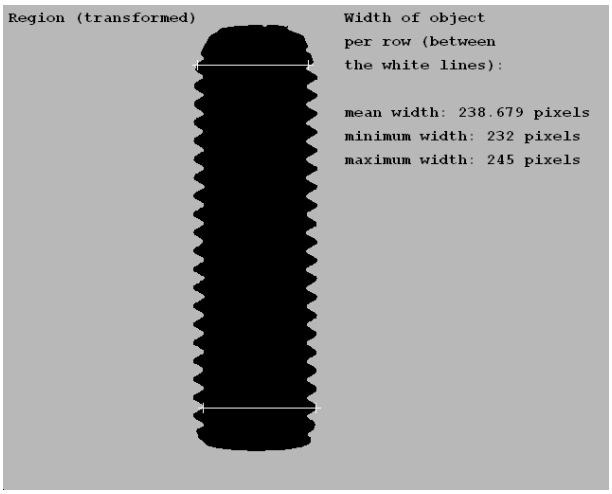

Figure 4.2: Between the two white lines for each row, the distance is measured via a region processing.

The operator get_region_runs examines a region row by row. In particular, it returns three tuples, one containing the row coordinates of the region and two containing the column coordinates where the region begins and ends in the corresponding rows (seen from left to right). The difference between the two tuples containing column coordinates results in a tuple containing the widths of the object for each row. Note that this proceeding works only for regions having exactly one start and one end point per row. Thus, before applying get_region_runs, small gaps that lead to more than one start and end point are eliminated by a closing using closing_circle.

Step 2: Calculate mean, minimum, and maximum width

```
meanDiameter := mean(Diameter)
minDiameter := min(Diameter)
```

The tuple containing the widths of the object in each row are used now to calculate the mean, minimum, and maximum horizontal distance of the object (see figure 4.2).

In this approach, the column coordinates of the screw's border, which are used to calculate the horizontal distance in each row, are obtained by region processing. Alternatively, contour points can be obtained by a contour processing and their coordinates can be used for the width calculation. How to obtain contour points is, e.g., described in section 4.3 for the two thread edges EdgeContour0 and EdgeContour1.

4.3 Get Deviation of a Contour from a Straight Line

The second measuring approach in the HDevelop program %HALCONEXAMPLES%\solution_guide\2d_measuring\measure_screw.hdev uses contour processing to measure the deviations of the thread edges from their approximating straight lines, the so-called regression lines.

Individual points on the thread edges alternatively can be obtained by region processing, e.g., using the operator get_region_points, but for the calculation of the regression lines, a contour processing is necessary. The general steps applied here comprise

- the creation of an ROI,
- the extraction and alignment of contours,
- the determination of regression lines,
- the extraction of the contour points of the thread edges,
- the calculation of the horizontal distances between the thread edges and the regression lines, and
- the visualization of the result in a zoom window.

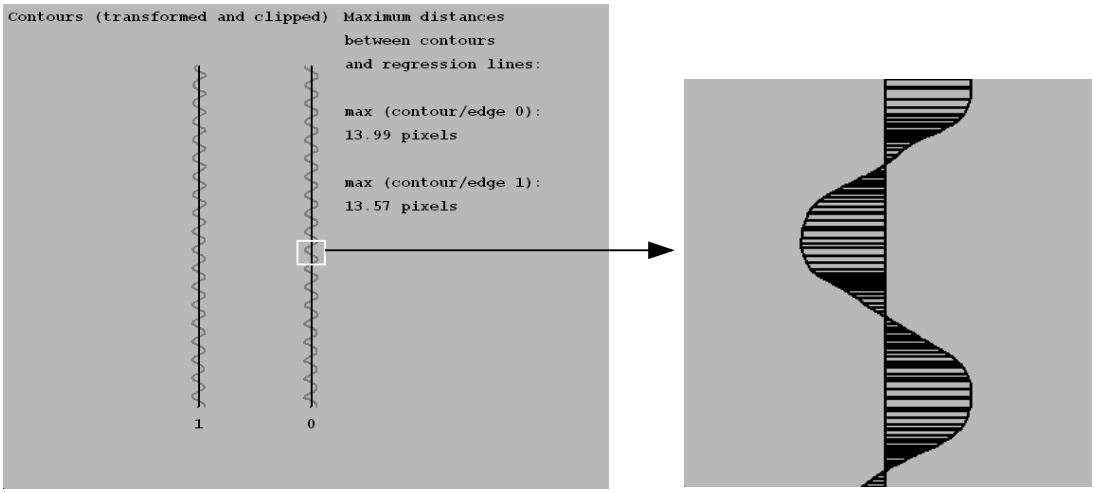

Figure 4.3: Measure the deviation of the contours from their regression lines: (left) contours of the thread edges and their regression lines, (right) visualization of deviation per row in a zoom window.

Step 1: Create ROI

```
boundary (Region, RegionBorder, 'inner_filled')
dilation_circle (RegionBorder, RegionDilation, 7.5)
reduce_domain (Image, RegionDilation, ImageReduced)
```

First, a region processing is used to create an ROI for the following contour processing. For this, we reduce the original region of the screw to its border by the operator `boundary` and use the morphological operator `dilation_circle` to enlarge it. The domain is reduced to the enlarged region by `reduce_domain` (see figure 4.4).

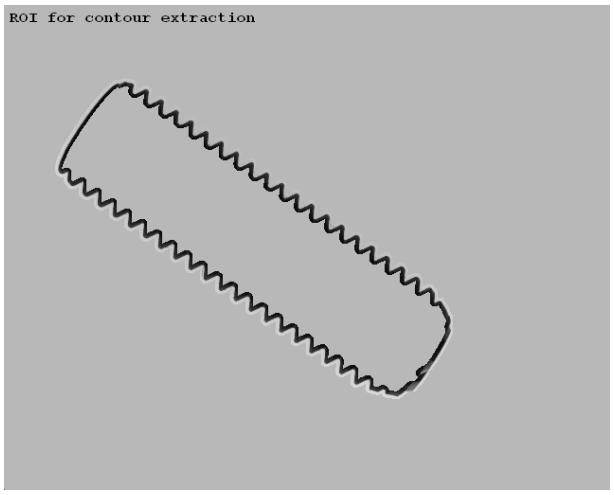

Figure 4.4: ROI for the subpixel-precise edge extraction.

Step 2: Extract and transform contours

```
sigma := 3
derivate_gauss (ImageReduced, DerivGauss, sigma, 'laplace')
zero_crossing_sub_pix (DerivGauss, Edges)
select_contours_xld (Edges, SelectedEdges, 'contour_length', 3000, 99999, \
                     -0.5, 0.5)
```

The ROI is now used as search space for the contour processing that starts with a subpixel-precise edge extraction. In many cases, the operator `edges_sub_pix` is the first choice when extracting edges. Here, it has the disadvantage that it works on the first derivative so that the curves are flattened slightly. Because we need the outer parts of the

contour, a curve flattening must be avoided. Thus, we use a Laplace filter, which leads to less smooth edges but matches the turning parts of the contour. The Laplace filter is applied using the operator `derivate_gauss` with the parameter `laplace`. The operator `zero_crossing_subpix` then returns the edge contours. From these, we select the contours with a minimum size using `select_contours_xld`.

The operator `affine_trans_contour_xld` then transforms the contours using the same homogeneous transformation matrix as used for the transformation of the region obtained in section 4.1 on page 35 (see figure 4.5).

```
affine_trans_contour_xld (SelectedEdges, ContoursAffineTrans, \
                          HomMat2DRotate)
```

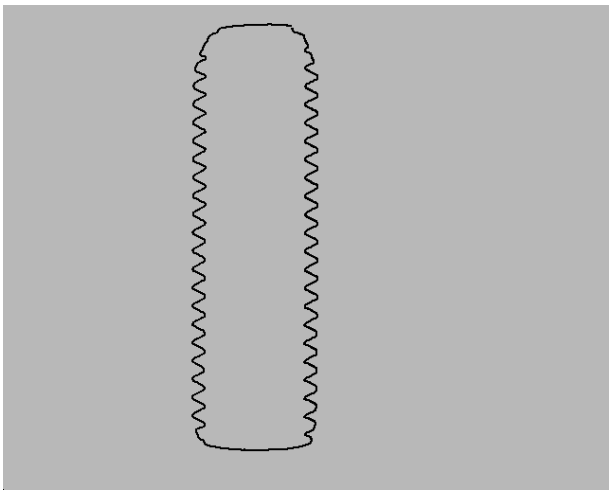

Figure 4.5: Extracted and transformed contours of the screw.

With `smallest_rectangle1_xld` and `clip_contours_xld`, the now vertical contour is clipped to get that part of the screw's border that contains the two separated thread edges on the left and right side of the screw.

```
smallest_rectangle1_xld (ContoursAffineTrans, Row11, Column11, Row21, \
                         Column21)
clip_contours_xld (ContoursAffineTrans, ClippedContours, Row11 + 90, 0, \
                   Row21 - 90, Width)
```

Step 3: Get regression lines

```
fit_line_contour_xld (ClippedContours, 'regression', -1, 0, 5, 2, RowBegin, \
                      ColBegin, RowEnd, ColEnd, Nr, Nc, Dist1)
```

The operator `fit_line_contour_xld` now uses the contours to compute the start (`RowBegin`, `ColBegin`) and end (`RowEnd`, `ColEnd`) points for the regression lines (see figure 4.6). To get the points of the regression lines, the parameter `Algorithm` must be set to `'regression'`.

Until now, we handled both contours together in tuples. The tuple `Edges` contains the contours of the two thread edges, and the tuples for the start and end points of the regression lines contain the points for both regression lines. With the operator `gen_contour_polygon_xld` we explicitly create the contours of the individual regression lines. For this, we use the corresponding start and end points as input, i.e., for the first regression line (`RegressContour0`) we use the start and end points with the index `0`, and for the second regression line (`RegressContour1`) we use the elements with index `1`.

```
gen_contour_polygon_xld (RegressContour0, [RowBegin[0],RowEnd[0]], \
                         [ColBegin[0],ColEnd[0]])
gen_contour_polygon_xld (RegressContour1, [RowBegin[1],RowEnd[1]], \
                         [ColBegin[1],ColEnd[1]])
```

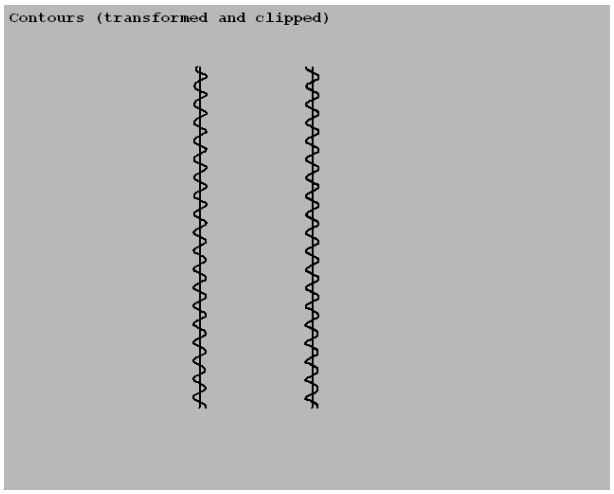

Figure 4.6: Clipped contours and the corresponding regression lines.

Step 4: Extract contour points of the thread edges

```
select_obj (ClippedContours, EdgeContour0, 1)
get_contour_xld (EdgeContour0, RowEdge0, ColEdge0)
select_obj (ClippedContours, EdgeContour1, 2)
get_contour_xld (EdgeContour1, RowEdge1, ColEdge1)
```

To get the deviation between the thread contours and their corresponding regression lines, we additionally need the contour points of the thread contours. The thread contours are stored both in the tuple `Edges`. Since we want to access the individual contours more than once, the usage of the indices may become a little bit confusing. To make the code clearer and also to apply further tuple operations to each contour later on, we select the elements of the tuple individually and assign concise names to them: `EdgeContour0` and `EdgeContour1`. In HDevelop, the selection of iconic objects is not realized via the operator `assign` but by the operator `select_obj`. Note that the index of iconic objects starts with `1` instead of `0`. For the thread contours `EdgeContour0` and `EdgeContour1`, a tuple containing the rows and columns of the contour points is obtained with `get_contour_xld`.

Step 5: Calculate the horizontal distances

```
distance_pc (RegressContour0, RowEdge0, ColEdge0, DistanceMin0, \
             DistanceMax0)
minDistance0 := min(DistanceMin0)
maxDistance0 := max(DistanceMin0)
meanDistance0 := mean(DistanceMin0)
```

The obtained contour points are used to calculate the distances between each contour point of the thread edge and the contour of the corresponding regression line. The operator `distance_pc` returns the minimum and maximum distances. The minimum distances between the contour points and the contour of the regression line correspond to the horizontal distances in approximately each row (as long as the screw is vertical). These in turn can be used to query the minimum, maximum, and mean horizontal distance between both contours (see figure 4.3, left). The code only shows the proceeding for `EdgeContour0` and `RegressContour0`.

Step 6: Visualize the result in a zoom window

```
dev_display (EdgeContour0)
dev_display (RegressContour0)
get_contour_xld (RegressContour0, RowContour0, ColContour0)
for i := 800 to 950 by 1
    projection_pl (RowEdge0[i], ColEdge0[i], RowContour0[0], ColContour0[0], \
                   RowContour0[1], ColContour0[1], RowProj0, ColProj0)
    gen_contour_polygon_xld (Contour, [RowEdge0[i],RowProj0], [ColEdge0[i], \
                             ColProj0])
    dev_display (Contour)
endfor
```

To visualize the individual horizontal distances between a thread contour and its regression line in a zoom window (see figure 4.3, right), the endpoints of the regression line are made explicit by `get_contour_points` and with these, the points of the thread contour are projected onto the regression line using `projection_pl`. The lines between the points and their projections are created by `gen_contour_polygon_xld` and visualized by the standard visualization operator `dev_display`.

4.4 Get the Distance between Straight Parallel Contours

Different approaches are available to measure the distance between straight parallel contours. Here, we introduce approaches that use

- contours obtained by line fitting together with a geometric operation,
- parallel polygon segments together with a geometric operation, or
- the smallest enclosing rectangle.

4.4.0.1 Using contours obtained by line fitting

A third measuring approach realized in the HDevelop program `%HALCONEXAMPLES%\solution_guide\2d_measuring\measure_screw.hdev` measures the distance between the two parallel contours of the regression lines `RegressContour0` and `RegressContour1`, which were obtained in section 4.3.

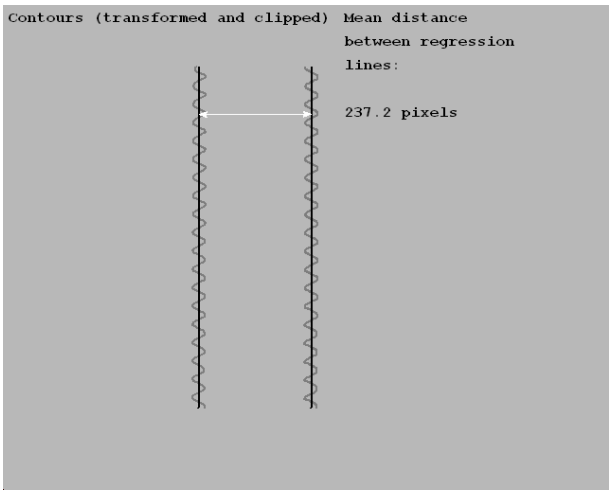

Figure 4.7: Distance between two regression lines.

For this, we compute the distances between the end points of the regression lines using the operator `distance_pp` (see section 2.4 on page 25). Before displaying the mean width of the object, we check if the distance between the two points at the top of the screw correspond to the distance between the points at the bottom, i.e., we check if the lines are parallel within a certain tolerance. The result of the distance measurement is displayed in figure 4.7.

```
distance_pp (RowBegin[1], ColBegin[1], RowEnd[0], ColEnd[0], Distance1)
distance_pp (RowBegin[0], ColBegin[0], RowEnd[1], ColEnd[1], Distance2)
if (abs(Distance1 - Distance2) < 1)
    disp_message (WindowID, 'Mean distance', 'image', 10, 720, 'black', \
                  'false')
    disp_message (WindowID, 'between regression', 'image', 60, 720, 'black', \
                  'false')
    disp_message (WindowID, 'lines:', 'image', 110, 720, 'black', 'false')
    disp_message (WindowID, ((Distance1 + Distance2) / 2)$'.4' + ' pixels', \
                  'image', 210, 720, 'black', 'false')
endif
```

4.4.0.2 Using polygons instead of lines

The HDevelop program %HALCONEXAMPLES%\solution_guide\2d_measuring\measure_metal_part_extended.hdev demonstrates a similar approach. As before, a contour is extracted and segmented into linear and circular contour segments (the segments are stored in the tuple ContoursSplit). In contrast to the approach described before, instead of fitting lines, the linear segments are approximated by Polygons using gen_polygons_xld. From these polygons the approximately parallel lines Parallels can be explicitly extracted by gen_parallels_xld.

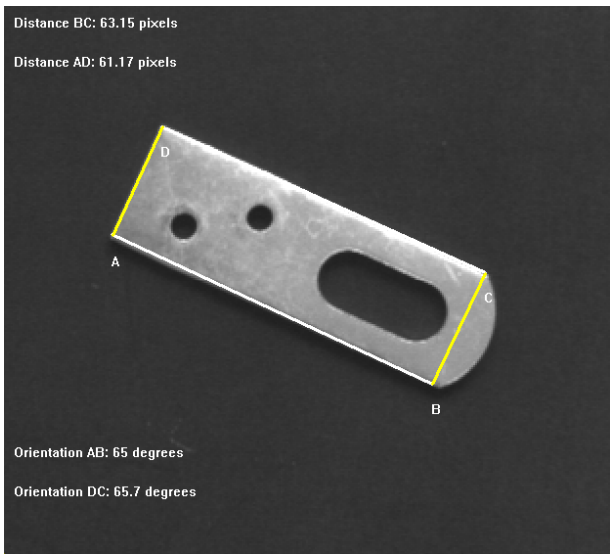

Figure 4.8: Distance between the endpoints of parallel polygon segments.

To get the end points and orientation of the corresponding line segments, we apply the operator get_parallels_xld for each pair of parallel lines. In HDevelop, the number of pairs, needed for creating the for-loop, is obtained by the operator count_obj, which counts the number of objects of a tuple containing iconic data. For control data, the operator assign would be used (see HDevelop User's Guide, section 8.5.3 on page 289). For a pair of parallel lines we now calculate the distances between the opposed end points with the geometric operation distance_pp. The result for the distance measurement as well as the obtained orientations of the lines are displayed in figure 4.8.

```
gen_polygons_xld (ContoursSplit, Polygons, 'ramer', 2)
gen_parallels_xld (Polygons, Parallels, 80, 75, 0.15, 'true')
count_obj (Parallels, NumberParallels)
for i := 1 to NumberParallels by 1
    select_obj (Parallels, SelectedParallel, i)
    get_parallels_xld (SelectedParallel, Row1Parallels, Col1Parallels, \
                       Length1Parallels, Phi1Parallels, Row2Parallels, \
                       Col2Parallels, Length2Parallels, Phi2Parallels)
    distance_pp (Row1Parallels[0], Col1Parallels[0], Row2Parallels[1], \
                 Col2Parallels[1], Distance2)
    distance_pp (Row1Parallels[1], Col1Parallels[1], Row2Parallels[0], \
                 Col2Parallels[0], Distance1)
endfor
```

4.4.0.3 Using the smallest enclosing rectangle

If you have a complex shape that is delimited by straight lines that are known to be parallel and you want to know the distance between them, you can also obtain the width of the object by computing the smallest enclosing rectangle for it. To do so, you do not even have to extract the individual segments, but simply extract the region or contour of the object and then apply smallest_rectangle2 to the region or smallest_rectangle2_xld to the contour. Depending on the dimension of your object, the returned parameter

Length1 or Length2 then represents half of the distance between the parallel lines. Figure 4.9 shows the smallest enclosing rectangle obtained in the HDevelop program %HALCONEXAMPLES%\solution_guide\2d_measuring\measure_metal_part_extended.hdev. Furthermore, for contours that approximate a rectangle, the fitting of rectangles to contours using fit_rectangle2_contour_xld is suitable (see section 4.9 on page 49).

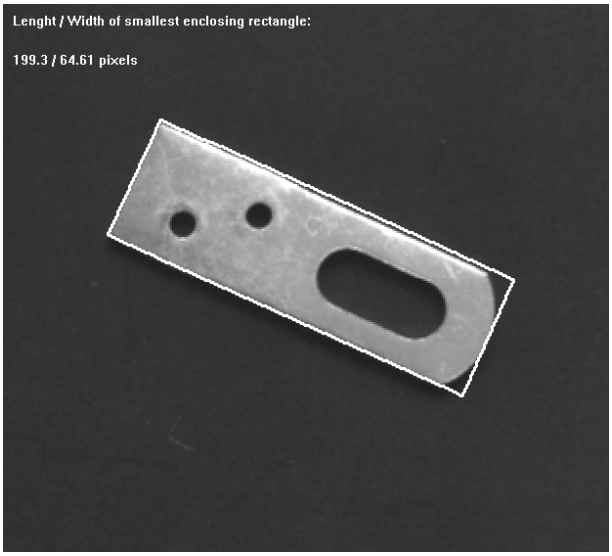

Figure 4.9: Length and width of the smallest enclosing rectangle of a region.

4.5 Get Width of Linear Structures

To get the width of thin linear structures, the operator lines_gauss can be used. Be aware that the linear structures are called lines, but in contrast to the XLD lines obtained by a line fitting (see section 2.2.4 on page 19), they are built by edge pairs, and for each line attributes like the width can be stored and queried.

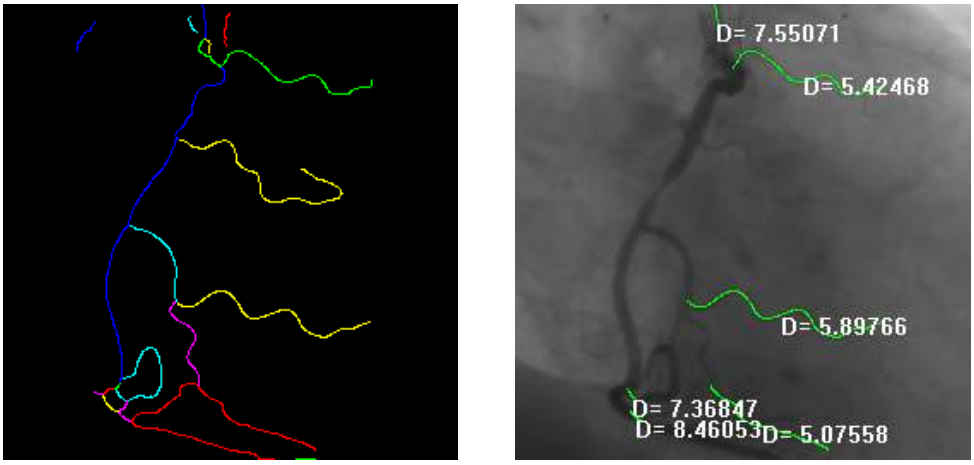

Figure 4.10: Linear structures obtained by lines_gauss in the HDevelop example angio.dev: (left) the extracted lines, (right) visualization of the diameters of the selected lines.

Examples showing how to apply the operator are

- %HALCONEXAMPLES%\hdevelop\Applications\Medicine\angio.dev (see figure 4.10) and
- %HALCONEXAMPLES%\hdevelop\Filter\Lines\lines_gauss.dev.

The latter is briefly introduced in the Solution Guide I, section 7.3.2 on page 73. For detailed descriptions of the parameter selection, follow the links to the corresponding sections in the Reference Manual.

Briefly, you can select whether bright or dark lines are detected and adjust parameters for the general line extraction. Additionally, you can set parameters that control which attributes are stored with the obtained lines. These attributes can then be queried with the operator `get_contour_attrib_xld`. Depending on the selected parameters in `lines_gauss` you can query the following parameters: the angle of the direction perpendicular to the line (`'angle'`), the magnitude of the second derivative (`'response'`), the line widths to the left or to the right of the line (`'width_left'`, `'width_right'`), the asymmetry of a line point (`'asymmetry'`), or the contrast of a line point (`'contrast'`).

4.6 Get Lines and Junctions of a Grid

The HDevelop program `%HALCONEXAMPLES%\solution_guide\2d_measuring\measure_grid.hdev` inspects a numeric keypad. In particular, the positions of the junctions of the grid separating the keys are measured.



Figure 4.11: Lines and junction points representing the grid that separates the keys.

The general steps of the program comprise

- the extraction of the region between and around the keys,
- the determination of the region's skeleton and the extraction of the corresponding linear contours,
- the separation of the horizontal and vertical lines,
- the intersection of the horizontal lines with the vertical lines to get the junction points of a regular grid, and
- the reduction of the point set to those points that represent a real existing junction.
- Additionally, the usability of region processing for the extraction of junction points is discussed.

Step 1: Get region between and around the keys

```
mean_image (Image, ImageMean, 7, 7)
dyn_threshold (Image, ImageMean, RegionDynThresh, 4, 'dark')
connection (RegionDynThresh, ConnectedRegions)
select_shape (ConnectedRegions, SelectedRegions, ['max_diameter', \
              'contlength'], 'and', [200,800], [99999,99999])
closing_circle (SelectedRegions, RegionClosing, 1.5)
```

First, the region representing the space between and around the keys is segmented and further processed via region processing. This includes the coarse segmentation of the image via a dynamic threshold (`dyn_threshold`), the selection of a connected region of a certain size (`connection` followed by `select_shape`), as well as the closing of small gaps by `closing_circle`. This is illustrated in figure 4.12, a-d.

Step 2: Get skeleton and the corresponding horizontal and vertical linear contours

```
skeleton (RegionClosing, Skeleton)
gen_contours_skeleton_xld (Skeleton, ContoursSkeleton, 1, 'filter')
segment_contours_xld (ContoursSkeleton, ContoursSplitSkeleton, 'lines', 5, \
                      2, 1)
select_contours_xld (ContoursSplitSkeleton, SelectedContours, \
                     'contour_length', 30, 1000, -0.5, 0.5)
union_collinear_contours_xld (SelectedContours, UnionCollinearContours, 100, \
                              10, 20, rad(10), 'attr_keep')
```

Then, the region is reduced to its `skeleton`, which is then transformed to a contour by `gen_contours_skeleton_xld`. The contour is segmented into individual lines (`segment_contours_xld`), from which those are selected by `select_contours_xld` that have a minimum contour length (see figure 4.12, e-f). Additionally, collinear lines are merged by `union_collinear_contours_xld` (see figure 4.13, left).

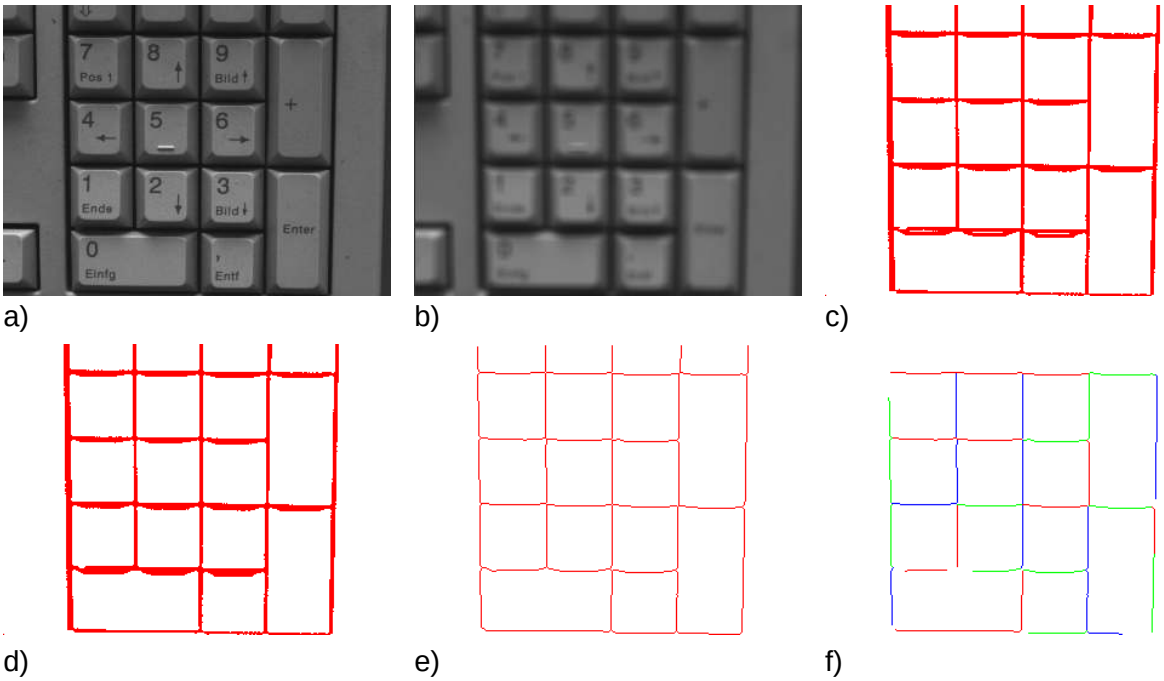

Figure 4.12: Extraction of region: (a) original image, (b) image processed by `mean_image`, (c) extracted region with gaps, (d) region after closing gaps by a morphological operator, (e) skeleton, (f) selected contour segments.

Now, lines are fitted to each contour by `fit_line_contour_xld` and the corresponding line contours are generated by `gen_contour_polygon_xld`. For each contour the orientation is checked within a tolerance of 0.05 rad in both directions and horizontal lines are stored in the tuple `LinesHorizontal` and vertical lines in the tuple `LinesVertical`. Both are first created by `gen_empty_obj` and then successively filled using `concat_obj`.

```
count_obj (UnionCollinearContours, NumberContours)
gen_empty_obj (LinesHorizontal)
gen_empty_obj (LinesVertical)
for i := 1 to NumberContours by 1
    select_obj (UnionCollinearContours, ObjectSelected, i)
    fit_line_contour_xld (ObjectSelected, 'tukey', -1, 0, 5, 2, RowBegin, \
                          ColBegin, RowEnd, ColEnd, Nr, Nc, Dist)
    gen_contour_polygon_xld (Contour, [RowBegin,RowEnd], [ColBegin,ColEnd])
    Phi := atan2(-Nr,Nc)
    if (abs(Phi) < rad(5))
        concat_obj (LinesVertical, Contour, LinesVertical)
    endif
    if (rad(85) < abs(Phi) and abs(Phi) < rad(95))
        concat_obj (LinesHorizontal, Contour, LinesHorizontal)
    endif
endfor
```

Step 3: Get junction points

Now, inside a loop, each horizontal line is intersected (`intersection_lines`) with each vertical line to get the junction points of the regular grid. This grid is built by lines of infinite length, so that the intersection leads to junction points also at the large keys (see figure 4.13, right).

```
RowJunction := []
ColJunction := []
RowRealJunction := []
ColRealJunction := []
count_obj (LinesHorizontal, NumberLH)
count_obj (LinesVertical, NumberLV)
for i := 1 to NumberLH by 1
    select_obj (LinesHorizontal, HorizontalLine, i)
    get_contour_xld (HorizontalLine, RowHorizontal, ColHorizontal)
    for j := 1 to NumberLV by 1
        select_obj (LinesVertical, VerticalLine, j)
        get_contour_xld (VerticalLine, RowVertical, ColVertical)
        intersection_lines (RowHorizontal[0], ColHorizontal[0], \
                            RowHorizontal[1], ColHorizontal[1], \
                            RowVertical[0], ColVertical[0], RowVertical[1], \
                            ColVertical[1], Row, Column, IsOverlapping)
        distance_ps (Row, Column, RowHorizontal[0], ColHorizontal[0], \
                     RowHorizontal[1], ColHorizontal[1], DistanceH, \
                     DistanceHMax)
        distance_ps (Row, Column, RowVertical[0], ColVertical[0], \
                     RowVertical[1], ColVertical[1], DistanceV, \
                     DistanceVMax)
        RowJunction := [RowJunction,Row]
        ColJunction := [ColJunction,Column]
```

Step 4: Reduce the point set

```
        if ((DistanceH <= 30) and (DistanceV <= 30))
            RowRealJunction := [RowRealJunction,Row]
            ColRealJunction := [ColRealJunction,Column]
        endif
    endfor
endfor
```

To get only those points of the grid that represent a real existing junction, for each junction point the distances to the two line segments used for its creation are computed by `distance_ps`. If both distances are less than 30 pixels, the point is assumed to be a real junction point (see figure 4.14, left).

Step 5: Junction points via region processing

Alternatively, junction points can also be obtained via region processing. Here, we apply `junctions_skeleton` to the skeleton we obtained in a preceding step. Since the operator returns regions instead of points, we apply

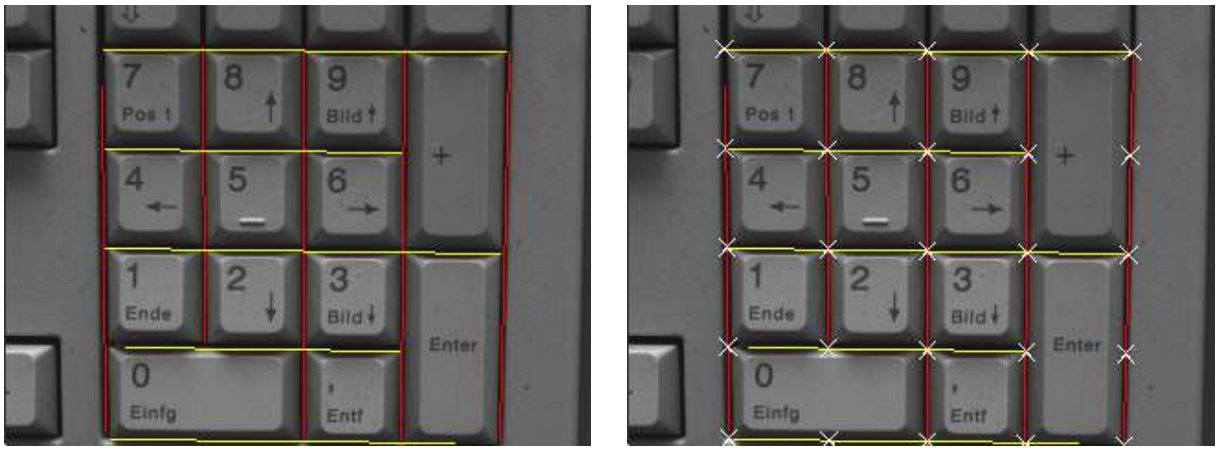

Figure 4.13: Get junction points: (left) collinear horizontal and vertical contours obtained by line fitting, (right) all junctions of the regular grid including junctions that do not represent a real existing junction between keys.

get_region_points to get the center positions of each junction. Note that in contrast to contour processing these junction positions are not based on a grid obtained by straight lines but on the region extracted between the keys. Depending on the region, the resulting junction points may be ambiguous and may not represent junctions of a regular grid (see figure 4.14, right).

```
junctions_skeleton (Skeleton, EndPoints, JuncPoints)
get_region_points (JuncPoints, RowJunctionRegionProcessing, \
                   ColumnJunctionRegionProcessing)
gen_cross_contour_xld (CrossCenter, RowJunctionRegionProcessing, \
                       ColumnJunctionRegionProcessing, 12, 0.785398)
```

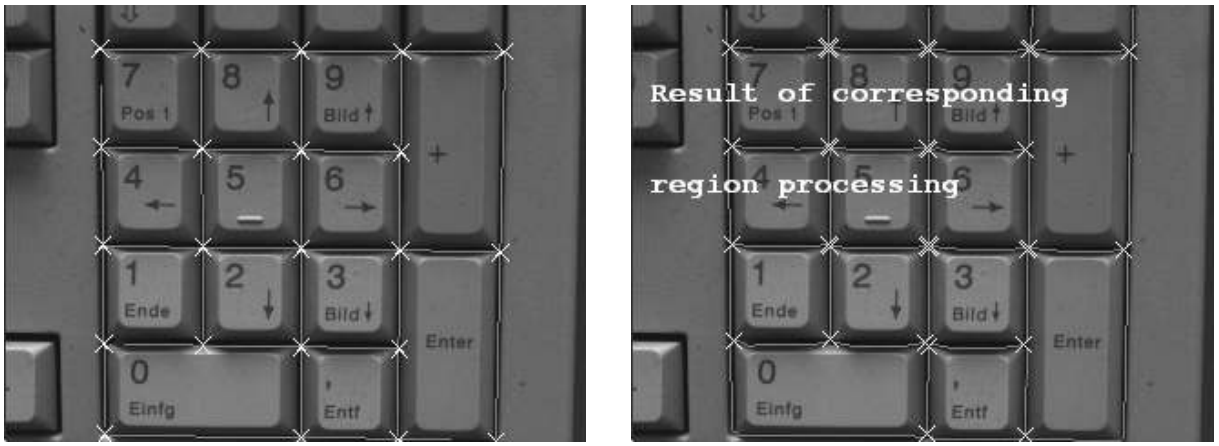

Figure 4.14: Get junction points: (left) lines fitted into linear contours and the junction points of the grid separating the keys, (right), skeleton and irregular junction points obtained by region processing.

4.7 Get Positions of Corner Points

Corner points are extracted in different ways. The HDevelop program %HALCONEXAMPLES%\solution_guide\2d_measuring\measure_metal_part_extended.hdev extracts the positions of the corners of a metal plate in an image by two different approaches. The first approach applies a point operator and the other one determines the corner points by intersecting lines.

The general steps of the program comprise

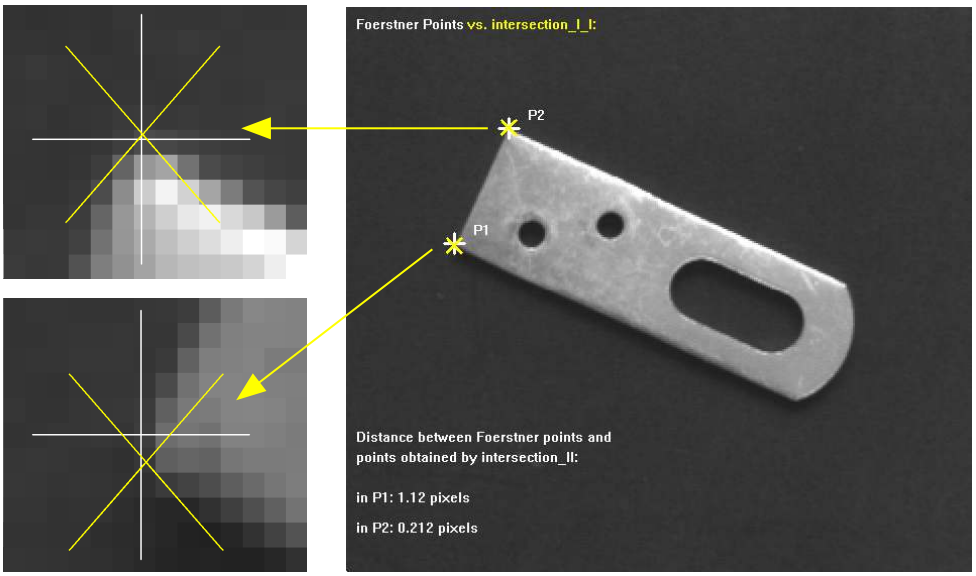

Figure 4.15: Förstner points (crosses parallel to coordinate axes) versus intersection points (inclined crosses).

- the determination of corner points via the point operator of Förstner,
- the determination of corner points by the intersection of lines, and
- the comparison of both approaches.

Step 1: Get Förstner points

```
points_foerstner (Image, 1, 2, 3, 200, 0.3, 'gauss', 'false', RowJunctions, \
                  ColJunctions, CoRRJunctions, CoRCJunctions, \
                  CoCCJunctions, RowArea, ColArea, CoRRArea, CoRCArea, \
                  CoCCArea)
```

The first approach is realized by a point operator. Here, the points (row and column coordinates stored in the tuples `RowJunctions` and `ColJunctions`) are extracted by `points_foerstner`.

Step 2: Get corner points by line intersection

```
edges_sub_pix (ImageReduced, Edges, 'lanser2', 0.5, 40, 90)
segment_contours_xld (Edges, ContoursSplit, 'lines_circles', 6, 4, 4)
sort_contours_xld (ContoursSplit, SortedContours, 'upper_left', 'true', \
                   'column')
count_obj (SortedContours, NumSegments)
for i := 1 to NumSegments by 1
    select_obj (SortedContours, SingleSegment, i)
    get_contour_global_attrib_xld (SingleSegment, 'cont_approx', Attrib)
        fit_line_contour_xld (SingleSegment, 'tukey', -1, 0, 5, 2, RowBegin, \
                              ColBegin, RowEnd, ColEnd, Nr, Nc, Dist)
        RowsBegin := [RowsBegin,RowBegin]
        ColsBegin := [ColsBegin,ColBegin]
        RowsEnd := [RowsEnd,RowEnd]
        ColsEnd := [ColsEnd,ColEnd]
endfor
```

The second approach intersects lines to get the positions of the corners. The adjacent lines building the corners are obtained by line fitting, i.e., edges are extracted using `edges_sub_pix`, the obtained contours are segmented by `segment_contours_xld` and sorted by `sort_contours_xld`, and to each linear segment a line is fitted via `fit_line_contour_xld`. The returned end points of the lines are stored in the tuples `RowsBegin`, `ColsBegin`, `RowsEnd`, and `ColsEnd`.

From these end points the intersection points of the lines (RowIntersect*, ColumnIntersect*) are calculated via intersection_lines.

```
intersection_lines (RowsBegin[0], ColsBegin[0], RowsEnd[0], ColsEnd[0], \
                    RowsBegin[1], ColsBegin[1], RowsEnd[1], ColsEnd[1], \
                    RowIntersect1, ColumnIntersect1, IsOverlapping1)
intersection_lines (RowsBegin[0], ColsBegin[0], RowsEnd[0], ColsEnd[0], \
                    RowsBegin[2], ColsBegin[2], RowsEnd[2], ColsEnd[2], \
                    RowIntersect2, ColumnIntersect2, IsOverlapping2)
```

Step 3: Compare the two approaches

```
distance_pp (RowJunctions[1], ColJunctions[1], RowIntersect1, \
             ColumnIntersect1, Distance1)
distance_pp (RowJunctions[0], ColJunctions[0], RowIntersect2, \
             ColumnIntersect2, Distance2)
```

To compare the results of both approaches, the distances between the points obtained by the line intersection and their corresponding Förstner points are computed by distance_pp and displayed in figure 4.15.

4.8 Get Angle between Adjacent Lines

With the end points of the adjacent lines obtained in section 4.7 we now can use the geometric operation angle_ll to get the angle between the adjacent lines and thus check whether both angles are exactly or only approximately right angled (see figure 4.16).

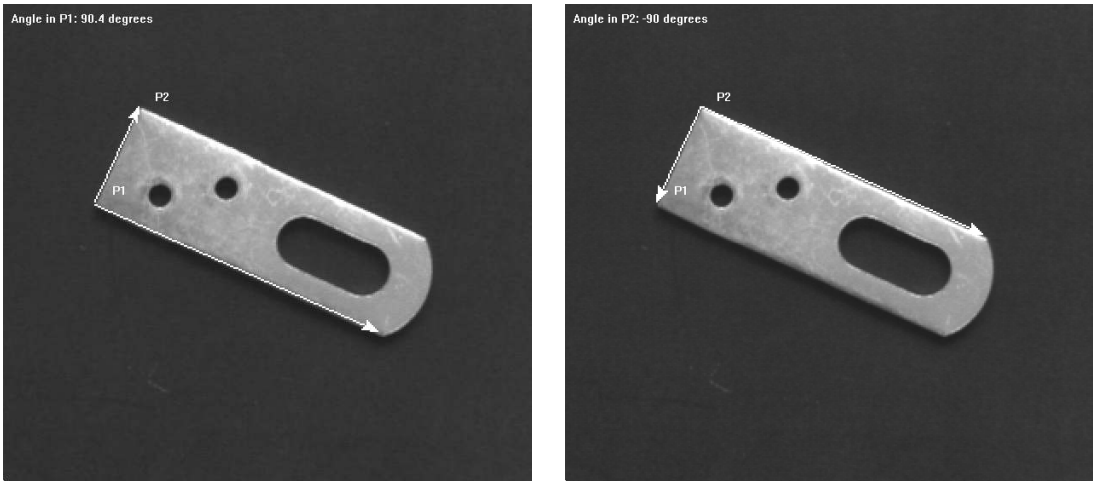

Figure 4.16: Angle between lines: (left) angle in P1, (right) angle in P2.

```
angle_ll (RowsBegin[0], ColsBegin[0], RowsEnd[0], ColsEnd[0], RowsBegin[1], \
          ColsBegin[1], RowsEnd[1], ColsEnd[1], Angle1)
angle_ll (RowsBegin[0], ColsBegin[0], RowsEnd[0], ColsEnd[0], RowsBegin[2], \
          ColsBegin[2], RowsEnd[2], ColsEnd[2], Angle2)
```

4.9 Get Positions, Orientations, and Extents of Rectangles

The HDevelop program %HALCONEXAMPLES%\solution_guide\2d_measuring\measure_chip.hdev extracts the rectangular shapes of the die and the frame of a chip. The relations between the two positions and orientations are needed, e.g., for a correct die bonding.

The general steps of the program comprise

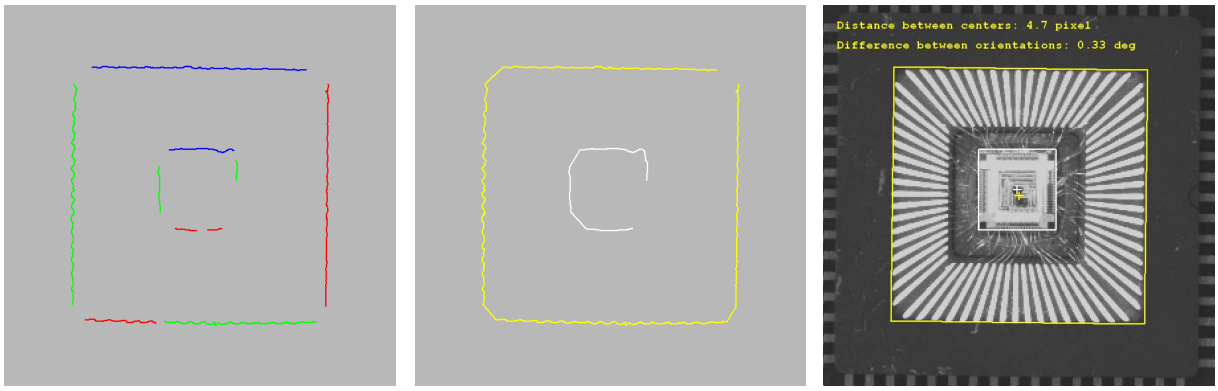

Figure 4.17: From left to right: selected contours, merged contours of the individual rectangles, results obtained by rectangle fitting.

- the creation of an ROI for the die,
- the extraction of the contours of the die,
- the fitting of a rectangle to the contours of the die,
- the creation of an ROI and the extraction of the contours of the frame,
- the fitting of a rectangle to the contours of the frame, and
- the comparison of the position and orientation of both rectangles.

Step 1: Create ROI for the die

```
fast_threshold (Image, Region, 120, 255, 20)
opening_rectangle1 (Region, RegionOpening, 4, 4)
connection (RegionOpening, ConnectedRegions)
fill_up (ConnectedRegions, RegionFillUp)
select_shape (RegionFillUp, SelectedRegions, ['rectangularity','area'], \
              'and', [0.8,700], [1,99999])
smallest_rectangle2 (SelectedRegions, Row, Column, Phi, Length1, Length2)
gen_rectangle2 (Rectangle, Row, Column, Phi, Length1, Length2)
```

The program starts with region processing. It coarsely determines the region of the die using `fast_threshold`. The operator `opening_rectangle1` suppresses the small wires. After separating the individual connected parts of the region with `connection`, we fill up the remaining holes (`fill_up`) and select a region of rectangular shape and a certain size (`select_shape`). The region is approximated by its smallest enclosing rectangle (`smallest_rectangle2` and `gen_rectangle2`), which leads to a pixel-precise approximation for the position, orientation, and extent of the rectangle.

Because we need subpixel precision here, region processing is not sufficient. Thus, the region of the rectangle is reduced to its slightly enlarged boundary (`boundary` followed by `dilation_rectangle1`) and the reduced image (obtained by `reduce_domain`) is used as ROI, i.e., it builds the search space for the following contour processing (see figure 4.18, left).

```
boundary (Rectangle, RegionBorder, 'inner_filled')
dilation_rectangle1 (RegionBorder, RegionDilation, 4, 4)
reduce_domain (Image, RegionDilation, ImageReduced)
```

Step 2: Extract contours of the die

```
edges_sub_pix (ImageReduced, Edges, 'canny', 1.5, 30, 40)
segment_contours_xld (Edges, ContoursSplit, 'lines', 5, 2, 2)
select_contours_xld (ContoursSplit, SelectedContours1, 'contour_length', 10, \
                     99999, -0.5, 0.5)
union_adjacent_contours_xld (SelectedContours1, UnionContours1, 30, 1, \
                             'attr_keep')
```

Inside the ROI, the subpixel-precise edges of the die's border are extracted by the operator edges_sub_pix. The edges are segmented into linear contours using the operator segment_contours_xld with the parameter Mode set to 'lines'. The contours having a minimum length are selected by select_contours_xld. The contours that belong to the border are now adjacent within a certain tolerance. To merge the contours that are neighboring within a range of 30 pixels, the operator union_adjacent_contours_xld is applied.

Step 3: Fit rectangle to the contours of the die

```
fit_rectangle2_contour_xld (UnionContours1, 'tukey', -1, 0, 0, 3, 2, Row1, \
                            Column1, Phi1, Length11, Length12, PointOrder1)
gen_rectangle2_contour_xld (Rectangle1, Row1, Column1, Phi1, Length11, \
                            Length12)
```

The operator fit_rectangle2_contour_xld now uses the obtained contour to get the position, orientation, and extent of the best-fitting rectangle of the die. The corresponding rectangle is then created by gen_rectangle2_contour_xld.

Step 4: Create ROI and extract contours of the frame

```
threshold_sub_pix (ImageReduced1, Border1, 70)
```

A similar procedure is applied for the border of the frame. The extraction of the ROI (see figure 4.18, right) is slightly different because the appearance of both objects in the image differs. Furthermore, the operator threshold_sub_pix instead of edges_sub_pix extracts the contours. The ROI in this case is needed to reduce the number of contours to investigate rather than to reduce the runtime of the contour extraction.

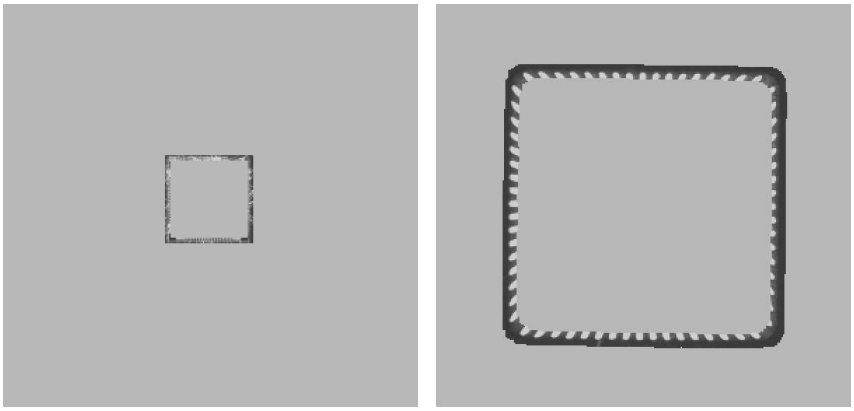

Figure 4.18: ROIs for the rectangle fitting: (left) ROI for the die, (right) ROI for the frame.

Step 5: Fit rectangle to the contours of the frame

Again, the adjacent contours are merged, the parameters of the best-fitting rectangle are obtained for the merged contour, and the corresponding rectangle is created and displayed.

Step 6: Compare the position and orientation of both rectangles

```
distance_pp (Row1, Column1, Row2, Column2, Distance)
DifferenceOrientation := Phi1 - Phi2
```

With the parameters of the rectangles for both shapes, the distance between their center positions (distance_pp) and the difference between their orientations (Phi1 and Phi2 were obtained automatically by the rectangle fitting) are calculated. Figure 4.17 shows the obtained contours and results.

An example that fits rectangles to contours and additionally gets the distances of the contour's points from the fitted rectangle using the operator dist_rectangle2_contour_points_xld is %HALCONEXAMPLES%\hdevelop\XLD\Features\fit_rectangle2_contour_xld.dev.

4.10 Get Radii of Circles and Circular Arcs

The HDevelop program %HALCONEXAMPLES%\solution_guide\2d_measuring\measure_circles.hdev extracts the radii of circular shapes that are punched out of a metal plate. The image of the plate is acquired using a back light to get a good contrast between fore- and background. Region processing, in particular the extraction of the smallest enclosing circle for a region, would be possible for some of the shapes (after suppressing gaps or protrusions with a morphological operator), but for others it is unsuitable since circles have to be fitted only to parts of their contour (see section 3.2 on page 31, c). Thus, region processing is used only to create an ROI for the following contour processing.

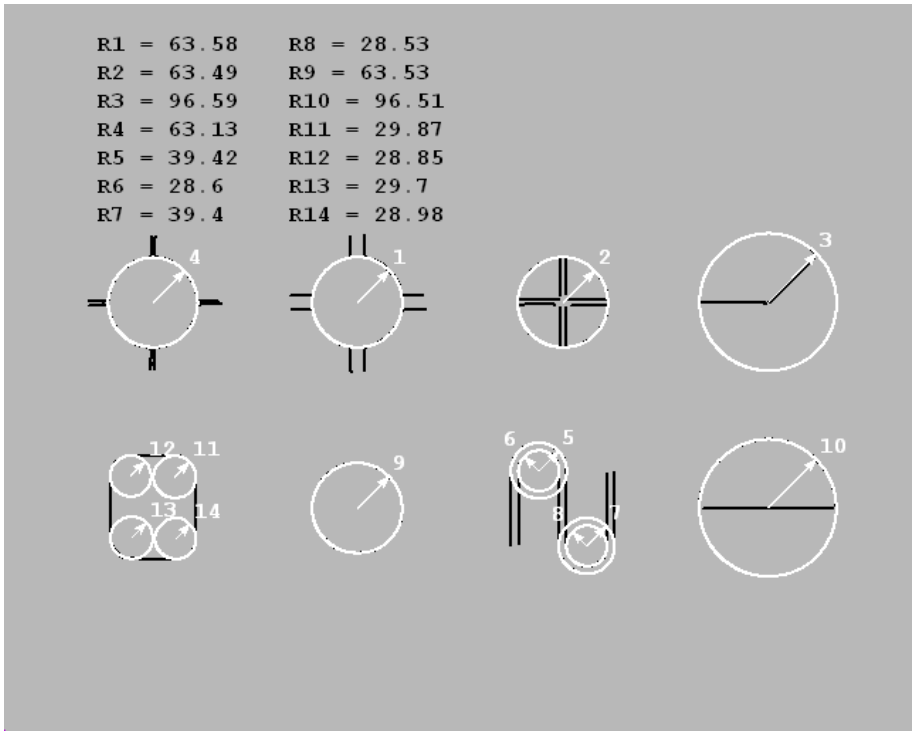

Figure 4.19: Circle fitting: black contours overlaid by the white fitted circles and display of their radii.

The general steps of the program comprise

- the creation of an ROI,
- the extraction of circular contour segments, and
- the fitting of circles to the circular contour segments.

Step 1: Create ROI

```
fast_threshold (Image, Region, 200, 255, 20)
connection (Region, ConnectedRegions)
select_shape (ConnectedRegions, SelectedRegions, 'area', 'and', 70, 50000)
boundary (SelectedRegions, RegionBorder, 'inner_filled')
dilation_circle (RegionBorder, RegionDilation, 3.5)
union1 (RegionDilation, RegionUnion)
reduce_domain (Image, RegionUnion, ImageReduced)
```

To extract the bright regions of the circular shapes a fast_threshold is applied. Connected regions are separated by connection and regions with a minimum size are selected for the further processing using select_shape (see figure 4.20, left). The regions are restricted to their borders by the operator boundary. These borders are enlarged a bit by a dilation (dilation_circle). The dilated regions are merged (union1) so that the image can be reduced to a region that contains all parts needed for the further tasks (reduce_domain). The reduced image is used as an ROI, i.e., it builds the search space for the subpixel-precise edge extraction.

Step 2: Extract circular contour segments

```
edges_sub_pix (ImageReduced, Edges, 'canny', 1.5, 10, 40)
segment_contours_xld (Edges, ContoursSplit, 'lines_circles', 5, 2, 2)
select_contours_xld (ContoursSplit, SelectedContours, 'contour_length', 25, \
                     99999, -0.5, 0.5)
count_obj (SelectedContours, NumberContours)
gen_empty_obj (Circles)
for i := 1 to NumberContours by 1
    select_obj (SelectedContours, ObjectSelected, i)
    get_contour_global_attrib_xld (ObjectSelected, 'cont_approx', Attrib)
    if (Attrib == 1)
        concat_obj (Circles, ObjectSelected, Circles)
    endif
endfor
union_cocircular_contours_xld (Circles, UnionContours, rad(60), rad(10), \
                               rad(30), 100, 50, 10, 'true', 1)
```

The edges obtained by `edges_sub_pix` are segmented into linear and circular segments by `segment_contours_xld`. Because more contours exist than needed for the circle extraction, only the contours having a minimum contour length are selected by `select_contours_xld`. For these, it is checked if they are circular, i.e., the value for `'cont_approx'` is queried by `get_contour_global_attrib_xld` and if it is `1` the contour is stored in the tuple `Circles`. Now, all circular contours that lie approximately on the same circle (i.e., they are cocircular) are merged by `union_cocircular_contours_xld` (see figure 4.20, right). These contours are now used for the circle fitting.

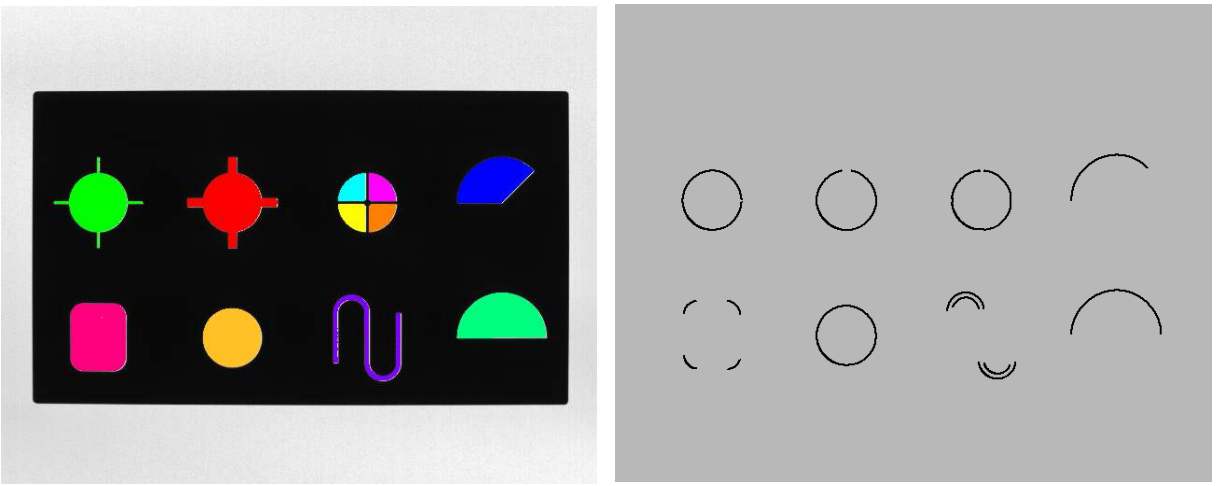

Figure 4.20: Circle fitting: (left) original image overlaid by the extracted regions, (right) circular contours selected for the circle fitting.

Step 3: Fit circles to the circular contour segments

```
count_obj (UnionContours, NumberCircles)
for i := 1 to NumberCircles by 1
    select_obj (UnionContours, ObjectSelected, i)
    fit_circle_contour_xld (ObjectSelected, 'algebraic', -1, 0, 0, 3, 2, \
                            Row, Column, Radius, StartPhi, EndPhi, \
                            PointOrder)
    gen_circle_contour_xld (ContCircle, Row, Column, Radius, 0, rad(360), \
                            'positive', 1.5)
    dev_display (ContCircle)
endfor
```

For the circle fitting, the operator `fit_circle_contour_xld` is applied to each contour. It returns, amongst others, the center and radius of the circle that fits best to the contour. The corresponding circle is generated with the operator `gen_circle_contour_xld`, which then can be displayed or processed further. Figure 4.19 shows the extracted contours overlaid by their best-fitting circles as well as information about their radii.

4.11 Get Deviation of a Contour from a Circle

The HDevelop program %HALCONEXAMPLES%\solution_guide\2d_measuring\measure_pump.hdev shows a second example for the extraction of circles in an image. Here, not only the radius of a best-fitting circle must be found for a contour, but also the deviation of the contour from the circle.

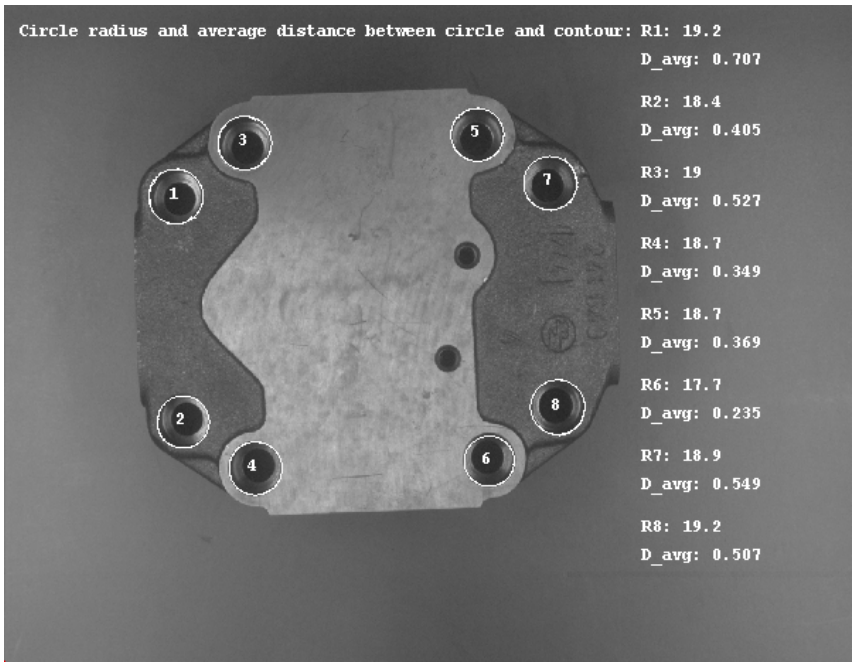

Figure 4.21: Circles are fitted into the circular contours and for each circle the radius and the deviation of the contour from the circle are displayed.

The general steps of the program comprise

- the creation of an ROI,
- the extraction of circular contour segments,
- the fitting of circles into the circular contour segments, and
- the calculation of the average distance between a circular contour segment and the corresponding fitted circle.

Step 1: Create ROI

```
fast_threshold (Image, Region, 0, 70, 150)
connection (Region, ConnectedRegions)
select_shape (ConnectedRegions, SelectedRegions, ['outer_radius', \
              'anisometry','area'], 'and', [5,1,100], [50,1.8,99999])
shape_trans (SelectedRegions, RegionTrans, 'outer_circle')
dilation_circle (RegionTrans, RegionDilation, 5.5)
union1 (RegionDilation, RegionUnion)
reduce_domain (Image, RegionUnion, ImageReduced)
```

The approach, like others before, starts with the creation of a suitable ROI. To do so, fast_threshold is applied, the connected regions are separated by connection, shapes with a certain outer radius, anisometry, and area are selected using select_shape, and the regions are transformed into their outer circles by shape_trans. These circles are enlarged by dilation_circle, the regions are merged into a single region by union1, and the image is reduced to the obtained region (reduce_domain). The reduced image builds the search space for the contour processing.

Step 2: Extract circular contour segments

```
threshold_sub_pix (ImageReduced, Border, 80)
select_shape_xld (Border, SelectedXLD, ['contlength','outer_radius'], 'and', \
                  [70,15], [99999,99999])
segment_contours_xld (SelectedXLD, ContoursSplit, 'lines_circles', 4, 2, 2)
select_shape_xld (ContoursSplit, SelectedXLD3, ['outer_radius', \
                 'contlength'], 'and', [15,30], [45,99999])
union_cocircular_contours_xld (SelectedXLD3, UnionContours2, 0.5, 0.1, 0.2, \
                               2, 10, 10, 'true', 1)
sort_contours_xld (UnionContours2, SortedContours, 'upper_left', 'true', \
                   'column')
```

Contours are created using the operator `threshold_sub_pix`. To select the relevant contours from the obtained set of contours, the operator `select_shape_xld` is applied, searching for contours of a specific length and with a certain outer radius. The relevant contours are then segmented into lines and circles with `segment_contours_xld`. From the segments, again contours with a specific contour length and outer radius are selected. Cocircular contours are merged by `union_cocircular_contours_xld` (see figure 4.22) and finally the contours are sorted by `sort_contours_xld`.

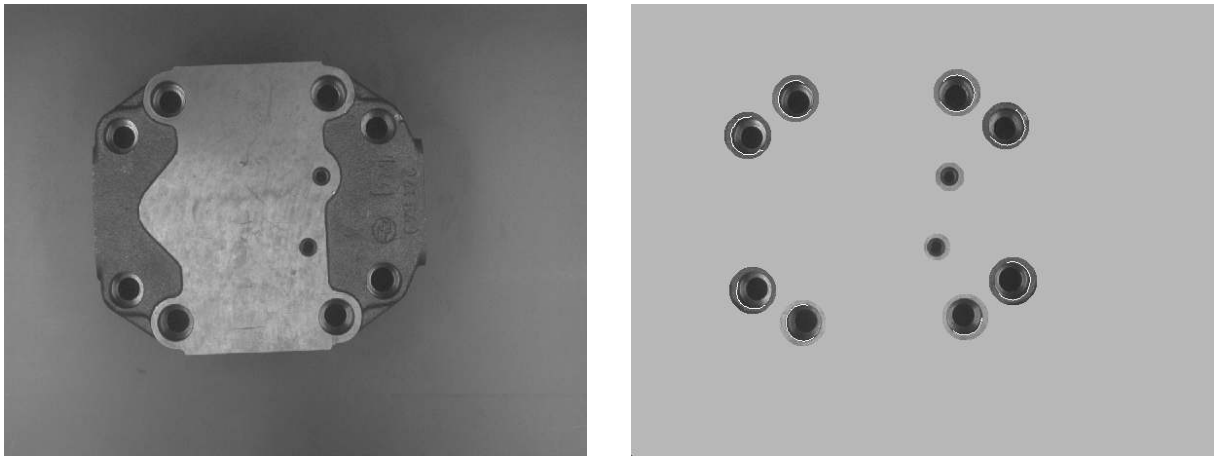

Figure 4.22: ROI for circle fitting: (left) original image of a pump, (right) ROI and extracted circular contours.

Step 3: Fit circles to the circular contour segments

```
count_obj (SortedContours, NumSegments)
for i := 1 to NumSegments by 1
    select_obj (SortedContours, SingleSegment, i)
    NumCircles := NumCircles + 1
    fit_circle_contour_xld (SingleSegment, 'atukey', -1, 2, 0, 5, 2, Row, \
                            Column, Radius, StartPhi, EndPhi, PointOrder)
    gen_circle_contour_xld (ContCircle, Row, Column, Radius, 0, rad(360), \
                            'positive', 1)
```

Since the final contours are all circular, the best fitting circle is calculated for each contour by `fit_circle_contour_xld`. If also linear contours were contained in the set of contours, you would have to extract the circular segments first, like in the example in section 4.10 on page 52. The best fitting circles are now generated by `gen_circle_contour_xld`.

Step 4: Calculate the deviation of the circular contour segments from the fitted circles

```
    dist_ellipse_contour_xld (SingleSegment, 'algebraic', -1, 0, Row, \
                              Column, 0, Radius, Radius, MinDist, MaxDist, \
                              AvgDist, SigmaDist)
endfor
```

To get the deviation of the contour from the generated ellipses (or circles in this case), the operator dist_ellipse_contour_xld is applied. Be aware that only the deviation between the fitted circle and the contour segment used for the fitting is calculated. The quality of the fitting in relation to the real circle also depends on the coverage of the circle by the contour segment. For the circle with the index 6 in figure 4.21, e.g., less than half of the circle was covered by the contour segment (see figure 4.22, right). Thus, despite the good result for the deviation between contour segment and fitted circle, the result is less satisfying in an optical inspection than for the other circles that have a larger deviation but a bigger coverage.

4.12 Inspect Ball Grid Array (BGA)

Another application with circular objects is the inspection of a ball grid array (BGA). A BGA consists of very small objects, which have an approximately symmetrical gray value distribution, and for which the transition area between fore- and background can be rather large compared to the region of the object. Because the standard region or contour-based approaches work with hard transitions (see figure 4.23), for symmetric objects with a large transition area it is recommended to extract object features with an approach that considers the gray value features instead. Available operators comprise area_center_gray, which is used to check the gray value volume and center position of each ball, and elliptic_axis_gray, which returns the length of the axes and the orientation of the ellipse having the same orientation and aspect ratio as the input region.

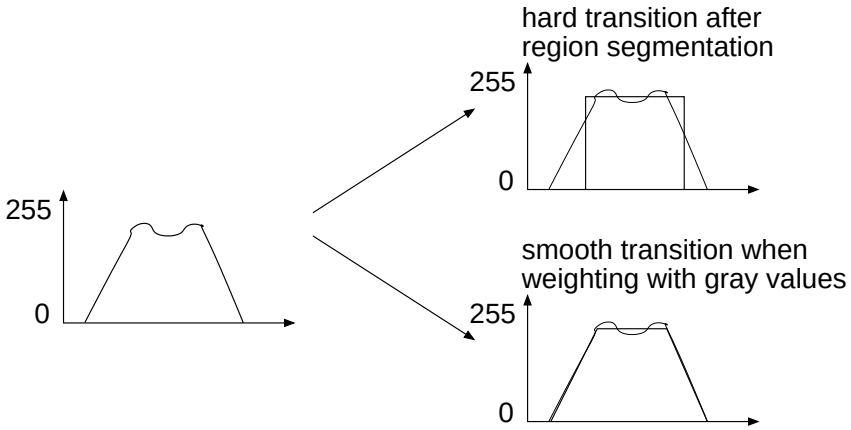

Figure 4.23: Weighting with gray values leads to smooth transitions, opposite to the hard transition of a standard region segmentation.

The HDevelop program %HALCONEXAMPLES%\solution_guide\2d_measuring\inspect_bga.hdev shows how the balls of a BGA can be checked for deformations and their correct positions in the grid. The latter is realized by comparing them with the balls of a reference BGA.

The general steps of the program comprise

- the extraction of the balls of the reference BGA and the determination of their positions,
- the sorting of the balls of the reference BGA,
- the extraction of the balls in a second BGA and their sorting according to the reference BGA, and
- the inspection of the second BGA, as well as a comparison between the positions of both BGAs.

Step 1: Extract balls in the reference BGA and determine their positions

```
fast_threshold (Image, Region, 95, 255, 3)
connection (Region, ConnectedRegions)
select_shape (ConnectedRegions, SelectedRegions, ['area','anisometry'], \
              'and', [20,1.0], [100,1.7])
dilation_rectangle1 (SelectedRegions, RegionDilation, 3, 3)
area_center_gray (RegionDilation, Image, Volume, Row, Column)
```

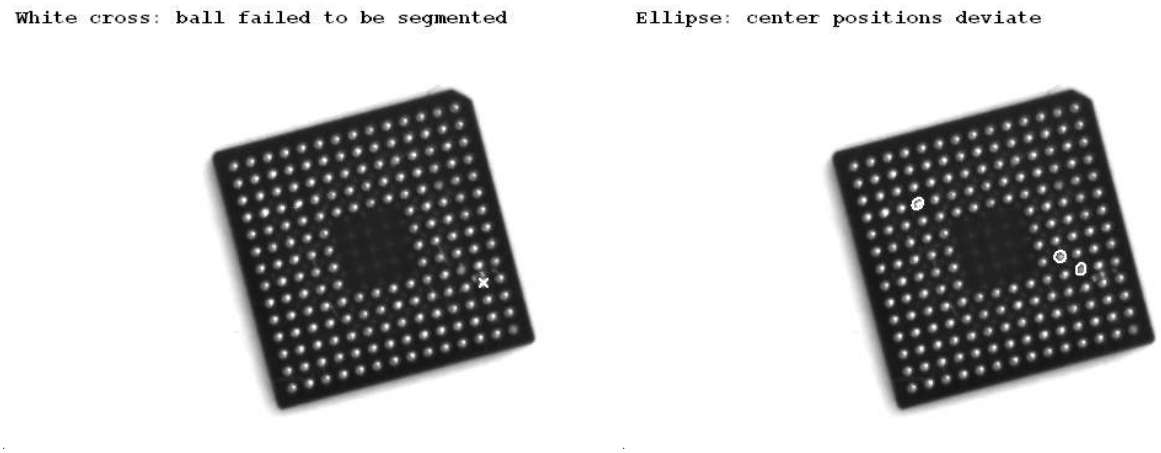

Figure 4.24: Irregularities of a BGA: (left) missing ball marked by a cross, (right) balls with center positions that deviate from the reference positions marked by ellipses.

The program starts with the extraction of the balls from the reference image via a region processing. Often, an additional gray value scaling is recommended, which adapts the gray value distribution according to two thresholds that depend on the fore- and background of the balls. Here, it is not necessary as the gray value distribution for all balls is rather constant. The obtained regions are slightly enlarged and inside each region the operator `area_center_gray` computes the gray value volume, i.e., the sum of the gray values of all pixels of the region, and the position of the region's center of gravity.

Step 2: Sort the balls of the reference BGA

The obtained center positions of the balls (`Row`, `Column`) are returned in an arbitrary order, i.e., the index of a variable does not contain information about the position of the corresponding ball in the grid. To compare the center positions of corresponding balls in different BGAs, a comparable sequence of the balls is needed, i.e., we have to spatially sort the balls. In a first step, we determine their positions in the grid separately for the rows and columns. To do so, we normalize the BGA as follows: We apply `gen_region_points` to create a region described by the center points of the balls and use its enclosing rectangle (obtained by `smallest_rectangle2`, see figure 4.25, left) to define a transformation matrix.

```
gen_region_points (RegionBGACenters, Row, Column)
smallest_rectangle2 (RegionBGACenters, RowBGARect, ColumnBGARect, \
                     PhiBGARect, Length1BGARect, Length2BGARect)
BallsPerRow := 14
BallsPerCol := 14
BallDistCol := 2 * Length1BGARect / (BallsPerCol - 1)
BallDistRow := 2 * Length2BGARect / (BallsPerRow - 1)
hom_mat2d_identity (HomMat2DIdentity)
hom_mat2d_rotate (HomMat2DIdentity, -PhiBGARect, RowBGARect, ColumnBGARect, \
                  HomMat2DRotate)
hom_mat2d_translate (HomMat2DRotate, -RowBGARect + Length2BGARect, \
                     -ColumnBGARect + Length1BGARect, HomMat2DTranslate)
hom_mat2d_scale (HomMat2DTranslate, 1 / BallDistRow, 1 / BallDistCol, 0, 0, \
                 HomMat2DScale)
affine_trans_point_2d (HomMat2DScale, Row, Column, RowNormalized, \
                       ColNormalized)
BGARowIndex := round(RowNormalized)
BGAColIndex := round(ColNormalized)
```

With it, we transform the balls so that the grid becomes horizontal, the center position of the ball in the upper left corner is placed in the origin of the coordinate system, and the distance between the individual balls becomes 1. The rounded values for the transformed ball positions then describe the indices of the ball's positions separately for the rows and columns of a regular grid. Figure 4.25, right, shows the normalized grid, which is scaled again for visualization purposes.

Instead of separate lists for the rows and columns, we want to obtain a single sorted list of indices, which is ordered consecutively from left to right and from top to bottom. Therefore, we create a tuple that has the capacity for all

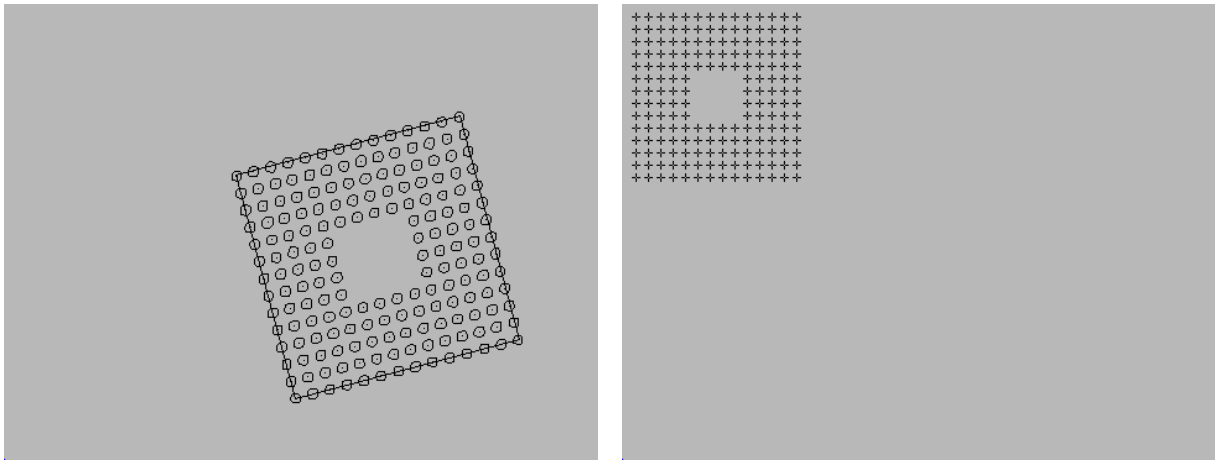

Figure 4.25: Normalization of the grid for the reference BGA: (left) smallest rectangle enclosing the region that is built by the center points of the balls, (right) transformed and normalized grid (scaled for visualization purposes).

grid points of the BGA (`BallMatrix`), i.e., its size is defined by the maximum numbers of balls per row and column. Because the actual balls of the BGA are not placed all over this grid, we first assign the start value `-1` to all instances. Now, with the help of the indices that we have obtained separately for the rows and columns of the extracted balls (`BGARowIndex`, `BGAColIndex`), we sort the balls by assigning new values to the corresponding instances of `BallMatrix`. After the sorting, the value of `BallMatrix` with the index of a point coordinate in the sorted grid returns either the index of the corresponding point coordinate in the unsorted grid (see figure 4.26), or the value `-1` if the grid position is not occupied by a ball.

```
NumBalls := |Row|
BallMatrix := gen_tuple_const(BallsPerRow * BallsPerCol,-1)
for i := 0 to NumBalls - 1 by 1
    BallMatrix[BGARowIndex[i] * BallsPerCol + BGAColIndex[i]] := i
endfor
```

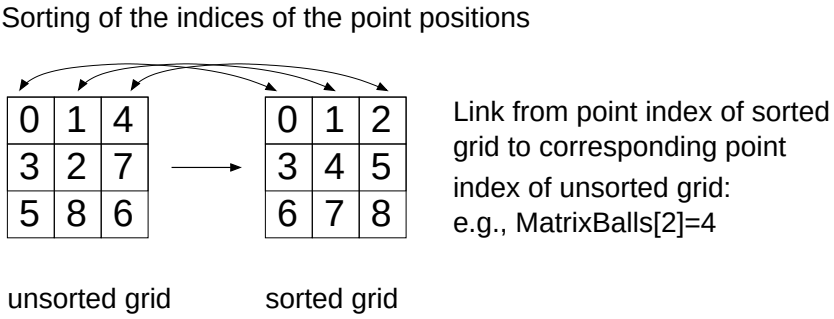

Figure 4.26: Sorting of the point indices.

Step 3: Extract balls in a second BGA and sort them according to the reference

```
elliptic_axis_gray (RegionDilation, Image, RaCheck, RbCheck, PhiCheck)
AnisometryCheck := RaCheck / RbCheck
```

Now, a second image is processed, which contains the BGA we want to check for irregularities. Again, the regions of the balls are extracted and slightly enlarged via a region processing. The operators `area_center_gray` and `elliptic_axis_gray` are applied to get the features of the regions under consideration of their gray values. The latter operator returns the radii and orientation of the ellipse having the same moments as the region. The center points obtained by `area_center_gray` are transformed (see figure 4.27) and sorted like the center points of the reference image. Except for the additional application of `elliptic_axis_gray` and an anisometry check, which are both needed to investigate the balls in a later step, the processing is the same as for the reference BGA.

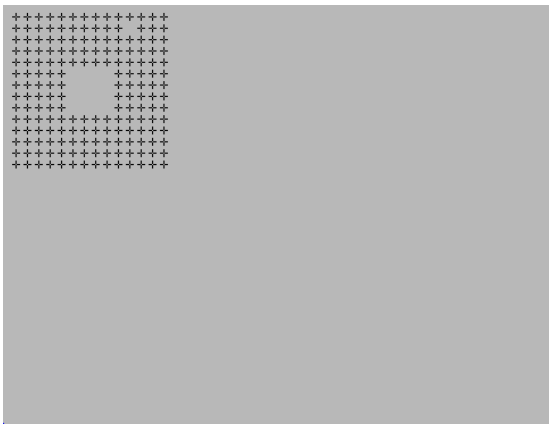

Figure 4.27: Transformed and normalized grid of the BGA to be checked (scaled for visualization purposes).

Step 4: Inspect the second BGA and compare it to the reference BGA

```
j := 0
for i := 0 to BallsPerRow * BallsPerCol - 1 by 1
    if (BallMatrix[i] >= 0 and BallMatrixCheck[i] >= 0)
        Rows1[j] := Row[BallMatrix[i]]
        Cols1[j] := Column[BallMatrix[i]]
        Rows2[j] := RowCheck[BallMatrixCheck[i]]
        Cols2[j] := ColumnCheck[BallMatrixCheck[i]]
        Phi2[j] := PhiCheck[BallMatrixCheck[i]]
        Ra2[j] := RaCheck[BallMatrixCheck[i]]
        Rb2[j] := RbCheck[BallMatrixCheck[i]]
        Anisometry2[j] := AnisometryCheck[BallMatrixCheck[i]]
        Volume2[j] := VolumeCheck[BallMatrixCheck[i]]
        j := j + 1
    endif
endfor
```

Then, the BGA of the second image is evaluated further. Until now, we have only links from the point indices in the sorted grid to the point indices in the unsorted grid. Now, we create tuples that contain the actual data of the existing balls in the specified order. In particular, tuples for the row and column coordinates of the balls in the reference BGA (`Rows1`, `Cols1`) and in the BGA to be checked (`Rows2`, `Cols2`), as well as for the ellipse radii (`Ra2`, `Rb2`), anisometry values (`Anisometry2`), and the gray value volumes (`Volume2`) of the second BGA are created. These tuples are reduced sets of data as they contain only the data for the grid positions that are occupied by balls in both BGAs, i.e., the size of the tuples is related to the actual number of extracted balls in the second image and not to the number of possible grid positions.

To compare the center positions of the balls of the second BGA with the center positions of the balls of the reference BGA, we superimpose both (reduced) sets of positions, i.e., we transform the balls of the reference BGA so that they have the same position, orientation, and scale as the corresponding balls of the BGA to be checked. For the superimposition, the operator `vector_to_rigid` determines the affine 2D transformation by the point correspondences between both sets of coordinates. With the obtained transformation matrix the reduced set of positions for the reference BGA (`Rows1`, `Cols1`) is transformed into `RowTrans` and `ColumnTrans`. To check also for missing balls in the second BGA, we further transform the set of unsorted reference positions originally obtained by `area_center_gray` (`Row`, `Column`), i.e., the set that still contains all positions of the regular grid, including the positions that regularly do not contain balls (marked by the value `-1` in `BallMatrix`) and the positions of the balls that are only detected in the reference BGA.

```
vector_to_rigid (Rows1, Cols1, Rows2, Cols2, HomMat2D)
affine_trans_point_2d (HomMat2D, Rows1, Cols1, RowTrans, ColumnTrans)
affine_trans_point_2d (HomMat2D, Row, Column, RowTransFull, ColumnTransFull)
```

Then, the distance between the sorted points of the BGA to be checked (`Rows2`, `Cols2`) and the sorted and transformed points of the reference BGA (`RowTrans`, `ColumnTrans`) is calculated by `distance_pp`.

```
distance_pp (Rows2, Cols2, RowTrans, ColumnTrans, Distance)
```

Now, the complete grid is investigated again. For each position of the regular grid, the existence of a corresponding ball in both BGAs is checked. If the grid position contains a ball in both sets (both indices are larger than -1), the sorted and reduced sets of data can be used for the comparison. First, the distance between the corresponding center positions is queried. If it is larger than 0.05 pixels, the ellipse for the ball is stored in the tuple `Deviation`. If it is smaller than 0.05 pixels, further features are checked, in particular the anisometry, i.e., the deformation of the circle (ellipse for deformed ball stored in `Deformation`), and the range of the gray value volume (ellipse for outlier stored in `Volume`).

```
j := 0
for i := 0 to BallsPerRow * BallsPerCol - 1 by 1
    if (BallMatrix[i] >= 0 and BallMatrixCheck[i] >= 0)
        gen_ellipse (Ellipse, Rows2[j], Cols2[j], Phi2[j], Ra2[j], Rb2[j])
        if (Distance[j] > 0.05)
            concat_obj (EllipseDeviation, Ellipse, EllipseDeviation)
        else
            if (Anisometry2[j] > 1.2)
                concat_obj (EllipseDeformation, Ellipse, EllipseDeformation)
            else
                if (Volume2[j] < 5500 or Volume2[j] > 10000)
                    concat_obj (EllipseVolume, Ellipse, EllipseVolume)
                else
                    concat_obj (EllipseCorrect, Ellipse, EllipseCorrect)
                endif
            endif
        endif
        j := j + 1
```

If a ball exists in the reference BGA but not in the BGA to be checked, a cross at the ball's position is created (`gen_cross_contour_xld`) and stored in the tuple `Missing`. The different results can then be visualized. In figure 4.24, e.g., the missing balls (left) and the balls with deviating center positions (right) are displayed by a cross or ellipse, respectively.

```
    else
        if (BallMatrix[i] >= 0)
            gen_cross_contour_xld (Cross, RowTransFull[BallMatrix[i]], \
                                   ColumnTransFull[BallMatrix[i]], 10, \
                                   0.785398)
            concat_obj (Missing, Cross, Missing)
        endif
    endif
endfor
```

The operators considering the gray value features are more precise than the corresponding operators for regions or contours. Nevertheless, since their calculation is rather complex, they are only recommended for very small symmetric objects.

4.13 Extract Contours from Color Images

Some features may only be detected when working with color images instead of gray value images, since they have the same gray value but a different color.

When extracting edges or lines from color images, three operators are available. With `edges_color_sub_pix` you can extract subpixel-precise edges directly from your color image. A pixel-precise approach is provided by `edges_color`. For thin linear structures like those described in section 4.5 on page 43, but in a color image, `lines_color` is the suitable operator. It works similar to the approach described for gray value images but with a more limited number of attributes that can be stored with the lines. HDevelop examples for the contour extraction using color are:

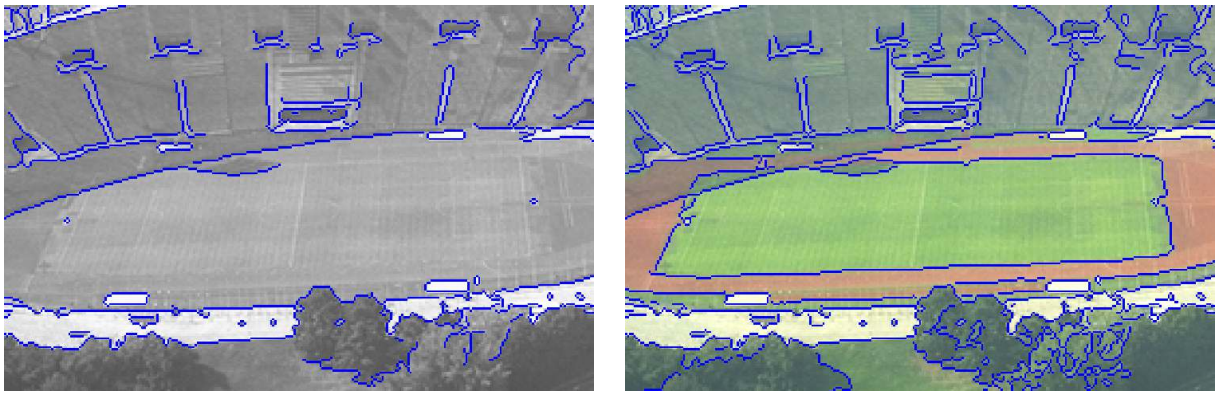

Figure 4.28: A soccer field: (left) the different parts cannot be distinguished in the gray value image, (right) the edges separating the different parts are successfully extracted in the color image.

- `%HALCONEXAMPLES%\hdevelop\Filter\Edges\edges_color_sub_pix.dev` for the subpixel-precise edge extraction using color,
- `%HALCONEXAMPLES%\hdevelop\Filter\Edges\edges_color.dev` for the pixel-precise edge extraction using color (see also description in the Solution Guide I, section 6.1.4.2 on page 63), and
- `%HALCONEXAMPLES%\hdevelop\Filter\Lines\lines_color.dev` for the extraction of thin linear structures using color (see also the description in the Solution Guide I, section 14.3.4 on page 166),

Figure 4.28 shows some results of the second example in the list. A soccer field contains red and green parts in the color image. In the gray value image (left) the red and green parts cannot be distinguished. In the color image (right), the separating edges are successfully extracted using `edges_color`.

After the extraction of the edges, measurements can be applied as described in the previous sections.

Chapter 5

Miscellaneous

The previous sections mainly handled the actual measuring approaches that are common for measuring tasks in machine vision. Several tasks need further processing that is applied in addition to the actual measuring tools:

- If you need to compare parts of similar objects with each other, section 5.1 proposes an approach for the unambiguous identification of the corresponding object parts.
- In many applications, the dimensions of the measured objects must be determined in world coordinates, e.g., in μm. Section 5.2 shortly shows how to measure in world coordinates. There, the applied camera calibration additionally compensates perspective distortions in the image. More detailed information about measuring in world coordinates can be found in the Solution Guide III-C.
- The application of a simple affine 2D transformation, which is needed for various reasons to translate, rotate, or scale an image, a region, or a contour, is shortly described in section 4.1 on page 35.
- When working with a line scan camera, we recommend to read the Solution Guide II-A, section 6.6 on page 39.

5.1 Identify Corresponding Object Parts

In many applications, similar objects must be measured and the results must be compared to the results obtained for a reference image or reference data stored in a Computer Aided Design (CAD) model. In the latter case, you can import ARC/INFO or DXF files via `read_contour_xld_arc_info` or `read_contour_xld_dxf`, respectively. If you wish to create an image containing the CAD model you can create an artificial image by `gen_image_const` and paint the contour of the CAD model into it using `paint_xld`. To identify errors of an object, e.g. a specific drill hole that is missing, the corresponding parts of the measured object and the reference object must be clearly identified. The HDevelop program `%HALCONEXAMPLES%\solution_guide\2d_measuring\measure_metal_part_id.hdev` measures the drill holes of metal parts. The first image is used as reference image. The program detects missing drill holes as well as drill holes that deviate more than 2 pixels in their center position or radius from the corresponding drill holes of the part in the reference image.

The general steps of the program comprise

- the alignment (here, the rotation into a defined orientation) of the object,
- the measurements in the image coordinate system,
- the creation of an object coordinate system,
- the transformation of the measurement results into the object coordinate system,
- the storage of the reference data, and
- the comparison of the results for other images to the reference data.

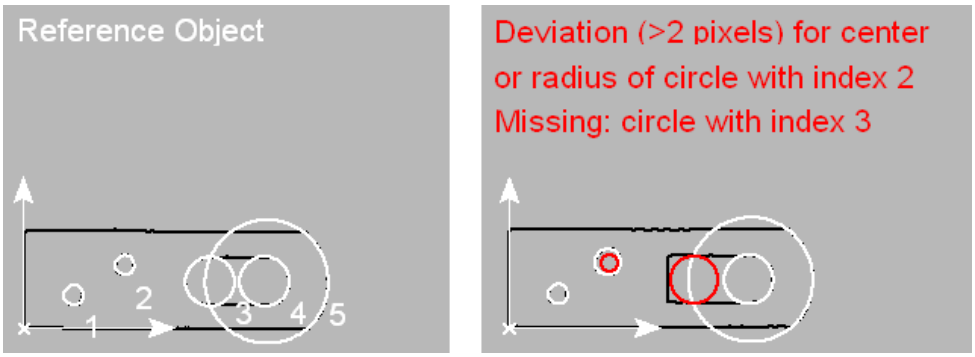

Figure 5.1: Compare parts of two similar objects: (left) reference object with indices of the parts, (right) object to inspect, deviations marked.

Step 1: Extract and rotate contours to get a horizontal object

```
threshold (Image, Region, 90, 255)
dilation_rectangle1 (Region, RegionDilation, 10, 10)
reduce_domain (Image, RegionDilation, ImageReduced)
```

For each image, an ROI for the following contour processing is created. To do so, the region of the object is obtained with `threshold`, the region is enlarged with `dilation_rectangle1`, and the image is reduced to this region by `reduce_domain`. Inside the ROI, `threshold_sub_pix` is applied to extract the contours of the metal part's boundary.

```
threshold_sub_pix (ImageReduced, Edges, 75)
```

The metal parts can be arbitrarily positioned and oriented in the image. Thus, we rotate their contours, so that every metal part is horizontal when being inspected. To realize the rotation, for each image the orientation and center position of the object's region are obtained by `orientation_region` and `area_center`. These are used to create a transformation matrix (`vector_angle_to_rigid`) and the transformation matrix is used for the affine 2D transformation that rotates the contours (`affine_trans_contour_xld`).

```
orientation_region (Region, OrientationRegion)
area_center (Region, Area, RowCenter, ColumnCenter)
vector_angle_to_rigid (RowCenter, ColumnCenter, OrientationRegion, \
                       RowCenter, ColumnCenter, 0, HomMat2DRotate)
affine_trans_contour_xld (Edges, ContoursAffineTrans, HomMat2DRotate)
```

Step 2: Measure

```
segment_contours_xld (ContoursAffineTrans, ContoursSplit, \
                      'lines_circles', 6, 4, 4)
sort_contours_xld (ContoursSplit, SortedContours, 'upper_left', 'true', \
                   'column')
```

The rotated contours of each metal part are segmented into lines and circles, which are sorted according to their spatial position. The sorting of the segments is important to have the circles of the images to measure and the circles of the reference image in the same sequence. The sorted contours are now used to find the best-fitting lines and circles for the segments (see also, e.g., section 4.10 on page 52).

```
for I := 1 to NumberSegments by 1
    select_obj (SortedContours, ObjectSelected, I)
    get_contour_global_attrib_xld (ObjectSelected, 'cont_approx', \
                                   Attrib)
    if (Attrib == 1)
        fit_circle_contour_xld (ObjectSelected, 'algebraic', -1, 0, 0, \
                                3, 2, Row, Column, Radius, StartPhi, \
                                EndPhi, PointOrder)
        gen_circle_contour_xld (ContCircle, Row, Column, Radius, \
                                StartPhi, EndPhi, PointOrder, 1.5)
        RowsE := [RowsE,Row]
        ColsE := [ColsE,Column]
        RadiiE := [RadiiE,Radius]
        dev_display (ContCircle)
    else
        fit_line_contour_xld (ObjectSelected, 'tukey', -1, 0, 5, 2, \
                              RowBegin, ColBegin, RowEnd, ColEnd, Nr, \
                              Nc, Dist)
        gen_contour_polygon_xld (Line, [RowBegin,RowEnd], [ColBegin, \
                                 ColEnd])
        concat_obj (Lines, Line, Lines)
    endif
endfor
```

The circle data is the actual feature we want to obtain for each image and which we want to compare to the results of the reference image.

Step 3: Create object coordinate system

```
select_contours_xld (Lines, LinesVertical, 'direction', rad(88), \
                     rad(92), 0, 0)
count_obj (LinesVertical, NumberLV)
select_contours_xld (Lines, LinesHorizontal, 'direction', rad(-2), \
                     rad(2), 0, 0)
count_obj (LinesHorizontal, NumberLH)
```

The lines are now used to create an object coordinate system with the lower left corner of the horizontal metal part as origin. The axes are built by the vertical line on the left border and the horizontal line at the lower border of the metal part. To determine the coordinates of the origin in the image coordinate system, both lines are intersected similar to the approach used in section 4.6 on page 44. To do so, first all horizontal and vertical lines are separated by selecting the lines with a specific direction.

Whereas the example in section 4.6 on page 44 intersected all vertical lines with all horizontal lines, here only the two lines needed as coordinate axes for the object coordinate system are intersected. Thus, we first determine the row and column coordinates of the endpoints belonging to the vertical line with the lowest column coordinate.

```
ColVmin := 0
RowHmax := 0
for I := 1 to NumberLV by 1
    select_obj (LinesVertical, SelectedV, I)
    get_contour_xld (SelectedV, RowV, ColV)
    if (I == 1)
        ColVmin := ColV[0]
        RowA1 := RowV[0]
        ColA1 := ColV[0]
        RowA2 := RowV[1]
        ColA2 := ColV[1]
    else
        if (ColV[0] < ColVmin)
            ColVmin := ColV[0]
            RowA1 := RowV[0]
            ColA1 := ColV[0]
            RowA2 := RowV[1]
            ColA2 := ColV[1]
        endif
    endif
endfor
```

Then, we determine the row and column coordinates of the horizontal line with the highest row coordinate (in the image coordinate system).

```
for J := 1 to NumberLH by 1
    select_obj (LinesHorizontal, SelectedH, J)
    get_contour_xld (SelectedH, RowH, ColH)
    if (RowH[0] > RowHmax)
        RowHmax := RowH[0]
        RowB1 := RowH[0]
        ColB1 := ColH[0]
        RowB2 := RowH[1]
        ColB2 := ColH[1]
    endif
endfor
```

The intersection is done via the operator `intersection_lines` and results in the point coordinates `Row0` and `Col0`, i.e., the origin of the object coordinate system.

```
intersection_lines (RowA1, ColA1, RowA2, ColA2, RowB1, ColB1, RowB2, \
                    ColB2, Row0, Col0, IsOverlapping)
```

Step 4: Transform results into the object coordinate system

```
hom_mat2d_identity (HomMat2DIdentityResults)
hom_mat2d_slant (HomMat2DIdentityResults, rad(180), 'x', 0, 0, \
                 HomMat2DSlantResults)
hom_mat2d_translate (HomMat2DSlantResults, Row0, -Col0, \
                     HomMat2DTranslateResults)
affine_trans_pixel (HomMat2DTranslateResults, RowsE, ColsE, RowsELocal, \
                    ColsELocal)
```

To transform the already obtained center points of the fitted circles from the image coordinate system into the object coordinate system, we create a transformation matrix. Because the coordinates of the image coordinate system are seen from left to right and from top to bottom, and we want the local coordinate system seen from left to right but from bottom to top, we horizontally mirror the coordinate system by adding a slant of 180° to the transformation matrix using the operator `hom_mat2d_slant`. Because the local coordinate system is parallel to the image coordinate system, no rotation is necessary, but we add a translation by `hom_mat2d_translate` so that `Row0` and `Col0` describe the new origin. The final affine 2D transformation is now applied to the positions of the circle centers, so that the actual results of the measurement are available in the local coordinate system. The transformation of the results is done via `affine_trans_pixel`.

Step 5: Store the results for the first image as reference

```
RowsELocalRef := RowsELocal
ColsELocalRef := ColsELocal
RadiiERef := RadiiE
NumberRowsERef := |RowsELocal|
```

For the first image, we store the results so that we have them still available as reference when measuring the metal parts of the other images. The circles of the reference image are shown in figure 5.2.



Figure 5.2: Circles fitted to the rotated contours of the reference image.

Step 6: Compare the results for other images to the reference image

```
ID_Deviation := []
ID_Missing := []
NumberRowsE := |RowsE|
if (NumberRowsE == NumberRowsERef)
    distance_pp (RowsELocalRef, ColsELocalRef, RowsELocal, \
                 ColsELocal, DistanceEllipseCenters)
    DiffRadius := abs(RadiiE - RadiiERef)
    for I := 0 to |DistanceEllipseCenters| - 1 by 1
        if (DistanceEllipseCenters[I] > 2 or DiffRadius[I] > 2)
            ID_Deviation := [ID_Deviation,I + 1]
        endif
    endfor
endif
```

For the comparison of the reference image with the image to measure, we first check whether the number of obtained circles is equal. If so, we check for small deviations of the positions or radii between the corresponding circles. To check the deviation, the distance between the center points of the circles are determined by `distance_pp` and the difference between the circle radii is computed. If at least one of them is bigger than 2 pixels, the deviating circles are marked in the image.

If the number of circles in both images are not equal, the sorted circles are compared with each other as shown in the following code. In particular, each result of the image to measure is compared to the result of the reference image having the same index (this is the reason for sorting the segments at the beginning of the contour processing). If the position and the radius allow us to conclude that the circle is the same in both images, i.e., the deviation for both is less than 10 pixels, it is checked for deviations that are larger than 2 pixels. If the deviations of position and radius are larger than 10 pixels, we assume that the circle is not the same. Then, we compare the same circle of the image to measure with the circle of the reference image having the next higher index. This procedure continues until either the corresponding circle is found or all remaining circles of the reference image were checked. Figure 5.3 shows the result for one of the images to measure.

```
if (NumberRowsE < NumberRowsERef)
    J := 0
    for I := 0 to NumberRowsE - 1 by 1
        OK := 0
        while (OK == 0)
            distance_pp (RowsELocalRef[J], ColsELocalRef[J], \
                         RowsELocal[I], ColsELocal[I], Distance)
            DiffRadius := abs(RadiiE[I] - RadiiERef[J])
            if ((Distance < 10) and (DiffRadius < 10))
                if (Distance > 2 or DiffRadius > 2)
                    ID_Deviation := [ID_Deviation,J + 1]
                endif
                OK := 1
            else
                ID_Missing := [ID_Missing,J + 1]
            endif
            if (J == NumberRowsERef - 1)
                OK := 1
            endif
            J := J + 1
        endwhile
    endfor
endif
```

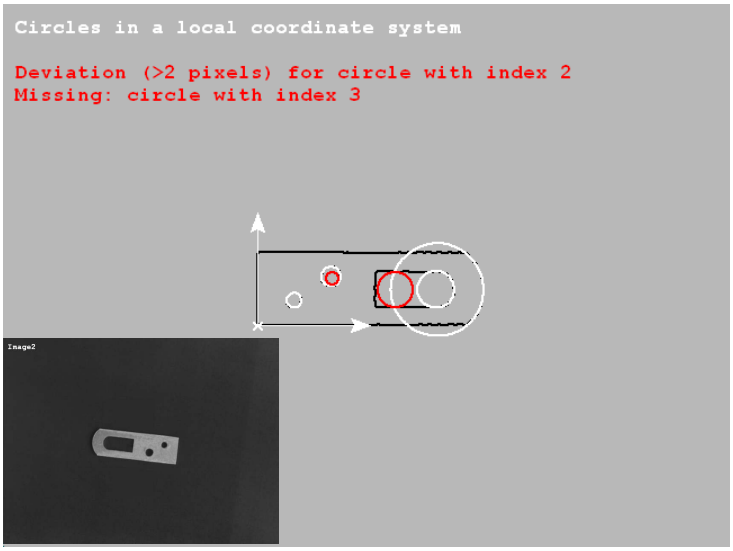

Figure 5.3: Comparison of the circle data to the circle data of a reference image: in image 2, the circle with index 2 deviates more than 2 pixels in its size or position, the circle with index 3 is missing.

5.2 Measure in World Coordinates

In many applications, the dimensions of the measured objects must be determined in world coordinates, e.g., in μm. A second reason for measuring in world coordinates is to compensate radial and perspective distortions. For measuring in world coordinates, a camera calibration must be applied. It results in the exterior camera parameters, i.e., data describing the relation of the camera to the plane in which the 2D measurements are realized. With the obtained data, two kinds of transformations can be applied:

- You can either measure the features of interest in the distorted image and afterwards transform them into the world plane, or
- you use the data to first transform the image and then apply your measurements in the transformed image.

Which approach to choose depends on the basic tools you use for the measuring. If you obtain your measurement results by contour processing, it is recommended to first measure and then transform the resulting points or contours into world coordinates. To do so, after the camera calibration you apply the operators `image_points_to_world_plane` or `contour_to_world_plane_xld`, respectively. For detailed information about how to transform image into world coordinates or vice versa we recommend to read the Solution Guide III-C, section 3.3 on page 75.

If you measure via region processing, the transformation of results can become rather complex, so it is recommended to first transform, i.e., rectify, the image and then measure in the transformed image. For detailed information about rectifying images, we recommend to read the Solution Guide III-C, section 3.4 on page 78.

In the following, we briefly show how to apply a camera calibration, rectify an image that has perspective distortions because of an oblique view, and apply measurements in the rectified image. In particular, the HDevelop example `%HALCONEXAMPLES%\solution_guide\2d_measuring\measure_perspective_scratch.hdev` measures the lengths of scratches on a planar anodized aluminum surface.

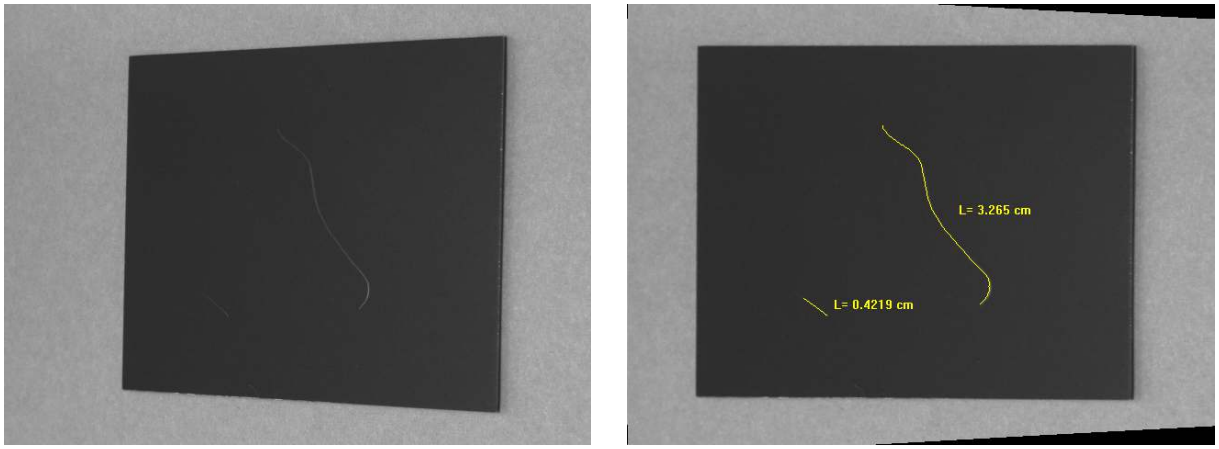

Figure 5.4: Image to measure: (left) original image with perspective distortions, (right) transformed image and the results of the measurement (L=length).

The general steps of the program comprise

- the calibration of the camera,
- the transformation of the image, and
- the measurements in the transformed image.

Step 1: Calibrate the camera

The example starts with the camera calibration (see Solution Guide III-C, section 3.2 on page 59 for details). For this, multiple images are needed, each containing a calibration plate that is placed in a different position and orientation. In one of the calibration images, in this case in the first one, the calibration plate must be placed in the measuring plane, i.e., it must be parallel (with a known distance) to the anodized aluminum plate we want to investigate.

To calibrate the camera, information about the used calibration plate and initial values for the internal camera parameters must be known. The information on the used standard calibration plate, i.e., the positions of the marks inside the calibration plate coordinate system, is stored in the file `'caltab_30mm.descr'`. This and other information is added to a so-called calibration data model.

```
CaltabName := 'caltab_30mm.descr'
gen_cam_par_area_scan_division (0.012, 0, 0.0000055, 0.0000055, Width / 2, \
                                Height / 2, Width, Height, StartCamPar)
create_calib_data ('calibration_object', 1, 1, CalibDataID)
set_calib_data_cam_param (CalibDataID, 0, [], StartCamPar)
set_calib_data_calib_object (CalibDataID, 0, CaltabName)
```

In the program, the images containing calibration plates are read. For each image in the loop, find_calib_object searches for the calibration plate in the image and determines the marks, calculates their 2D positions in the image, and estimates the pose of the calibration plate. The contours and point coordinates of the marks are accessed from the calibration data model with get_calib_data_observ_contours and get_calib_data_observ_points, respectively.

```
for I := 1 to NumImages by 1
    read_image (Image, 'scratch/scratch_calib_' + I$'02d')
    find_calib_object (Image, CalibDataID, 0, 0, I, [], [])
    get_calib_data_observ_contours (Caltab, CalibDataID, 'caltab', 0, 0, I)
    get_calib_data_observ_points (CalibDataID, 0, 0, I, RCoord, CCoord, \
                                  Index, StartPose)
endfor
```

With the obtained data of the calibration plates, the operator calibrate_cameras determines the internal and external camera parameters, which are then queried using get_calib_data.

```
calibrate_cameras (CalibDataID, Error)
get_calib_data (CalibDataID, 'camera', 0, 'params', CamParam)
get_calib_data (CalibDataID, 'calib_obj_pose', [0,1], 'pose', PoseCalib)
```

Step 2: Transform the image

```
tuple_replace (PoseCalib, 5, PoseCalib[5] - 90, PoseCalibRot)
set_origin_pose (PoseCalibRot, -0.04, -0.03, 0.00075, Pose)
```

The pose of the measuring plane, i.e., the external camera parameters obtained for the image in which the calibration plate lies in the measuring plane, is now stored in the variable PoseCalib. Since the calibration plate was rotated by 90° (the black triangular mark normally has to be placed in the upper left corner), we add a rotation to the corresponding parameter of the pose using tuple_replace. Note that poses can be defined by different sequences of translations and rotations (see Solution Guide III-C, section 2.1.5 on page 21). If you are not sure about the sequence used for the pose you want to change, you can also convert the pose to a homogeneous transformation matrix with pose_to_hom_mat3d, explicitly add a local rotation to the axis you want to change using hom_mat_3d_rotate_local, and convert the resulting homogeneous transformation matrix back to a pose using hom_mat3d_to_pose.

Additionally, we apply the operator set_origin_pose to the pose to add a translation to the z-coordinate to compensate for the distance between the calibration pattern and the measuring plane, which is described by the known thickness of the calibration plate. The translations in x- and y- direction are applied mainly so that the rectified image optimally fits the displaying window.

From the corrected pose, the operator pose_to_hom_mat3d creates a homogeneous transformation matrix. This is used by gen_image_to_world_plane_map to generate a projection map that describes the mapping between the image plane and the plane z=0 of a world coordinate system. This map can be used now to transform the images with the operator map_image so that the measuring plane is rectified with a scaling described by PixelDist. Here, we transform two images, one containing the calibration plate that is placed in the measuring plane (see figure 5.5), and the other containing the scratches we want to investigate (see figure 5.4). The first one is transformed mainly for visualization purposes, whereas the latter is the actual image we wanted to obtain. This image (ModelImageMapped) is used now for the actual measurement.

```
PixelDist := 0.00013
pose_to_hom_mat3d (Pose, HomMat3D)
gen_image_to_world_plane_map (Map, CamParam, Pose, Width, Height, Width, \
                              Height, PixelDist, 'bilinear')
Imagefiles := ['scratch/scratch_calib_01','scratch/scratch_perspective']
for I := 1 to 2 by 1
    read_image (Image, Imagefiles[I - 1])
    map_image (Image, Map, ModelImageMapped)
endfor
```

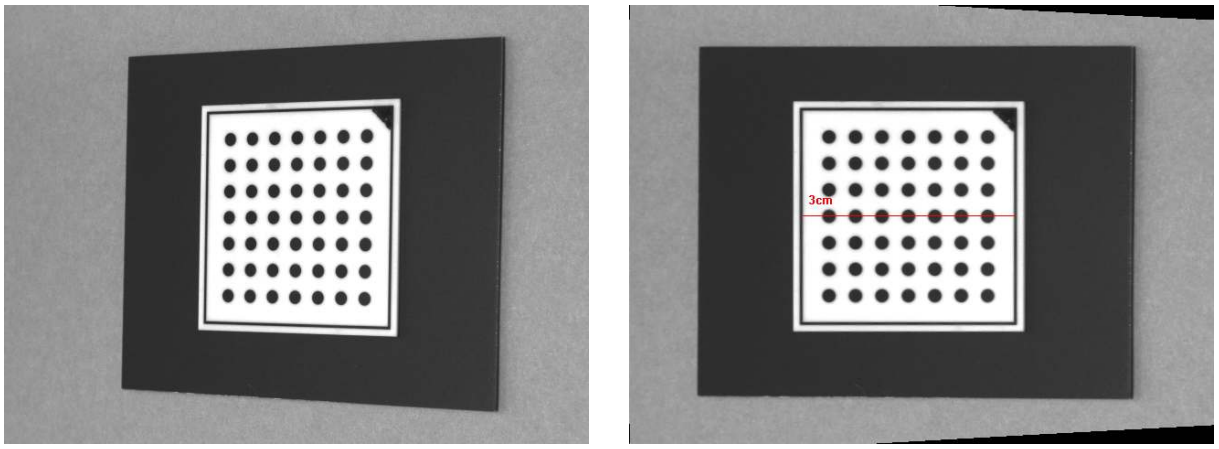

Figure 5.5: Image with the calibration plate in the measuring plane: (left) perspectively distorted image, (right) image after transformation.

Step 3: Measure in the transformed image

```
fast_threshold (ModelImageMapped, Region, 0, 80, 20)
fill_up (Region, RegionFillUp)
erosion_rectangle1 (RegionFillUp, RegionErosion, 5, 5)
reduce_domain (ModelImageMapped, RegionErosion, ImageReduced)
fast_threshold (ImageReduced, Region1, 55, 100, 20)
dilation_circle (Region1, RegionDilation1, 2.0)
erosion_circle (RegionDilation1, RegionErosion1, 1.0)
connection (RegionErosion1, ConnectedRegions)
select_shape (ConnectedRegions, SelectedRegions, ['area','ra'], 'and', [40, \
              15], [2000,1000])
```

The measurement starts with the extraction of the aluminum plate and the following code searches for scratches having a minimum size and extent. For this, a classical region processing is applied as described in section 2.1 on page 11. In particular, the region of the aluminum plate is extracted using `fast_threshold`, `fill_up` fills the remaining holes in the region, and an erosion (`erosion_rectangle1`) suppresses the edges of the border for the later extraction of the scratches. Inside this region, the scratches are extracted by `fast_threshold` and processed by some morphological operators (`dilation_circle` and `erosion_circle`). The obtained region is separated into connected components by `connection` and components with a specific size and extent are selected as scratches.

In a loop, the individual scratches are reduced to their medial axis by `skeleton`. The skeletons are converted into contours by `gen_contours_skeleton_xld` and for each contour, the length (`length_xld`) and center position (`area_center_points_xld`) are obtained like introduced in section 2.2.5 on page 20. The results are visualized in figure 5.4.

```
count_obj (SelectedRegions, NumScratches)
for I := 1 to NumScratches by 1
    select_obj (SelectedRegions, ObjectSelected, I)
    skeleton (ObjectSelected, Skeleton)
    gen_contours_skeleton_xld (Skeleton, Contours, 1, 'filter')
    length_xld (Contours, ContLength)
    area_center_points_xld (Contours, Area, Row, Column)
endfor
```

Index

2D measuring
first example, 35
overview, 7
2D measuring in color image, 60
2D measuring tools, 11
overview, 27
2D measuring with blob analysis, 11
2D measuring with contour processing, 14
2D measuring with geometric operations, 25
2D measuring with template, 63
2D metrology, 21

align image or region for 2D measuring, 35

blob analysis vs. contour processing, 31

combine XLD contours, 17
compute mean of values, 37
compute parallel XLD contours, 42
count objects, 31
create XLD contours, 15

edge extraction (pixel-precise), 15
edge extraction (subpixel-precise), 15
extract features for blob analysis, 14
extract features of XLD contours, 20
extract subpixel edges without smoothing, 38

fit XLD contours to polygons, 42
fit XLD contours to regression line, 39

measure 2D area, 29
measure 2D area with gray-value moments, 56
measure 2D dimensions, 30
measure 2D distance, 30
measure 2D distance between point and contour, 40
measure 2D distance of parallel XLD contours, 41
measure 2D orientation, 29
measure 2D orientation of rectangle, 49
measure 2D orientation with gray-value moments, 56
measure 2D position, 30
measure 2D position of corner points, 47
measure 2D position of grid junctions, 44
measure 2D position of rectangle, 49
measure 2D position with gray-value moments, 56
measure 2D radius of circle, 52
measure 2D size of rectangle, 49
measure 2D width (pixel-precise), 36
measure 2D width of lines, 43
measure angle between 2D lines, 49
measure angle between 2D objects, 29
measure deviation from straight 2D line, 37
measure deviation of XLD contour from 2D circle, 54
measuring and comparison 2D, 7

perform fitting of XLD contours, 19
preprocess image, 12
process regions, 12
process XLD contours, 16

rectify image for 2D measuring, 68

segment image(s) for blob analysis, 12
segment XLD contours, 18
simplify XLD contours, 18
subpixel thresholding, 16
suppress XLD contours, 17

transform results of 2D measuring into 3D (world) coordinates, 68

use region of interest for edge extraction (subpixel-precise), 38

XLD contour coordinates, 40