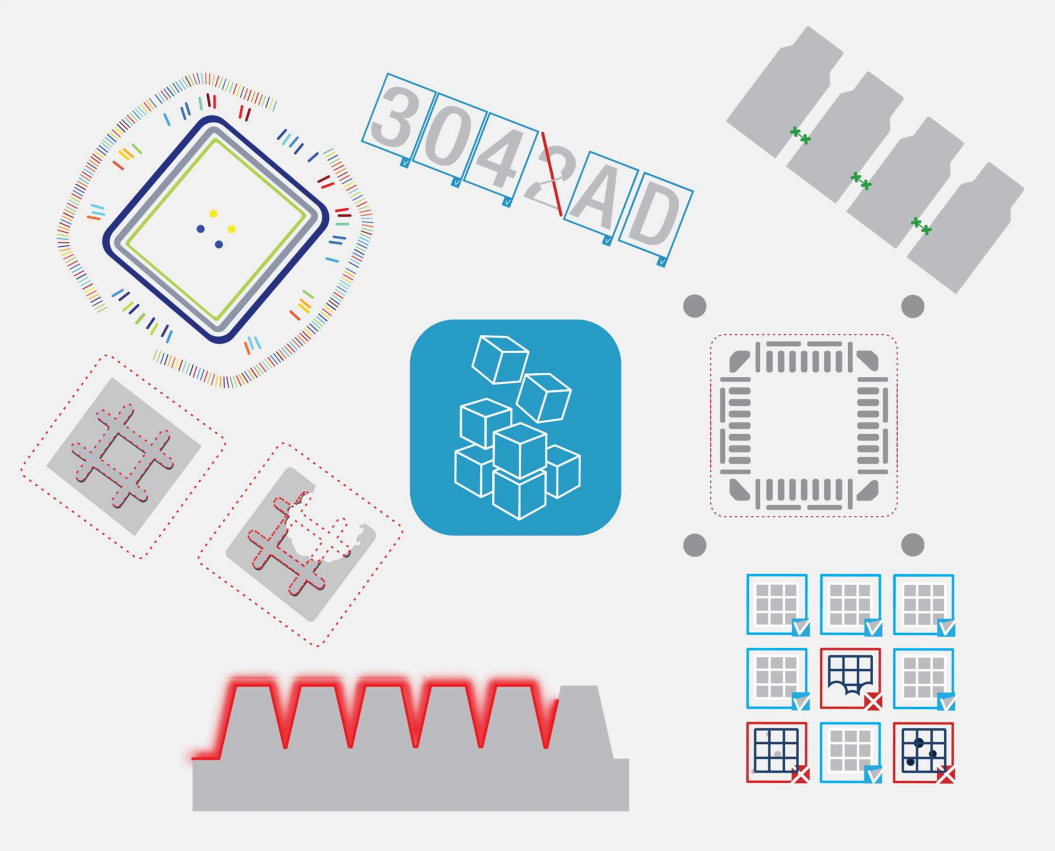
euresys
Empowering Computer Vision

USER GUIDE

Open eVision

3D Processing Tools



This documentation is provided with Open eVision 2.16.1 (doc build 1156).
www.euresys.com

Contents

1. Dealing with Pixel Containers and Files

1.1. Pixel Container Definition

Images

Open eVision image objects contain image data that represents rectangular images.

Each image object has a data buffer, accessible via a pointer, where pixel values are stored contiguously, row by row.

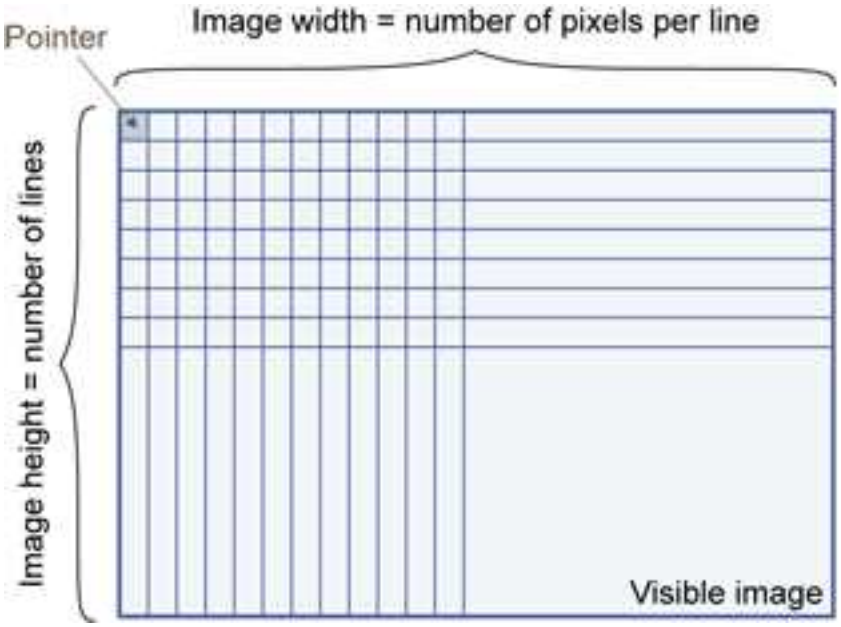


Image main parameters

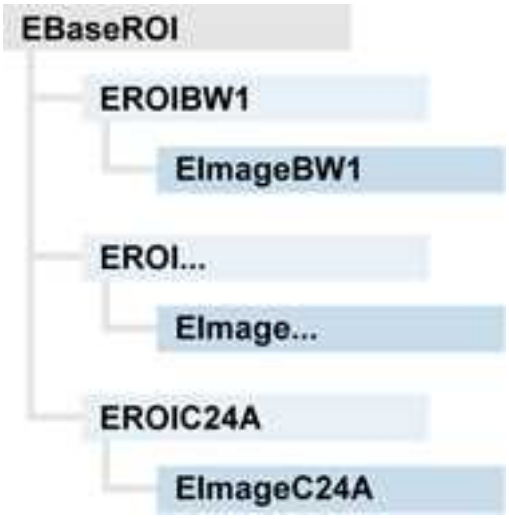
An Open eVision image object has a rectangular array of pixels characterized by `EBaseROI` parameters .

- `Width` is the number of columns (pixels) per row of the image.
- `Height` is the number of rows of the image. (Maximum width / height is 32,767 (2^{15}-1) in Open eVision 32-bit, and 2,147,483,647 (2^{31}-1) in Open eVision 64-bit.)
- `Size` is the width and height.

The `Plane` parameter contains the number of color components. Gray-level images = 1. Color images = 3.

Classes

Image and ROI classes derive from abstract class `EBaseROI` and inherit all its properties.



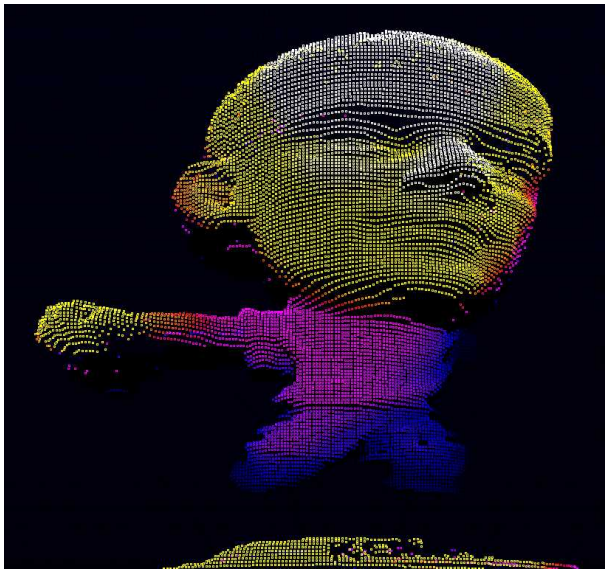
Depth maps

A depth map is a way to represent a 3D object using a 2D grayscale image where each pixel in the image represents a 3D point.

The pixel coordinates are the representation of the X and Y coordinates of the point while the grayscale value of the pixel is a representation of the Z coordinate of the point.

Point clouds

A point cloud (https://en.wikipedia.org/wiki/Point_cloud) is an unstructured set of 3D points representing discrete positions on the surface of an object.



3D point clouds are produced by various 3D scanning techniques, such as Laser Triangulation, Time of Flight or Structured Lighting.

1.2. Pixel Container Types

Reference

Images

Several image types are supported according to their pixel types: black and white, gray levels, color, etc.

Easy.GetBestMatchingImageType returns the best matching image type for a given file on disk.

BW1	1-bit black and white images (8 pixels are stored in 1 byte)	EImageBW1
BW8	8-bit grayscale images (each pixel is stored in 1 byte)	EImageBW8
BW16	16-bit grayscale images (each pixel is stored in 2 bytes)	EImageBW16
BW32	32-bit grayscale images (each pixel is stored in 4 bytes)	EImageBW32
C15	15-bit color images (each pixel is stored in 2 bytes). Compatible with Microsoft® Windows RGB15 color images and MultiCam RGB15 format.	EImageC15

C16	16-bit color images (each pixel is stored in 2 bytes). Compatible with Microsoft® Windows RGB16 color images and MultiCam RGB16 format.	EImageC16
C24	C24 images store 24-bit color images (each pixel is stored in 3 bytes). Compatible with Microsoft® Windows RGB24 color images and MultiCam RGB24 format.	EImageC24
C24A	C24A images store 32-bit color images (each pixel is stored in 4 bytes). Compatible with Microsoft® Windows RGB32 color images and MultiCam RGB32 format.	EImageC24A

Depth Maps

8 and 16-bit depth map values are stored in buffers compatible with the 2D Open eVision images.

EDepth8	8-bit depth map (each pixel is stored in 1 byte as an integer)	EDepthMap8
EDepth16	16-bit depth map (each pixel is stored in 2 bytes as a fixed point)	EDepthMap16
EDepth32f	32-bit depth map (each pixel is stored in 4 bytes as a float)	EDepthMap32f

Point Clouds

Point Cloud	Set of points coordinates (stored as float)	EPointCloud

1.3. Supported Image File Types

Reference

Type	Description
BMP	Uncompressed image data format (Windows Bitmap Format)
JPEG	Lossy data compression standard issued by the Joint Photographic Expert Group registered as ISO/IEC 10918-1. Compression irretrievably loses quality.
JFIF	JPEG File Interchange Format
JPEG-2000	Data compression standard issued by the Joint Photographic Expert Group registered as ISO/IEC 15444-1 and ISO/IEC 15444-2. Open eVision supports only lossy compression format, file format and code stream variants.

Type	Description
	- **code stream** describes the image samples. - **file format** includes meta-information such as image resolution and color space.
PNG	Lossless data compression method (Portable Network Graphics).
Serialized	Euresys proprietary image file format obtained from the **serialization** of Open eVision image objects.
TIFF	Tag Image File Format is currently controlled by Adobe Systems and uses the LibTIFF third-party library to process images written for 5.0 or 6.0 TIFF specification. File **save** operations are lossless and use CCITT 1D compression for 1-bit binary pixel types and LZW compression for all others. File **load** operations support all TIFF variants listed in the LibTIFF specification.

1.4. Pixel and File Types Compatibility

Depth map to image conversion

For 8- and 16-bit depth maps, the `AsImage()` method returns a compatible image object (respectively `EImageBW8` and `EImageBW16`) that can be used with Open eVision's 2D processing features.

Pixel and file types compatibility

Pixel access

The recommended method to access pixels is to use `SetImagePtr` and `GetImagePtr` to embed the image buffer access in your own code. See also Image Construction and Memory Allocation and Retrieving Pixel Values.

Use of the following methods should be limited because of the overhead incurred by each function call:

Direct access

`EROIBW8::GetPixel` and `SetPixel` methods are implemented in all images and ROI classes to read and write a pixel value at given coordinates. To scan all pixels of an image, you could run a double loop on the X and Y coordinates and use `GetPixel` or `SetPixel` each iteration, but this is not recommended.

TIP
For performance reasons, these accessors should not be used when a significant number of pixels needs to be processed. When that is the case, retrieving the internal buffer pointer using `GetBufferPtr()` and iterating on the pointer is recommended.

Quick Access to BW8 Pixels

In BW8 images, a call to `EBW8PixelAccessor::GetPixel` or `SetPixel` will be faster than a direct `EROIBW8::GetPixel` or `SetPixel`.

Supported structures

- `EBW`, `EBW8`, `EBW32`
- `EC5` (*), `EC6` (*), `EC24` (*)
- `EC24A`
- `EDepth8`, `EDepth6`, `EDepth32f`,

(*) These formats support RGB15 (5-5-5 bit packing), RGB16 (5-6-5 bit packing) and RGB32 (RGB + alpha channel) but they must be converted to/from EC24 using `EasyImage::Convert` before any processing.

NOTE
Transition with versions prior to eVision 6.5 should be seamless: image pixel types were defined using typedef of integral types, pixel values were treated as unsigned numbers and implicit conversion to/from previous types is provided.

Pixel and File Type compatibility during Load or Save operations

Type	BMP	JPEG	JPEG2000	PNG	TIFF	Serialized
BW1	Ok	N/A	N/A	Ok	Ok	Ok
BW8	Ok	Ok	Ok	Ok	Ok	Ok
BW16	N/A	N/A	Ok	Ok	Ok (***)	Ok
BW32	N/A	N/A	N/A	N/A	Ok (***)	Ok
C15	Ok	Ok (**)	Ok (**)	Ok (**)	Ok (**)	Ok
C16	Ok	Ok (**)	Ok (**)	Ok (**)	Ok (**)	Ok
C24	Ok	Ok	Ok	Ok	Ok (**)	Ok
C24A	Ok	N/A	N/A	Ok	N/A	Ok
Depth8	Ok	Ok	Ok	Ok	Ok	Ok

Type	BMP	JPEG	JPEG2000	PNG	TIFF	Serialized
Depth16	N/A	N/A	Ok	Ok	Ok (***)	Ok
Depth32f	N/A	N/A	N/A	N/A	N/A	Ok

N/A: Not supported. An exception occurs if you use the combination.

Ok: Image integrity is preserved with no data loss (apart from JPEG and JPEG2000, lossy compression).

(**) C15 and C16 formats are automatically converted into C24 during the save operation.

(***) BW16 and BW32 are not supported by Baseline TIFF readers.

1.5. Color Types

EISH: Intensity, Saturation, Hue color system.

ELAB: CIE Lightness, a*, b* color system.

ELCH: Lightness, Chroma, Hue color system.

ELSH: Lightness, Saturation, Hue color system.

ELUV: CIE Lightness, u*, v* color system.

ERGB: NTSC/PAL/SMPTE Red, Green, Blue color system.

EVSH: Value, Saturation, Hue color system.

EXYZ: CIE XYZ color system.

EYIQ: CCIR Luma, Inphase, Quadrature color system.

EYSH: CCIR Luma, Saturation, Hue color system.

EYUV: CCIR Luma, U Chroma, V Chroma color system.

2. Manipulating Pixels Containers and Files

2.1. Pixel Container File Save

Images and depth maps

The `Save` method of an image or the `SaveImage` method of a depth map or a ZMap saves the image data of an image or of a depth map or a ZMap object into a file using two arguments:

- `Path`: path, file name and file name extension.
- `Image File Type`: if omitted, the file name extension is used.

Images bigger than 65,536 (either width or height) must be saved in Open eVision proprietary format.

`Save` throws an exception when:

- The requested image file format is incompatible with the image pixel types
- The Auto file type selection method and the file name extension is not supported

TIP
When saving a 16-bit depth map, the fixed point precision is lost and the pixels are considered as 16-bit integers.

Image file type arguments

Argument	Image File Type
`EImageFileType_Auto`(*)	Automatically determined by the filename extension. See below.
`EImageFileType_Euresys`	Open eVision Serialization.
`EImageFileType_Bmp`	Windows bitmap - BMP
`EImageFileType_Jpeg`	JPEG File Interchange Format - JFIF
`EImageFileType_Jpeg2000`	JPEG 2000 File format/Code Stream -JPEG2000
`EImageFileType_Png`	Portable Network Graphics - PNG
`EImageFileType_Tiff`	Tagged Image File Format - TIFF

(*) Default value.

Assigned image file type if argument is ImageFileType_Auto or missing

File name extension(*)	Automatically assigned image file type
BMP	Windows Bitmap Format
JPEG, JPG	JPEG File Interchange Format - JFIF
JP2	JPEG 2000 file format
J2K, J2C	JPEG 2000 Code Stream
PNG	Portable Network Graphics
TIFF, TIF	Tagged Image File Format

(*) Case-insensitive.

Saving JPEG and JPEG2000 lossy compressions

SaveJpeg and SaveJpeg2K specify the compression quality when saving compressed images. They have two arguments:

- Path: a string of characters including the path, filename, and file name extension.
- Compression quality of the image file, an integer value in range [0: 100].

SaveJpeg saves image data using JPEG File Interchange Format – JFIF.
SaveJpeg2K saves image data using JPEG 2000 File format.

JPEG compression values

JPEG compression	Description
JPEG_DEFAULT_QUALITY (-1)	Default quality (*)
100	Superb image quality, lowest compression factor
75	Good image quality (*)
50	Normal image quality
25	Average image quality
10	Bad Image quality

(*) The default quality corresponds to the good image quality (75).

Representative JPEG 2000 compression quality values

JPEG 2000 compression	Description
-1	Default quality (*)
1	Highest image quality, lowest compression factor
16	Good Image Quality (*) (16:1 rate)
512	Lowest image quality, highest compression factor

(*) The default quality corresponds to the good image quality (16:1 rate).

Saving point clouds

Use the following methods to save a point cloud in a specific format:

- `EPointCloud::Save`: Open eVision proprietary file format.
- `EPointCloud::SaveCSV`: CSV file.
- `EPointCloud::SaveOBJ`: OBJ file.
- `EPointCloud::SavePCD`: PCD file.
- `EPointCloud::SavePLY`: PLY file.
- `EPointCloud::SaveXYZ`: XYZ file.

TIP
The PCD format is supported in ASCII and binary modes.

2.2. Pixel Container File Load

Loading images and depth maps

- Use the `Load` method to load image data into an image object:
  - It has one argument: the **path:** path, filename, and file name extension.
  - File type is determined by the file format.
  - The destination image is automatically resized according to the size of the image on disk.
- The `Load` method throws an exception when:
  - File type identification fails
  - File type is incompatible with pixel type of the image object

TIP
Serialized image files of Open eVision 1.1 and newer are incompatible with serialized image files of previous Open eVision versions.

TIP
When loading a BW16 image (with integer values) in a depth map, the fixed point precision set in the depth map (0 by default) is left unchanged and used.

Loading point clouds

Use the following methods to load a point cloud saved in a specific format:

- `EPointCloud::Load`: Open eVision proprietary file format.
- `EPointCloud::LoadCSV`: CSV file.
- `EPointCloud::LoadOBJ`: OBJ file.
- `EPointCloud::LoadPCD`: PCD file.
- `EPointCloud::LoadPLY`: PLY file.
- `EPointCloud::LoadXYZ`: XYZ file.

TIP
- The PCD format is supported in ASCII and binary modes.
- The PLY is supported only in ASCII mode.

2.3. Memory Allocation

An image can be constructed with an internal or external memory allocation.

Internal memory allocation

The image object dynamically allocates and deallocates a buffer.

- Memory management is transparent.
- When the image size changes, reallocation occurs.
- When an image object is destroyed, the buffer is deallocated.

To declare an image with internal memory allocation:

a. Construct an image object, for instance `EImageBW8`, either with width and height arguments, OR using the `SetSize` function.

b. Access a given pixel. There are several functions that do this. `GetImagePtr` returns a pointer to the first byte of the pixel at the given coordinates.

External memory allocation

The user controls buffer allocation or links a third-party image in the memory buffer to an Open eVision image.

- Image size and buffer address must be specified.
- When an image object is destroyed, the buffer is unaffected.

To declare an image with external memory allocation:

a. Declare an image object, for instance `EImageBW8`.

b. Create a suitably sized and aligned buffer (see Image Buffer).

c. Assign the buffer to the image with `SetImagePtr`.

NOTE
If your buffer rows are not aligned on 4 bytes, you cannot use `SetImagePtr`. In that case, use `InitializeFromUnalignedBuffer` instead.
Please note, however, that this allocates the memory internally and copies the external buffer into the internal one instead of using the external one directly.

2.4. Image and Depth Map Buffer

Image and depth map pixels are stored contiguously, from left to right and from top row to bottom row, in Windows bitmap format (top-down DIB -device-independent bitmap-) into an associated buffer.

The buffer address is a pointer to the start address of the buffer, which contains the top left pixel of the image.

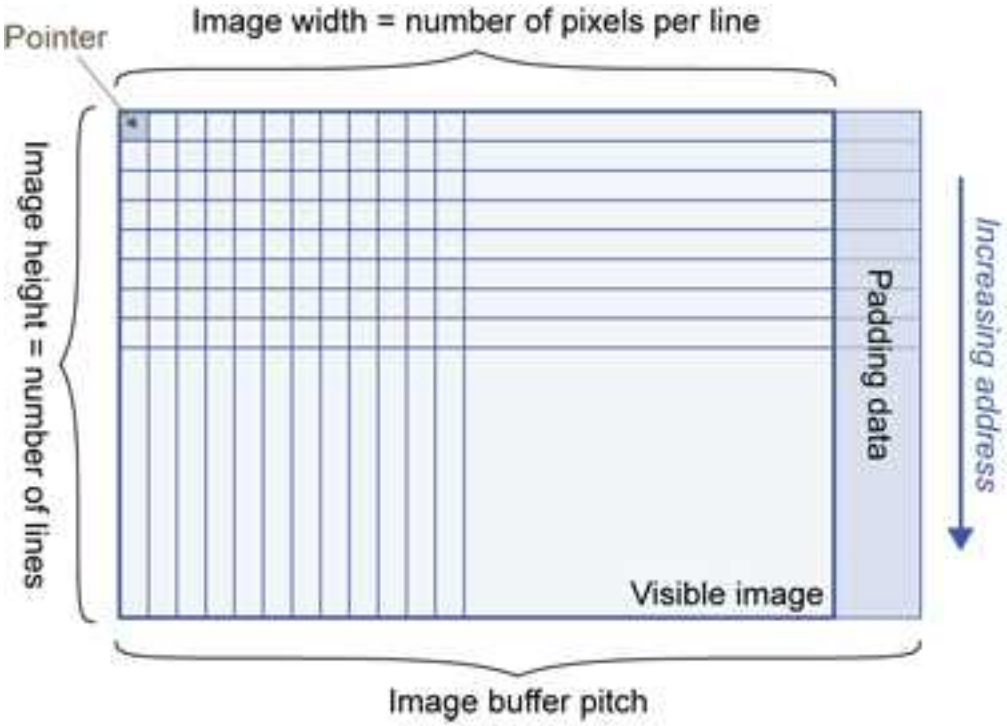


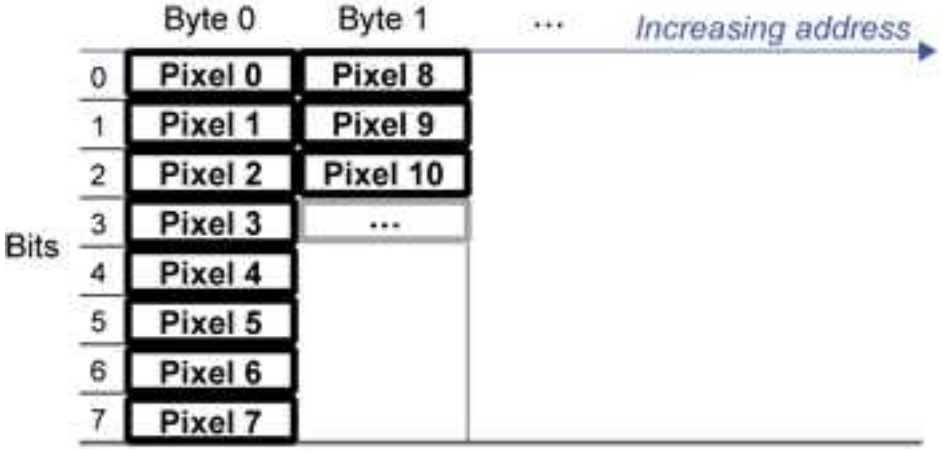
Image buffer pitch

- Alignment must be a multiple of 4 bytes.
- Open eVision 1.2 onwards default pitch is 32 bytes for performance reasons (Open eVision 1.1.5 was 8 bytes).

Memory layout

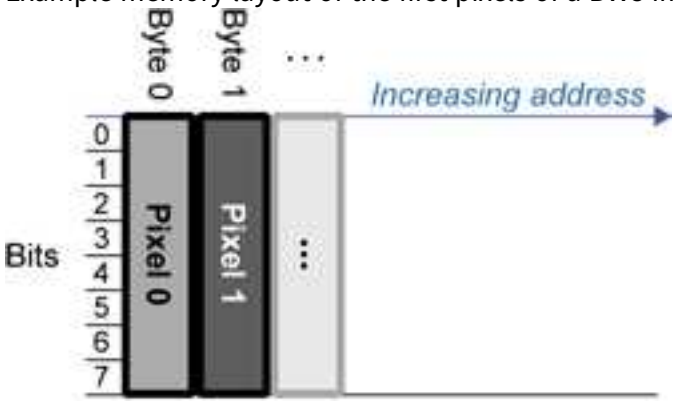
- EImageBW► stores 8 pixels in one byte.

  Example memory layout of the first 2 pixels of a BW1 image buffer:



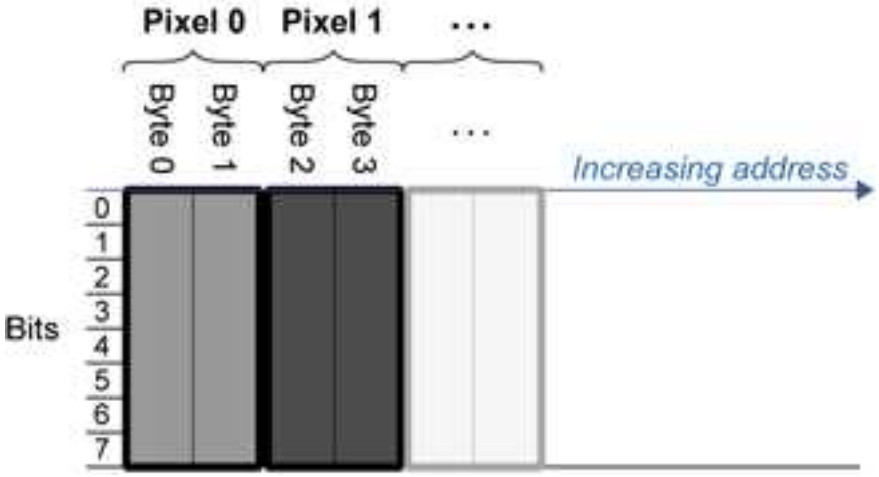
- EImageBW8 and EDepthMap8 store each pixel in one byte.

  Example memory layout of the first pixels of a BW8 image buffer:



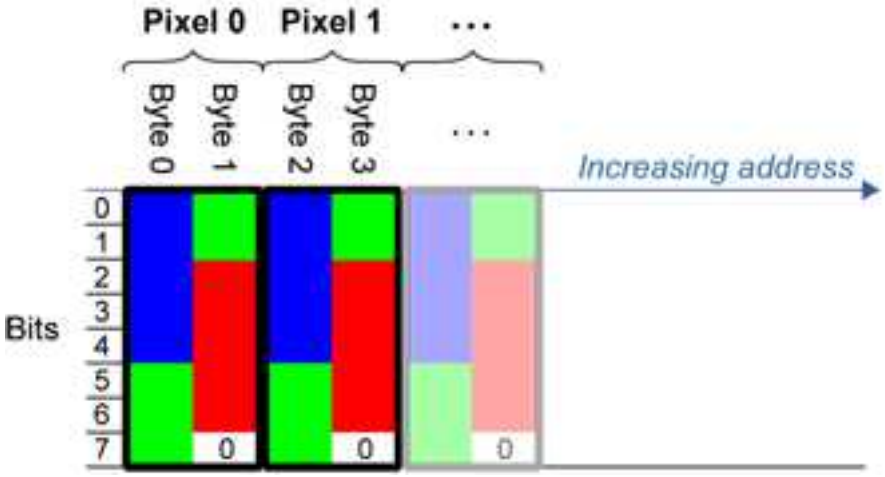
- EImageBW►6 stores each pixel in a 16-bit word (two bytes).

  Example memory layout of the first pixels of a BW16 image buffer:



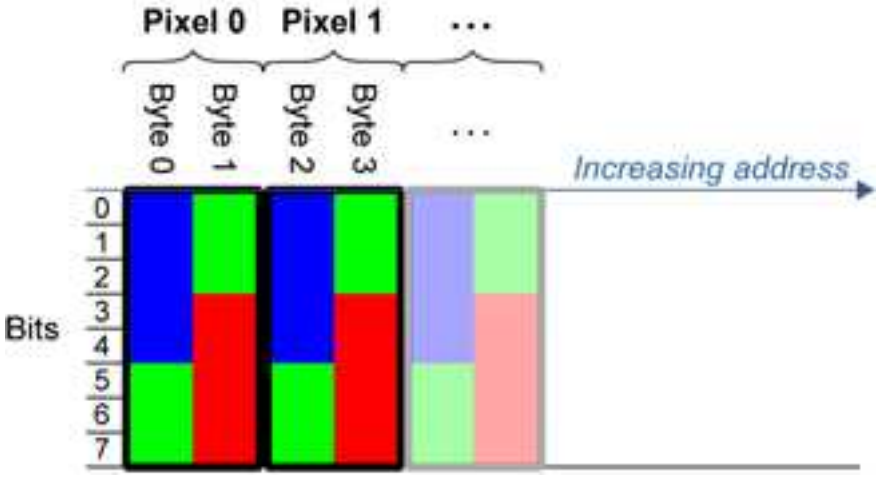
- EImageC►5 stores each pixel in 2 bytes. Each color component is coded with 5-bits. The 16th bit is left unused.

Example memory layout of the first pixels of a C15 image buffer:



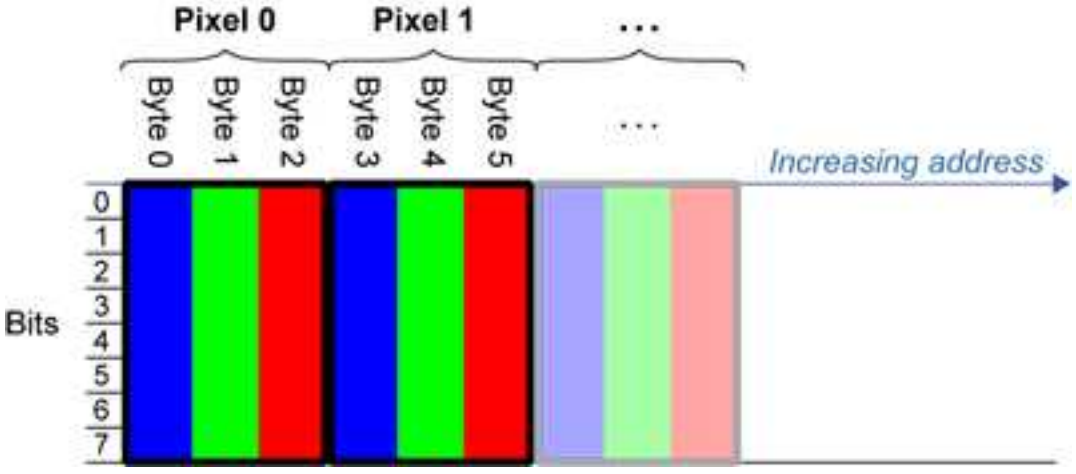
- EImageC►6 stores each pixel in 2 bytes. The first and third color components are coded with 5-bits.
  The second color component is coded with 6-bits.

  Example memory layout of the first pixels of a C16 image buffer:



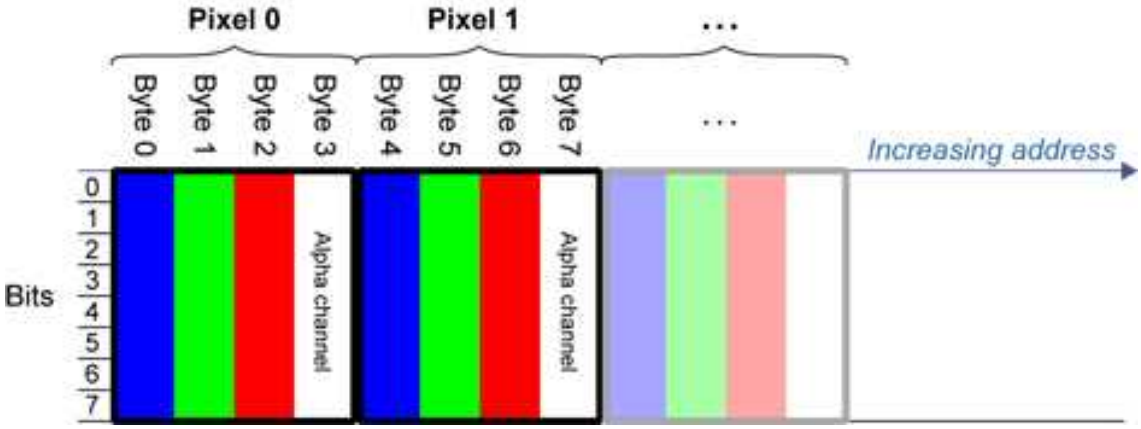
- EDepthMap►6 store each pixel in 2 bytes using a fixed point format.
- EImageC24 stores each pixel in 3 bytes. Each color component is coded with 8-bits.

  Example memory layout of the first pixels of a C24 image buffer:



- `EImageC24A` stores each pixel in 4 bytes. Each color component is coded with 8-bits. The alpha channel is also coded with 8-bits.

  Example memory layout of the first pixels of a C24A image buffer:



- `EDepthMap32f` store each pixel in 4 bytes using a float format.

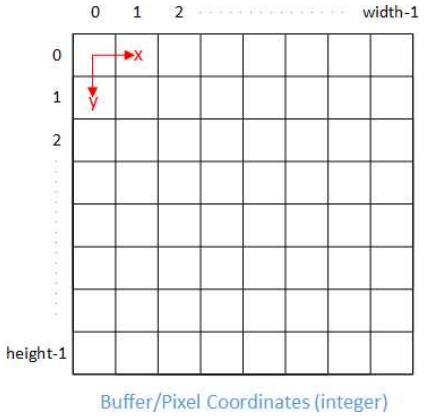
2.5. Image Coordinate Systems

The conventions below apply to all Open eVision functions and results.

- Pixel coordinates are usually given as integer numbers.
- Some results can use subpixel precision with real (floating point) numbers.
- Some exceptions apply and are documented per librarie.

Integer coordinates

- The origin (0,0) of the coordinate system is the upper left pixel of the image.
- The lower right pixel is (width-1, height-1).



Buffer/Pixel Coordinates (integer)

Real coordinates

- With floating point (x,y) coordinates, the origin is the upper left corner of the upper left pixel.
- The first pixel area ranges in [0,1[for X and Y axis.
- Coordinates greater or equal than the width or the height are outside the image.

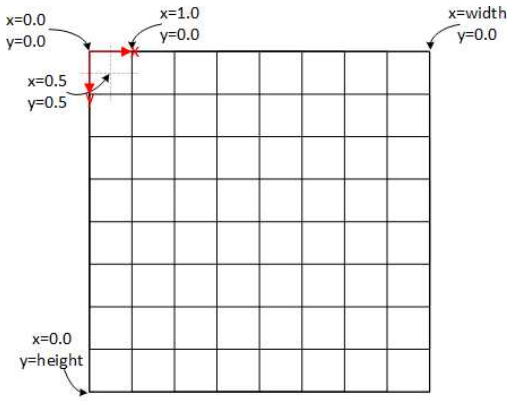


Image Coordinates (float)

2.6. Image Drawing and Overlay

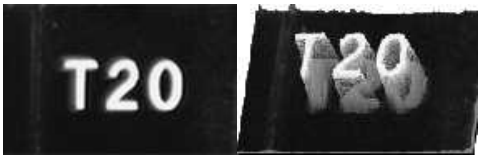
- Drawing uses Windows GDI (Graphics Device Interface) system calls.
  - MFC (Microsoft Foundation Class) applications normally use `OnDraw` event handler to draw, where a pointer to a device context is available.
  - Borland/CodeGear OWL or VCL use a `Paint` event handler.
- The color palette in 256-color display mode gives optimal rendering.
- Gray-level images can be improved using LUTs (LookUp Tables) (using histogram stretching techniques or pseudo-coloring).
- The zoom can be different horizontally and vertically.
- `DrawFrameWithCurrentPen` method draws a frame.
- *Non-destructive overlaying* drawing operations do not alter the image contents, such as `MoveTo`/`LineTo`.
- *Destructive overlaying* drawing operations alter the image contents by drawing inside the image such as `Easy::OpenImageGraphicContext`. Gray-level [color] images can only receive a gray-level [color] overlay.

2.7. 3D Rendering of 2D Images

These images are viewed by rotating them around the X-axis, then the Y-axis.

Gray 3D rendering

`Easy::Render3D` prepares a 3-dimensional rendering where gray-level values are altitudes. Magnification factors in the three directions (X = width, Y = height and Z = depth) can be given. The rendered image appears as independent dots whose size can be adjusted to make the surface more or less opaque.

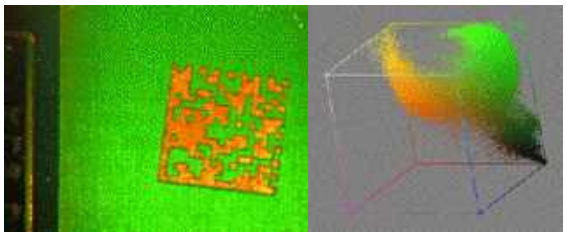


3D rendering

Color histogram 3D rendering

`Easy::RenderColorHistogram` prepares a 3-dimensional rendering of a color image histogram. The pixels are drawn in the RGB space (not XY-plane) to show clustering and dispersion of RGB values.
This function can process pixels in other color systems (using EasyColor to convert), but the raw RGB image is required to display the pixels in their usual colors.

Magnification factors in all three directions (X = red, Y = green and Z = blue) can be given.

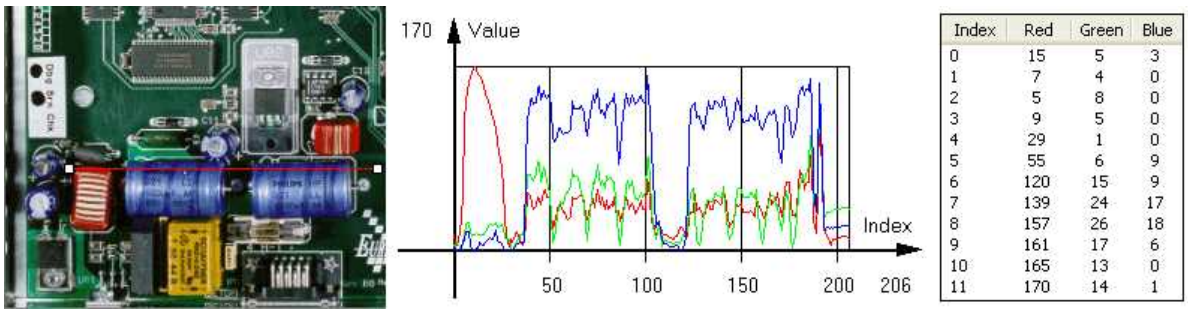


Color histogram rendering

2.8. Vector Types and Main Properties

A vector is a one-dimensional array of pixels (taken from an image profile or contour).

EVector is the base class for all vectors. It contains all non-type-specific methods, mainly for counting elements and serialization.



Index	Red	Green	Blue
0	15	5	3
1	7	4	0
2	5	8	0
3	9	5	0
4	29	1	0
5	55	6	9
6	120	15	9
7	139	24	17
8	157	26	18
9	161	17	6
10	165	13	0
11	170	14	1

Profile in a C24 image, RGB values plot along profile and RGB values array (EC24Vector)

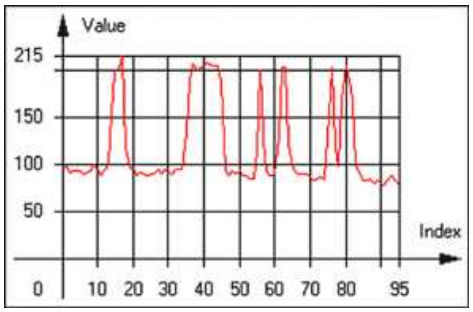
A vector manages an array of elements. Memory allocation is transparent, so vectors can be resized dynamically. Whenever a function uses a vector, the vector type, size and structure are automatically adjusted to suit the function needs.

The use of vectors is quite straightforward:

- To create a vector of the appropriate type:
  - Use its constructor and preallocate elements if required.
- To fill a vector with values:
  - Call the EVector::Empty member to empty it.
  - Call the EC24Vector::AddElement member to add elements one by one.
  - Use the indexing to access any element.
- To access a vector element, either for reading or writing:
  - Use the brackets operator EC24Vector::operator[].
- To determine the current number of elements:
  - Use the EVector::NumElements member.
- To draw the vector:
  - A pixel vector is a plot of the element values as a function of the element index, so its graphical appearance depends on its type. You can draw a vector in a window. For legibility, the drawing should appear on a neutral background.
  - Drawing is done in the device context associated to the desired window. By default, curves are drawn in blue and annotations in black. You can define: graphicContext, width, height, originX, originY, color0, color1 and color2.
  - The EC24Vector has three curves drawn instead of one, each corresponding to a color component. By default the red, blue and green pens are used.

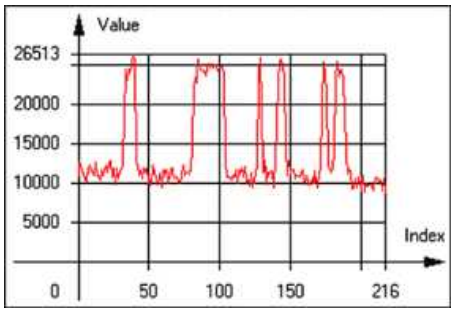
Vector types

- EBW8Vector: a sequence of gray-level pixel values, often extracted from an image profile (used by EasyImage::Lut, EasyImage::SetupEqualize, EasyImage::ImageToLineSegment, EasyImage::LineSegmentToImage, EasyImage::ProfileDerivative...).



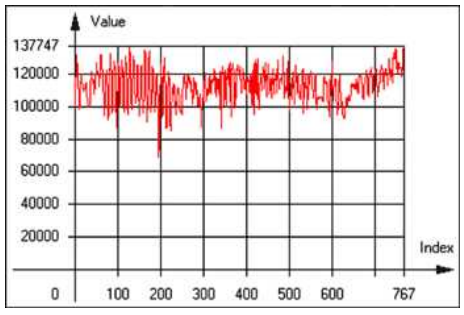
Graphical representation of an EBW8Vector (see Draw method)

- EBW►6Vector: a sequence of gray-level pixel values, using an extended range (16 bits), mainly for intermediate computations.



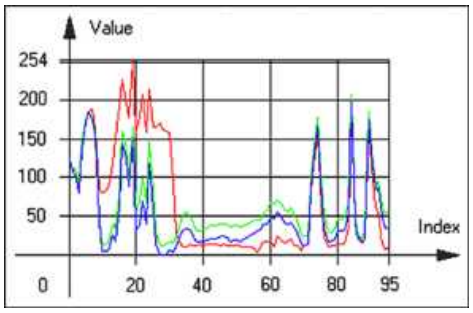
Graphical representation of an EBW►6Vector

- EBW32Vector: a sequence of gray-level pixel values, using an extended range (32 bits), mainly for intermediate computations
(used in EasyImage::ProjectOnARow, EasyImage::ProjectOnAColumn, ...).



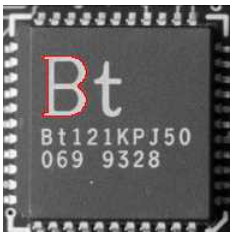
Graphical representation of an EBW32Vector

- EC24Vector: a sequence of color pixel values, often extracted from an image profile (used by EasyImage::ImageToLineSegment, EasyImage::LineSegmentToImage, EasyImage::ProfileDerivative, ...).



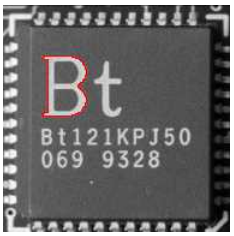
Graphical representation of an EC24Vector

- EBW8PathVector: a sequence of gray-level pixel values, extracted from an image profile or contour, with corresponding pixel coordinates (used by EasyImage::ImageToPath, EasyImage::PathToImage, ...).



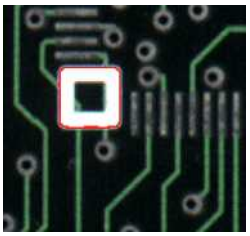
Graphical representation of an EBW8PathVector (see Draw method)

- EBW►6PathVector: a sequence of gray-level pixel values, extracted from an image profile or contour, with corresponding pixel coordinates (used by EasyImage::ImageToPath, EasyImage::PathToImage, ...).



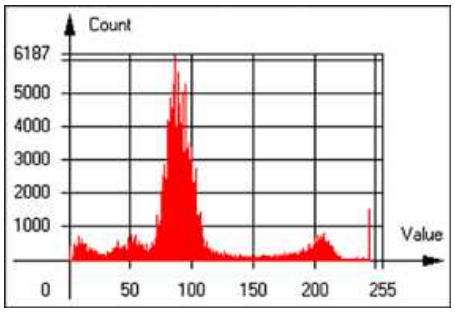
Graphical representation of an EBW►6PathVector (see Draw method)

- EC24PathVector: a sequence of color pixel values, extracted from an image profile or contour, with corresponding pixel coordinates
(used by EasyImage::ImageToPath, EasyImage::PathToImage, ...).



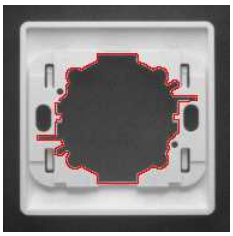
Graphical representation of an EC24PathVector (see Draw method)

- EBWHistogramVector: a sequence of frequency counts of pixels in a BW8 or BW16 image
(used by EasyImage::IsodataThreshold, EasyImage::Histogram, EasyImage::AnalyseHistogram, EasyImage::SetupEqualize, ...).



Graphical representation of an EBWHistogramVector (see Draw method)

- EPathVector: a sequence of pixel coordinates. The corresponding pixels need not be contiguous
(used by EasyImage::PathToImage and EasyImage::Contour).



Graphical representation of an EPathVector (see Draw method)

- EPeakVector: peaks found in an image profile
(used by EasyImage::GetProfilePeaks).
- EColorVector: a description of colors
(used by EasyColor::ClassAverages and EasyColor::ClassVariances).

2.9. ROI Main Properties

ROIs are defined by a width, a height, and **origin** x **and** y **coordinates**.
The origins are specified with respect to the top left corner in the parent image or ROI.
The ROI must be wholly contained in its parent image.
The processing/analysis time of a BW1 ROI is faster if `OrgX` and `Width` are multiples of 8.

Save and load

You can save or load an ROI as a separate image, to be used as if it was a full image. The ROIs perform **no memory allocation** at all and never duplicate parts of their parent image, the parent image provides them with access to its image data.

The image size of the new file must match the size of the ROI being loaded into it. The image around the ROI remains unchanged.

ROI Classes

An Open eVision ROI inherits parameters from the abstract class `EBaseROI`.

There are several ROI types, according to their pixel type. They have the same characteristics as the corresponding image types.

- `EROIBW►`
- `EROIBW8`
- `EROIBW►6`
- `EROIBW32`
- `EROIC►5`
- `EROIC►6`
- `EROIC24`
- `EROIC24A`

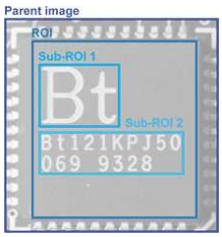
Attachment

An ROI must be `attached` to a parent (image/ROI) with parameters that set the parent, position and size, and these links are updated transparently, avoiding dangling pointers.
A normal image cannot be attached to another image or ROI.

Nesting

Set and Get functions change or query the width, height and position of the origin of an ROI, with respect to its immediate or topmost parent image.

An image may accommodate an arbitrary number of ROIs, which can be nested in a hierarchical way. Moving the ROI also moves the embedded ROIs accordingly. The image/ROI classes provide several methods to traverse the hierarchy of ROIs associated with an image.



Nested ROIs: Two sub-ROIs attached to an ROI, itself attached to the parent image

Cropping

`CropToImage` crops an ROI which is partially out of its image. The resized ROI never grows.
An exception is thrown if a function attempts to use an ROI that has limits that extend outside of the parents.

NOTE
(In Open eVision 1.0.1 and earlier, an ROI was silently resized or repositioned when placed out of its image and sometimes grew. If ROI limits extended outside parents, they were silently resized to remain within parent limits.)

Resizing and moving

ROIs can easily be resized and positioned by two functions and dragging handles:

- `EBaseROI::Drag` adjusts the ROI coordinates while the cursor moves.
- `EBaseROI::HitTest` informs if the cursor is placed over a dragging handle.
  - Once the handle is known, the cursor shape can be changed by an `OnSetCursor` MFC event handler. HitTest is unpredictable if called while dragging is in progress.
  - HitTest can be used in an OnSetCursor MFC event handler to change the cursor shape, or before a dragging operation like OnLButtonDown,
    (or EvSetCursor and EvLButtonDown in Borland/CodeGear's OWL)
    (or FormMouseMove and FormMouseDown in Borland/CodeGear's VCL).

2.10. Arbitrarily Shaped ROI (ERegion)

See also: example: Inspecting Pads Using Regions / code snippets: ERegion

Regions or arbitrarily shaped ROI

You define and use regions of interest (ROI) to restrict the area processed with your vision tool and to reduce and optimize the processing time.

In Open eVision:

- An **ROI** (ERoIxxx class) designates a rectangular region of interest.
- A **region** (ERegion class) designates an arbitrarily shaped ROI. With regions, you can determine precisely which part of the image, down to a single pixel, is used for your processing.

Currently, only the following Open eVision methods support ERegions:

Library	Method
EasyImage	EasyImage::Threshold
	EasyImage::Copy
	EasyImage::ConvolKernel
	EasyImage::ConvolSymmetricKernel
	EasyImage::ConvolLowpass►
	EasyImage::ConvolLowpass2
	EasyImage::ConvolLowpass3
	EasyImage::ConvolUniform
	EasyImage::ConvolGaussian
	EasyImage::ConvolHighpass►
	EasyImage::ConvolHighpass2
	EasyImage::ConvolGradientX
	EasyImage::ConvolGradientY
	EasyImage::ConvolGradient
	EasyImage::ConvolSobelX
	EasyImage::ConvolSobelY
	EasyImage::ConvolSobel
	EasyImage::ConvolPrewittX
	EasyImage::ConvolPrewittY
	EasyImage::ConvolPrewitt
	EasyImage::ConvolRoberts
	EasyImage::ConvolLaplacianX
	EasyImage::ConvolLaplacianY
	EasyImage::ConvolLaplacian8
	EasyImage::DilateBox
	EasyImage::ErodeBox
	EasyImage::OpenBox
	EasyImage::CloseBox
	EasyImage::WhiteTopHatBox
	EasyImage::BlackTopHatBox
	EasyImage::MorphoGradientBox
	EasyImage::ErodeDisk

Library	Method
	EasyImage::DilateDisk
	EasyImage::OpenDisk
	EasyImage::CloseDisk
	EasyImage::WhiteTopHatDisk
	EasyImage::BlackTopHatDisk
	EasyImage::MorphoGradientDisk
	EasyImage::Median
	EasyImage::ScaleRotate
	EasyImage::DoubleThreshold
	EasyImage::Histogram
	EasyImage::Area
	EasyImage::AreaDoubleThreshold
	EasyImage::BinaryMoments
	EasyImage::WeightedMoments
	EasyImage::GravityCenter
	EasyImage::PixelCount
	EasyImage::PixelMax
	EasyImage::PixelMin
	EasyImage::PixelAverage
	EasyImage::PixelStat
	EasyImage::PixelVariance
	EasyImage::PixelStdDev
	EasyImage::PixelCompare
Easy3D	EDepthMapToMeshConverter::Convert
	EDepthMapToPointCloudConverter::Convert
	EStatistics::ComputePixelStatistics
	EStatistics::ComputeStatistics
	E3DObjectExtractor::Extract
	EZMapToPointCloudConverter::Convert
EasyObject	EImageEncoder::Encode
EasyFind	EPatternFinder::Find
	EPatternFinder::Learn
EasyOCR2	EOCR2::Read
	EOCR2::Detect
EasyGauge	EPointGauge::Measure
	ELineGauge::Measure
	ERectangleGauge::Measure
	ECircleGauge::Measure
	EWedgeGauge::Measure
EasyMatch	EMatcher::LearnPattern
	EMatcher::Match
EasyQRCode	EQRCodeReader::SetSearchField
	EQRCodeReader::Read

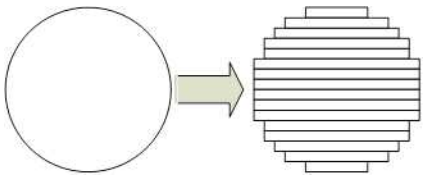
TIP
In the future Open eVision releases, the support of `ERegions` will be gradually extended to all operators.

Creating regions

Open eVision offers multiple ways to create regions, depending on the shape you need:

The ERegion is the base class for all regions and the most versatile. It encodes a region using a Run-Length Encoded (RLE) representation.

- The RLE representation of a region is made of runs (horizontal, 1-pixel high slices).
- The runs are stored in the form of their ordinate, starting abscissa and length.



Run-Length Encoding of a circle-shaped region

To create a region, either:

- Use one of the geometry-based region classes.
- Use the result of another tool, such as EasyFind, EasyMatch or EasyObject.
- Combine or modify other regions.
- Use a mask image.
- Directly provide the list of runs.

Geometry-based regions

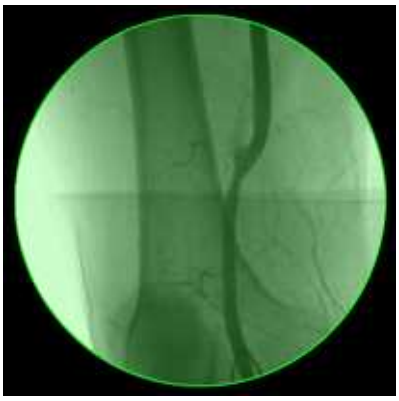
Geometry based regions are specialized classes of regions that are encompassed in simple geometries. Open eVision currently provides classes based on a rectangle, a circle, an ellipse or a polygon.

Use these classes to setup geometric regions and modify them with translation, rotation and scaling. The transformation operators return new regions, leaving the source object unchanged.

- ERectangleRegion
  - The contour of an ERectangleRegion class is a rectangle.
  - Define it using its center, width, height and angle.
  - Alternatively, use an ERectangle instance, such as one returned by an ERectangleGauge instance.

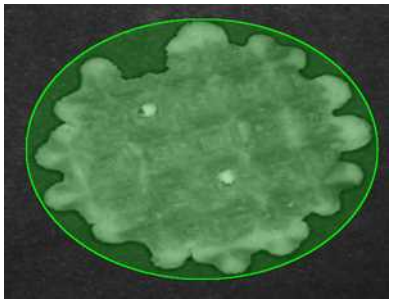
Rectangle region separating a bar code from the background

- `ECircleRegion`
  - The contour of an `ECircleRegion` class is a circle.
  - Define it using its center and radius or 3 non-aligned points.
  - Alternatively, use an `ECircle` instance, such as one returned by an `ECircleGauge` instance.



Circle region encompassing the useful part of an X-Ray image

- `EEllipseRegion`
  - The contour of an `EEllipseRegion` class is an ellipse.
  - Define it using its center, long and short radius and angle.



Ellipse region encompassing a waffle

- `EPolygonRegion`
  - The contour of an `EPolygonRegion` class is a polygon.
  - It is constructed using the list of its vertices.

Polygon region encompassing a key

Using the result of other tools

The `ERegion` class provides a set of specialized constructors to create regions from the results of another tool.

In a tool chain, these constructors restrict the processing of a tool to the area issued from the previous tool.

Open eVision provides constructors for the following tools:

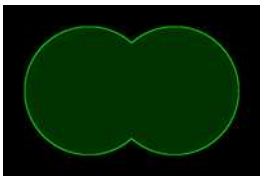
- EasyFind: `EFoundPattern`
- EasyMatch: `EMatchPosition`
- EasyGauge: `ECircle` and `ERectangle`
- EasyObject: `ECodedElement`

> **TIP**
> When compatible, Open eVision also provides specialized constructors for the geometry-based regions. For instance, `ECircleRegion` provides a constructor using an `ECircle`.

Combining regions

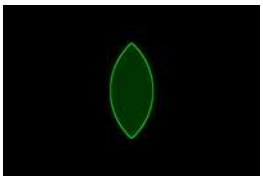
Use the following operations to create a new region by combining existing regions:

- Union
  - The `ERegion::Union(const ERegion&, const ERegion&)` method returns the region that is the addition of the two regions passed as arguments.



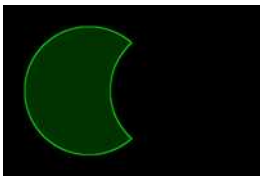
Union of 2 circles

- Intersection
  - The `ERegion::Intersection(const ERegion&, const ERegion&)` method returns the region that is the intersection of the two regions passed as argument.



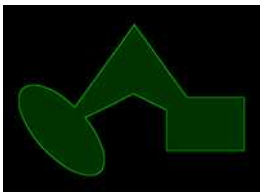
Intersection of 2 circles

- Subtraction
  - The `ERegion::Subtraction(const ERegion&, const ERegion&)` method returns the first region passed as argument after removing the second one.



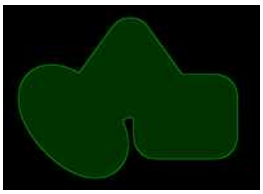
Subtraction of 2 circles

Morphological operations on regions



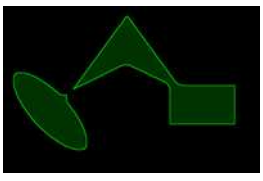
The initial arbitrary region used to illustrate the different morphological operations

- Grow
  - The `ERegion::Grow(int radius)` method returns a region that is the dilation of the region by a disk with a radius equals to the argument.



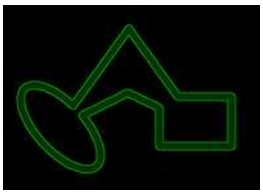
Grow of the arbitrary region

- Shrink
  - The `ERegion::Shrink(int radius)` method returns a region that is the erosion of the region by a disk with a radius equals to the argument.



Shrink of the arbitrary region

- Contour
  - The `ERegion::Contour(int thickness, bool centered = true)` method returns a region that is the contour of the region.



Contour of the arbitrary region

Free-hand drawing a region

- The `ERegionFreeHandPainter` class provides the methods that allow you to create a region by hand, using the mouse or any other user input method.
- The `RegionFreeHand` sample, available both in C++ and C#, shows how to use this class to draw a region on an image.

Using regions

The tools supporting regions provide methods that follow one of these conventions:

- `Method(const EImage& source, const ERegion& region)`
- `Method(const EImage& source, const ERegion& region, EImage& destination)`

> **NOTE**
> The source, the region and the destination must be compatible. It means that the region must at least partly fit in the source, and that source and destination must have the same size.

Preparing the region

- Open eVision automatically prepares the regions when it applies them to an image, but this preparation can take some time.
- If you do not want your first call to a method to take longer than the next ones, you can prepare the region in advance by using the appropriate `Prepare()` method.
- To manually prepare the regions, adapt the internal RLE description to your images.

Drawing regions

The `ERegion` classes provide several methods to display the regions:

- `ERegion::Draw()` draws the region area, in a semi-transparent way, in the provided device context.
- `ERegion::DrawContour()` draws the region contour in the provided device context.

- `ERegion::ToImage()` renders the region as a mask into the provided destination image.
  - You can configure the foreground and the background colors.
  - If you initialized your image with a width and a height, Open eVision renders the region inside those bounds.
  - If not, Open eVision resizes the image to contain the whole region.
  - Use `ToImage()` to create masks for the Open eVision functions that support them.

ERegions and EROIs

- The older `EROI` classes of Open eVision are compatible with the new regions.
- Some tools allow the usage of regions with source and/or destinations that are `ERoi` instead of `EImage` follow one of these conventions:
  - `Method(const ERoi& source, const ERegion& region)`
  - `Method(const ERoi& source, const ERegion& region, ERoi& destination)`

TIP
In that case, the coordinates used for the region are relative to the reduced ROI space instead of the whole image space .

ERegion and 3D

- The new regions are compatible with the 2.5D representations of Easy3D (`EDepthMap` and `EZMap`).
- You can also reduce the domain of processing when using these classes.

2.11. Flexible Masks

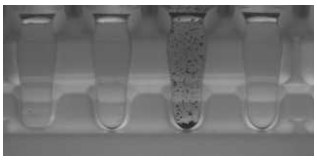
ROIs vs flexible masks

ROIs and masks restrict processing to part of an image:
- "ROI Main Properties" on page 26 apply to all Open eVision functions. Using Regions of Interest accelerates processing by reducing the number of pixels. Open eVision supports hierarchically nested rectangular ROIs.
- Flexible Masks are recommended to process disconnected ROIs or non-rectangular shapes. They are supported by some EasyObject and EasyImage library functions.

Flexible Masks

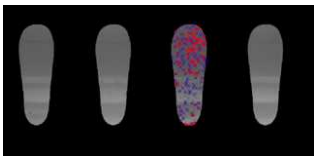
A flexible mask is a BW8 image with the same height and width as the source image. It contains shapes of areas that must be processed and ignored areas (that will not be considered during processing):

- All pixels of the flexible mask having a value of 0 define the ignored areas.
- All pixels of the flexible mask having any other value than 0 define the areas to be processed.



Source image

Associated mask

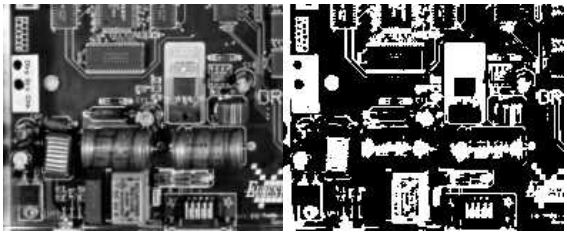


Processed masked image

A flexible mask can be generated by any application that outputs BW8 images and by some EasyObject and EasyImage functions.

Flexible Masks in EasyImage

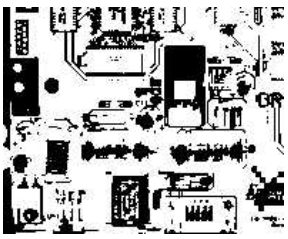
Code Snippets



Source image (left) and mask variable (right)

Simple steps to use flexible masks in Easyimage

1. **Call the functions from EasyImage that take an input mask as an argument**. For instance, one can evaluate the average value of the pixels in the white layer and after in the black layer.
2. **Display the results.**



Resulting image

EasyImage Functions that support flexible masks

- `EImageEncoder::Encode` has a flexible mask argument for BW1, BW8, BW16, and C24 source images.
- AutoThreshold.
- Histogram (function `HistogramThreshold` has no overload with mask argument).
- RmsNoise, SignalNoiseRatio.
- Overlay (no overload with mask argument for BW8 source images).
- ProjectOnAColumn, ProjectOnARow (Vector projection).
- ImageToLineSegment, ImageToPath (Vector profile).

Flexible Masks in EasyObject

A flexible mask can be generated by any application that outputs BW8 images or uses the Open eVision image processing functions.

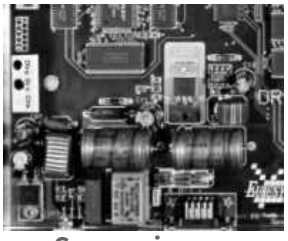
EasyObject can use flexible masks to restrict blob analysis to complex or disconnected shaped regions of the image.

If an object of interest has the same gray level as other regions of the image, you can define "keep" and "ignore" areas using flexible masks and `Encode` functions.

A flexible mask is a BW8 image with the same height and width as the source image.

- A pixel value of 0 in the flexible mask masks the corresponding source image pixel so it doesn't appear in the encoded image.
- Any other pixel value in the flexible mask causes the pixel to be encoded.

EasyObject functions that create flexible masks

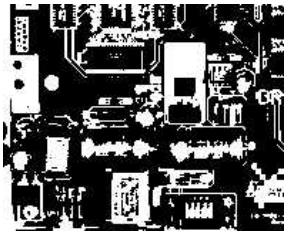


Source image

1) ECodedImage2::RenderMask: from a layer of an encoded image

1. To encode and extract a flexible mask, first construct a coded image from the source image.
2. Choose a segmentation method (for the image above the default method `GrayscaleSingleThreshold` is suitable).
3. Select the layer(s) of the coded image that should be encoded (i.e. white and black layers using minimum residue thresholding).
4. Make the mask image the desired size using `mask.SetSize(sourceImage.GetWidth(), sourceImage.GetHeight())`.

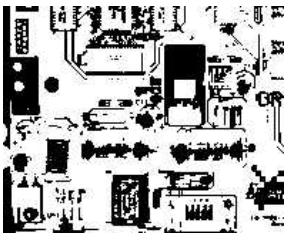
5. Exploit the flexible mask as an argument to `ECodedImage2::RenderMask`.



BW8 resulting image that can be used as a flexible mask

2) ECodedElement::RenderMask: from a blob or hole

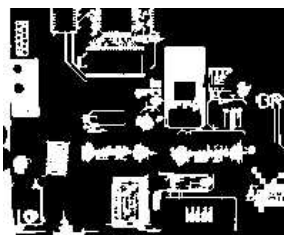
1. Select the coded elements of interest.
2. Create a loop extracting a mask from selected coded elements of the coded image using `ECodedElement::RenderMask`.
3. Optionally, compute the feature value over each of these selected coded elements.



BW8 resulting image that can be used as a flexible mask

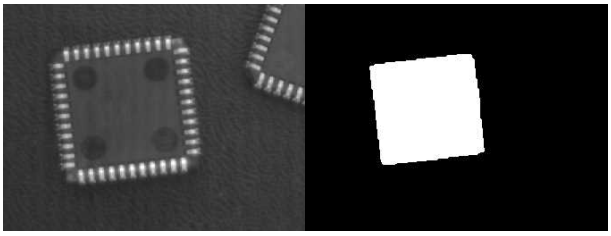
3) EObjectSelection::RenderMask: from a selection of blobs

`EObjectSelection::RenderMask` can, for example, discard small objects resulting from noise.



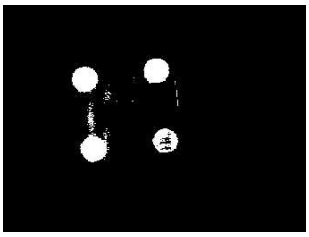
BW8 resulting image that can be used as a flexible mask

Example: Restrict the areas encoded by EasyObject



Find four circles (left) Flexible mask can isolate the central chip (right)

1. Declare a new `ECodedImage2` object.
2. Setup variables: first declare source image and flexible mask, then load them.
3. Declare an `EImageEncoder` object and, if applicable, select the appropriate segmenter. Setup the segmenter and choose the appropriate layer(s) to encode.
4. Encode the source image. Encoding a layer with just the area in the flexible mask is then pretty straightforward.
   We see that the circles are correctly segmented in the black layer with the grayscale single threshold segmenter:



5. Select all objects of the coded image.
6. Select objects of interest by filtering out objects that are too small.
7. Display the blob feature by iterating over the selected objects to display the chosen feature.

2.12. Profile

Code Snippets

Profile Sampling

A **profile** is a series of pixel values sampled along a line/path/contour in an image.

- `EasyImage::ImageToLineSegment` copies the pixel values along a given line segment (arbitrarily oriented and wholly contained within the image) to a vector. The vector length is adjusted automatically. This function supports flexible masks.
- A path is a series of pixel coordinates stored in a vector.
  `EasyImage::ImageToPath` copies the corresponding pixel values to the vector. This function supports flexible masks.

- A **contour** is a closed or not (connected) path, forming the boundary of an object. `EasyImage::Contour` follows the contour of an object, and stores its constituent pixels values inside a profile vector.

Profile Analysis

The profile can be processed to find peaks or transitions:

- A transition corresponds to an object edge (black to white or white to black). It can be detected by taking the first **derivative** of the signal (which transforms transitions (edges) into peaks) and looking for peaks in it.
  `EasyImage::ProfileDerivative` computes the first derivative of a profile extracted from a gray-level image.
  The `EBW8` data type only handles unsigned values, so the derivative is shifted up by 128. Values under [above] 128 correspond to negative [positive] derivative (decreasing [increasing] slope).
- A peak is the portion of the signal that is above [or below] a given threshold - the maximum or minimum of the signal. This may correspond to the crossing of a white or black line or thin feature. It is defined by its:
  - Amplitude: difference between the threshold value and the max [or min] signal value.
  - Area: surface between the signal curve and the horizontal line at the given threshold.

`EasyImage::GetProfilePeaks` detects max and min peaks in a gray-level profile. To eliminate false peaks due to noise, two selection criteria are used. The result is stored in a peaks vector.

Profile Insertion Into an Image

`EasyImage::LineSegmentToImage` copies the pixel values from a vector or constant to the pixels of a given line segment (arbitrarily oriented and wholly contained within the image).

`EasyImage::PathToImage` copies the pixel values from a vector or a constant to the pixels of a given path.

3. 3D Tools

3.1. Easy3D - Using 3D Toolset

Basic Concepts

Easy3D

Easy3D is a set of tools for solving computer vision problems using 3D acquisition and processing. Easy3D supports laser line triangulation for fast and precise acquisition of depth maps.

> **TIP**
> Depth maps are gray scale images where each pixel represents a displacement in the third dimension. Because of the acquisition procedure, they are usually not dimensionally correct. So, while Open eVision 2D image operators are compatible with depth maps, you should not use them for processes requiring precise measurements.

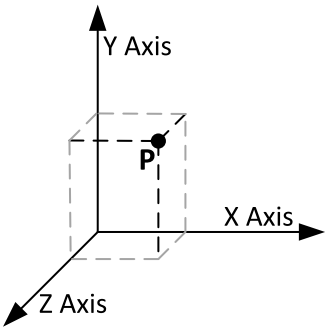
Easy3D provides a calibration tool to generate corrected, metric point clouds and meshes from depth maps. Most 3D operators work on point clouds or meshes. The included export functions to the standard PCD file format allows integration with other 3D tools.

Easy3D also allows the computation of ZMaps. A ZMap is the projection of a point cloud on a given reference plane. Like depth maps, ZMaps are gray scale images, but are also dimensionally correct. As such, they can be used with all Open eVision 2D functions.

All the Easy3D tools are placed in the Easy3D namespace.

3D representation

Open eVision uses a right-handed cartesian 3D coordinate system. In this system, each 3D point is represented by its 3 coordinates X, Y and Z.



Open eVision provides different containers to store 3D objects :

- Depth maps
- Point clouds
- Meshes
- ZMaps

Depth map

A depth map is a way to represent a 3D object using a 2D grayscale image where each pixel (u, v) in the image contains a third coordinate as its gray value.

The grayscale values of a depth map do not necessarily represent a Z metric coordinate. In the context of a laser triangulation setup, these values represent the displacement of the laser line profile, which is not the physical height of the 3D surface.

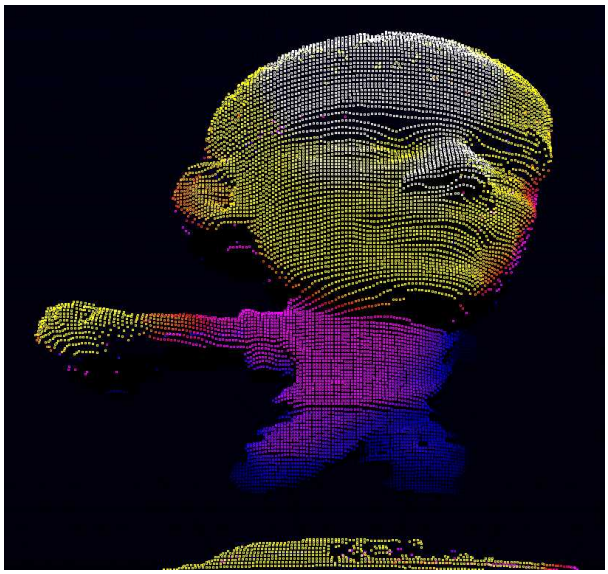
A depth map contains a gray scale image coded on 8, 16 or 32 bits per pixel.

- One specific gray value, called the undefined value, is reserved for the representation of invalid pixels.
- By default, this value is 0 for integer depth map types (EDepthMap8 and EDepthMap16).
- By default, this value is the lowest float value (-3.402823 e+38) for the 32 bits floating point depth map types (EDepthMap32f).

The calibration process aims to convert the depth map representation to real, metric 3D representations such as point clouds or meshes.

Point cloud

A point cloud is a set of 3D points (x, y and z coordinates) representing the scanned object in the world metric space.



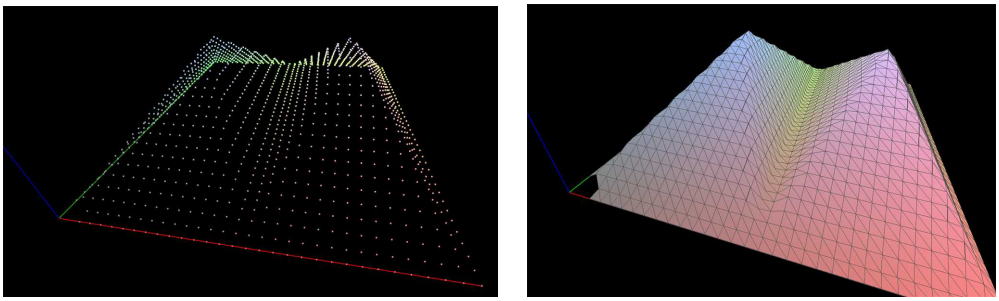
In addition to the calibration process included in Easy3D, point clouds can be produced using various 3D acquisition techniques, like stereo reconstruction or time of flight cameras.

Mesh

A Mesh is a geometric representation of a 3D surface, a set of connected 3D points.

In an `EMesh` object, 3 points are connected to define a triangle.

> **TIP**
> This kind of 3D representation is also called a "triangle mesh".



A point cloud and the corresponding mesh (displayed with Open eVision `E3DViewer`)

An `EMesh` object contains a point cloud and the indexes of the vertices of all mesh triangles.

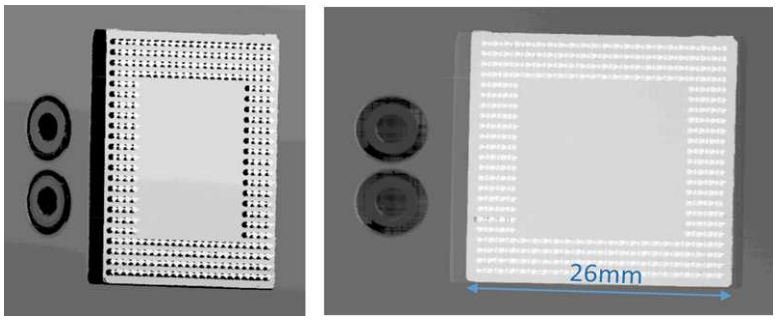
`EMesh` uses a metric space representation that can be generated from a depth map and that can be used to produce a ZMap.

ZMap

ZMaps are another representation for 3D data.

- They are grayscale images like depth maps but represent metric and corrected 3D points.
- They are convenient representations for measurement and matching.
- They are compatible with most of the 2D processing functions.

ZMaps are generated by the orthogonal projection of a point cloud or a mesh onto an arbitrary 3D reference plane.



A depth map and the corresponding ZMap

A ZMap contains an image in which each pixel value represents a positive distance from the reference plane.

> **TIP**
> Use the method `AsEImage()` to obtain a reference to the contained image.

A ZMap also contains the following information:

- The transformation from the World coordinates to the ZMap coordinates.
- The size of a pixel, called the "resolution".

> **TIP**
> Like in a depth map, a specific pixel value is reserved to represent undefined pixels. To get this pixel value, use the method `GetUndefinedValue()`.

Static Methods

EFilters class

The `EFilters` class contains static methods used to apply filters to ZMaps or depth maps.

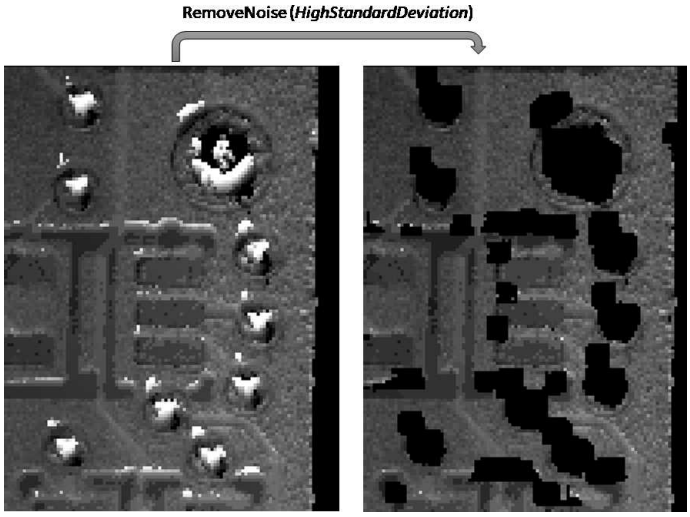
RemoveNoise

The `RemoveNoise()` method removes outliers from a depth map or a ZMap.

- It takes a depth map or a ZMap as input and generates a depth map or a ZMap respectively.

  The undefined points are not taken into account.
- It is based on a square moving kernel. The size of the kernel is (2 x `halfKernelSize` + 1) where `halfKernelSize` is a parameter of the method.
- The `threshold` parameter is scaled with regard to the Z resolution of the filtered depth map or ZMap.
- There are 3 variations of this filter, depending on the `method` parameter:
  - `ENoiseRemovalMethod_AbsoluteDifferenceFromMean` removes a point when it deviates from the average in the neighborhood, including itself. The threshold is an absolute difference.
  - `ENoiseRemovalMethod_RelativeDifferenceFromMean` removes a point when it deviates from the average in the neighborhood, including itself. The threshold is a multiple of the standard deviation.
  - `ENoiseRemovalMethod_HighStandardDeviation` removes a point when the standard deviation in the neighborhood, including itself, is higher than a defined threshold.

Example: Removing points showing a high standard deviation



The code below removes pixels with a standard deviation higher than a defined threshold.

```
// Load the ZMap data
EZMap<6> zmap;
zmap.Load(...);

// Compute the filtered ZMap. The new ZMap is called filteredZmap
// The size of the kernel is 7x7, the threshold is 30.0
EZMap<6> filteredZmap;
filteredZmap.SetSize(zmap);
EFilters::RemoveNoise(zmap, filteredZmap, ENoiseRemovalMethod_HighStandardDeviation, 3, 30.0, 0.0);
```

EStatistics class

The `EStatistics` class contains static methods used to compute statistics on ZMaps or depth maps.

ComputeAverageMap

The `ComputeAverageMap()` method computes the local average map.

- You can use this method as a low-pass filter.
- Undefined points are not taken into account.
- This method is based on a square moving kernel. The size of the kernel is (2 x `halfKernelSize` + 1) where `halfKernelSize` is a parameter of the method.

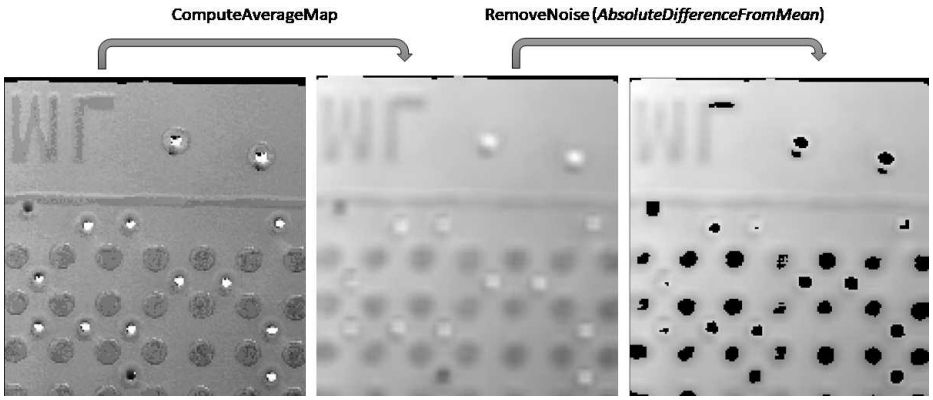
ComputeStandardDeviationMap

The `ComputeStandardDeviationMap()` method computes a map of the local standard deviation.

- You can use this method to visually determine the threshold value to use with the `RemoveNoise()` method when using the `ENoiseRemovalMethod_HighStandardDeviation` setting.

> **NOTE**
> Be aware, however, that in the generated map, a pixel with the value 0 can either be undefined or have a standard deviation equal to zero.

Example: Using a low pass filter on a ZMap, then removing points showing a deviation larger than a defined threshold



The code below first applies a low pass filter, then removes from the result the pixels showing a deviation from the neighborhood larger than the defined threshold.

```
// Load the ZMap data
EZMap<6> zmap;
zmap.Load(...);

// Compute the filtered ZMap. The new ZMap is called averagedZMap
// The size of the kernel is 7x7, the threshold is 30.0
EZMap<6> averagedZMap;
averagedZMap.SetSize(zmap);
EStatistics::ComputeAverageMap(zmap, averagedZMap, 3, 0.2);

// Compute the filtered ZMap. From averagedZMap, compute filteredZMap
// The size of the kernel is 3<x3>, the threshold is 20.0
EZMap<6> filteredZMap;
filteredZMap.SetSize(zmap);

EFilters::RemoveNoise(averagedZMap, filteredZMap, ENoiseRemovalMethod_AbsoluteDifferenceFromMean, <5>, 20.0, 0.2);
```

ComputePixelStatistics

The `ComputePixelStatistics()` method returns basic statistical information about pixel values:

- Minimum
- Maximum
- Average
- Standard deviation
- Number of valid (not undefined) pixels).

Use an `ERegion` object to specify the region of the ZMap or depth map used to compute the statistics.

ComputeStatistics

The `ComputeStatistics()` method returns the same information as the `ComputePixelStatistics()` method, but scaled with respect to the Z resolution.

Use an `ERegion` object to specify the region of the ZMap or depth map used to compute the statistics.

Point Cloud

Mapping Attributes

- In addition to the (x, y, z) coordinates, you can store other components in an `EPointCloud` such as normals, colors, intensities, textures, indexes, confidences and other custom attributes.
- When you use additional components, a mapping exists between each 3D point and an attribute and the different operations performed on the point cloud conserve this mapping.
- To add components to an `EPointCloud`, use the functions `FillAttributeBuffer` or `AddCustomAttributeBuffer`.
  - You can also save and load these attributes from point cloud files.
  - Several file formats are supported, but we recommend the formats `PCD` and `PLY` for handling additional components.

Coordinates Transformations

Geometric transformations

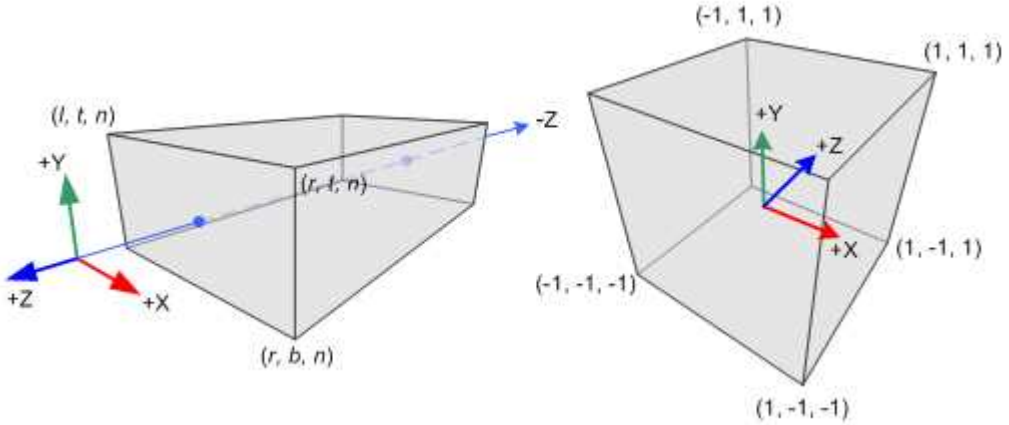
Transforms allow you to reposition the point cloud inside the 3D space.

Open eVision provides you with the following basic transformations:

- Rotation around the X, Y or Z axis
- Translation along the X, Y and/or Z axis
- Scaling, around the origin, and either isotropic (the same in all directions) or anisotropic (different along the different axis)

It also provides you with projection transformations, both orthographic and perspective:

- An orthographic projection transforms a volume of space in the shape of a rectangular parallelepiped (and the points it contains) into the canonical view (a cubic space of size 2 and centered on the origin).



- A perspective projection transforms a volume of space in the shape of a frustum (basically a truncated pyramid) into the canonical view. This projection allows you to simulate the perspective effect given by an eye or a camera.
- Use the class `E3DTransformMatrix` to create the geometric transformations. The class `EAffineTransformer` applies a transformation defined by a `E3DTransformMatrix` to a point cloud.

Reducing a Point Cloud

Cropping

Cropping allows you to exclude points from the point cloud based on geometrical considerations.

Open eVision provides the following cropping functions:

- `ESimpleCropper`: simple cropping on the X, Y and/or Z coordinates (aligned rectangle 3D region)
- `ERectangularCropper`: cropping the points outside (or inside) an oriented rectangular parallelepiped
- `ESphericalCropper`: cropping the points outside (or inside) a sphere.
- `EPlaneCropper`: cropping the points depending on their position with respect to a plane

These classes produce a new point cloud with the selected points.

Decimation

- Open eVision offers 2 capabilities to decimate an `EPointCloud`:
  - `ERandomDecimator` decimates the cloud by copying a specified number of points, randomly selected, to a new point cloud.
  - `EGridDecimator` splits the space using a grid of given size; the new cloud is created by averaging the points of every grid together, resulting in a regularly sampled cloud.
- To use `ERandomDecimator`, specify the number of points to keep as a parameter of the constructor.

```
EPointCloud pc;
pc.LoadPCD("c:\\images\\data.pcd");
```

```
// Explicitly decimate the point cloud

ERandomDecimator decimator(5000);
EPointCloud pcDecimated;

decimator.Decimate(pc, pcDecimated);
pcDecimated.SavePCD("c:\\images\\decimatedData.pcd");
```

- To use `EGridDecimator`, specify the cell size, either as a `E3DPoint` or as a float if cell is cubic.

```
EPointCloud pc;
pc.LoadPCD("c:\\images\\data.pcd");

// Explicitly decimate the point cloud

EGridDecimator decimator(0.f);
EPointCloud pcDecimated;

decimator.Decimate(pc, pcDecimated);
pcDecimated.SavePCD("c:\\images\\decimatedData.pcd");
```

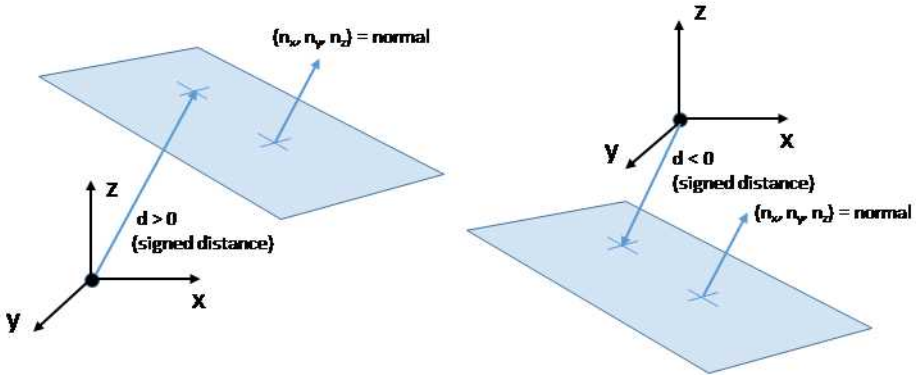
Managing Planes

E3DPlane

A plane can be represented as an `E3DPlane` object.

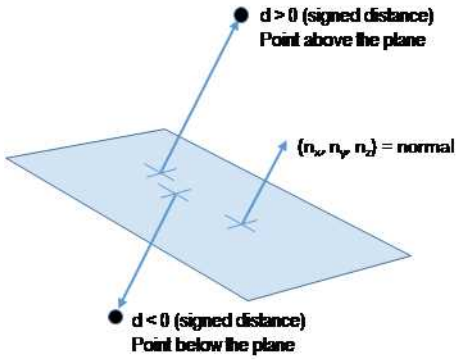
This plane is characterized by:

- Its normal which is a vector of norm 1, perpendicular to the plane.
- Its signed distance from the origin, which is the smallest distance from the origin to the plane. The signed distance is positive when the vector binding the origin to the closest point on the plane has the same direction as the normal and is negative when it has the opposite direction.



Once a plane is defined, you can measure the signed distance between this plane and any point in the space (using the method `DistanceTo()`):

- A positive distance means that the vector connecting the plane to the point has the same direction as the normal.
- A negative distance means that the vector has the opposite direction.



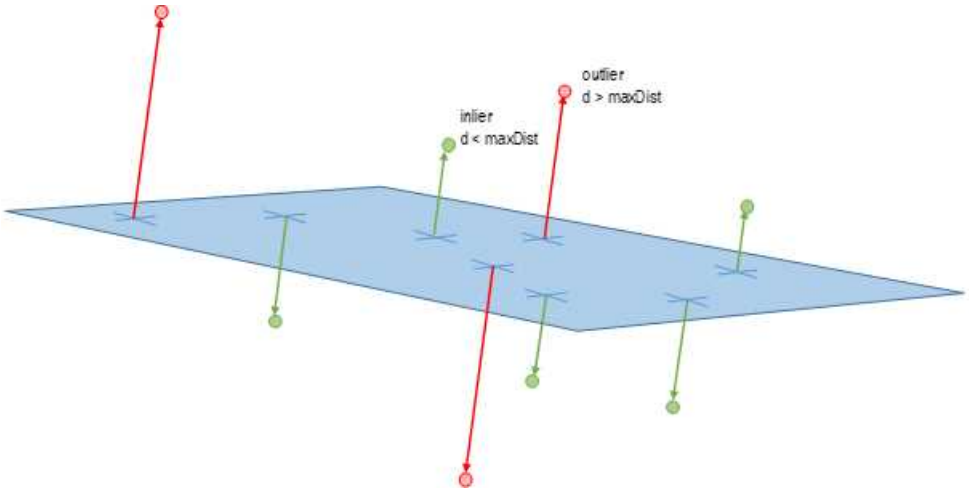
EPlaneFinder

You can search for a plane in a point cloud using the object `EPlaneFinder` object.

The main parameters of this object are:

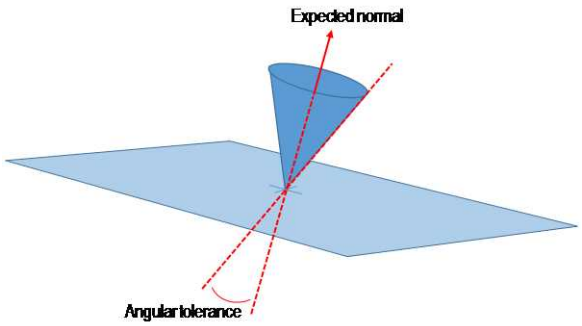
- The maximum distance between the searched plane and a point that belongs to this plane.
- The expected ratio between the numbers of inliers and the total number of points in the point cloud.
  - An **inlier** is a point that belongs to a plane (closer than this maximum distance).
  - An **outlier** is a point that is not an inlier.

The picture below illustrates how points of the space are classified as inliers (in green) and outliers (in red) according to their distance to the searched plane.



- A `EPlaneFinder` object produces a `E3DPlane` object.
  - The algorithm searches for a plane containing as many inliers as possible.
  - This plane is the biggest plane if the samples are evenly distributed.
- The maximum distance between the plane and the inliers is a mandatory parameter.
  - It should include the deviation due to the noise.
  - It should also take the warpage into account.

- The parameter that specifies the ratio of inliers with respect to the total number of points has a default value of 0.3. This means that we estimate that about 30% of the points belong to the plane.
  - This parameter is not as critical as the maximum distance.
  - It affects the maximum time that the algorithm spends to search a plane and its robustness.
- For more fine-grained control, you can specify the ratio of inliers as a range.
  - The min of the range is the minimum ratio of inliers for a plane to be considered as valid.
  - The algorithm stops searching for a plane when it finds one with the max of the range inliers.
  - The bigger the min of the range and the smaller the max, the faster the algorithm is.
  - Specifyng the range as a single value x is equivalent to setting a range of [x/2, x].
- You can specify the expected normal vector to the searched plane.
  - Specify also an angular tolerance with respect to this direction.
  - The algorithm only searches for a plane that satisfies the condition.
  - Set this condition may speed up the plane search.



- You can specify 1 or 2 points contained in the searched plane.
  - These points are not specified as inliers (points closer to the plane than its maximum distance) but as points exactly contained in the main plane.
  - They may not be exactly in the final plane after the final fitting step detailed below.
  - The algorithm only searches for a plane that satisfies the condition.
  - Set this condition may speed up the plane search.

Once the main plane is found, a fit is done on all the inliers points and the result is returned (see `EPlaneFitter` below).

Decimation

By default, the `EPlaneFinder` decimates the input point cloud to accelerate the search.

- The default decimator reduces the input point cloud to 10,000 points.
- You can disable this decimation.
- You can change the number of points the cloud is reduced to.
- You can decimate a point cloud explicitly.
  - Use an `ERandomDecimator` object.
  - Use the decimated point cloud as input for the `EPlaneFinder`.
  - Disable the default decimator.

EPlaneFitter

The EPlaneFitter operator computes a fit on all the points of a point cloud and returns a E3DPlane object. The “average” plane, that minimizes the orthogonal distance of the points to the plane, is returned.

Aligning

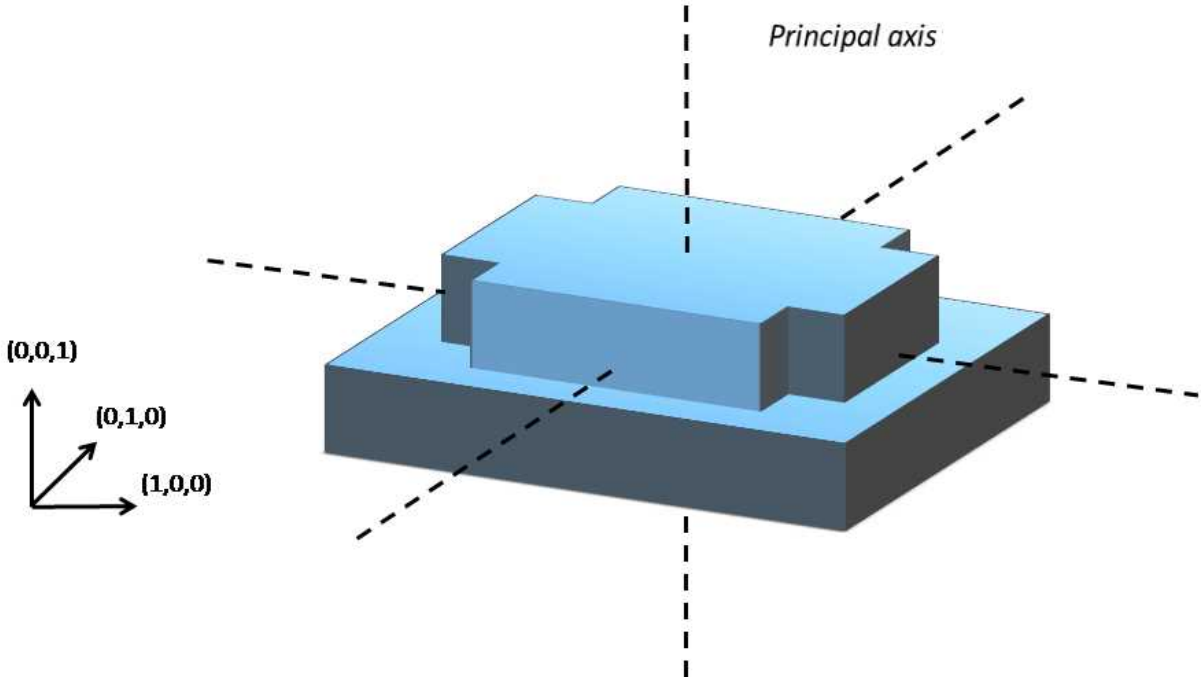
EPrincipalAxisExtractor

The EPrincipalAxisExtractor computes the “principal axis” of an object from a point cloud (EPointCloud) and returns a E3DTranformMatrix containing a solid transformation that defines a new orthogonal basis.

This new orthogonal basis has the following characteristics:

- The center is the center of gravity of the point cloud.
- The axes are oriented along the “principal axis” of the object. This is the result of the “PCA” calculation (principal axis analysis).
- The directions of the axes are selected so that the new basis is as close as possible of the basis defined by the reference transformation.

The next figure illustrates the orientation of the principal axes of an object.



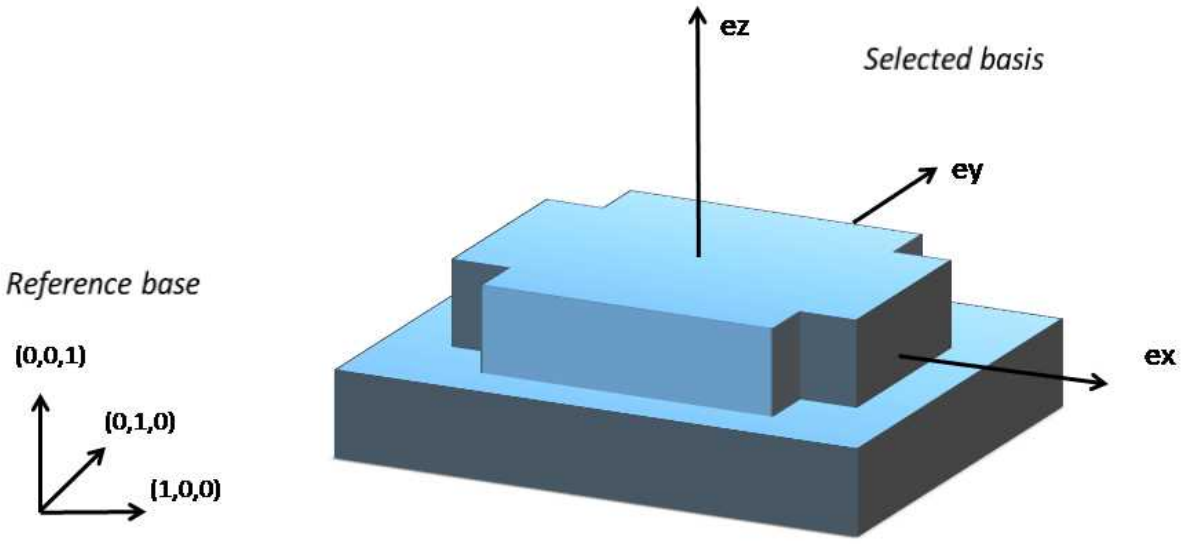
The principal axes extraction is done using the Extract() method that takes a EPointCloud as input and returns an E3DTransformMatrix. Optionally, you can pass 3 other output parameters by reference to retrieve the value of the standard deviation along the 3 principal axes.

You can use the returned E3DTranformMatrix object to transform the 3D coordinates of a point. For example, apply the transformation matrix to the origin (0, 0, 0) to return the center of gravity of the object.

Specification of a reference transformation

The reference transformation is an optional parameter of the `EPrincipalAxisExtractor` object. It defines a reference basis used to select an orthogonal basis out of the principal axes. The selected basis will be the closest to the reference basis.

TIP
If no reference transformation was supplied, the default reference basis is ((0, 0, 1), (0, 1, 0), (0, 0, 1)), that corresponds to the identity transformation. On the figure below, the default reference basis determines the direction of the axes **ex**, **ey** and **ez**.



EFeaturesAligner

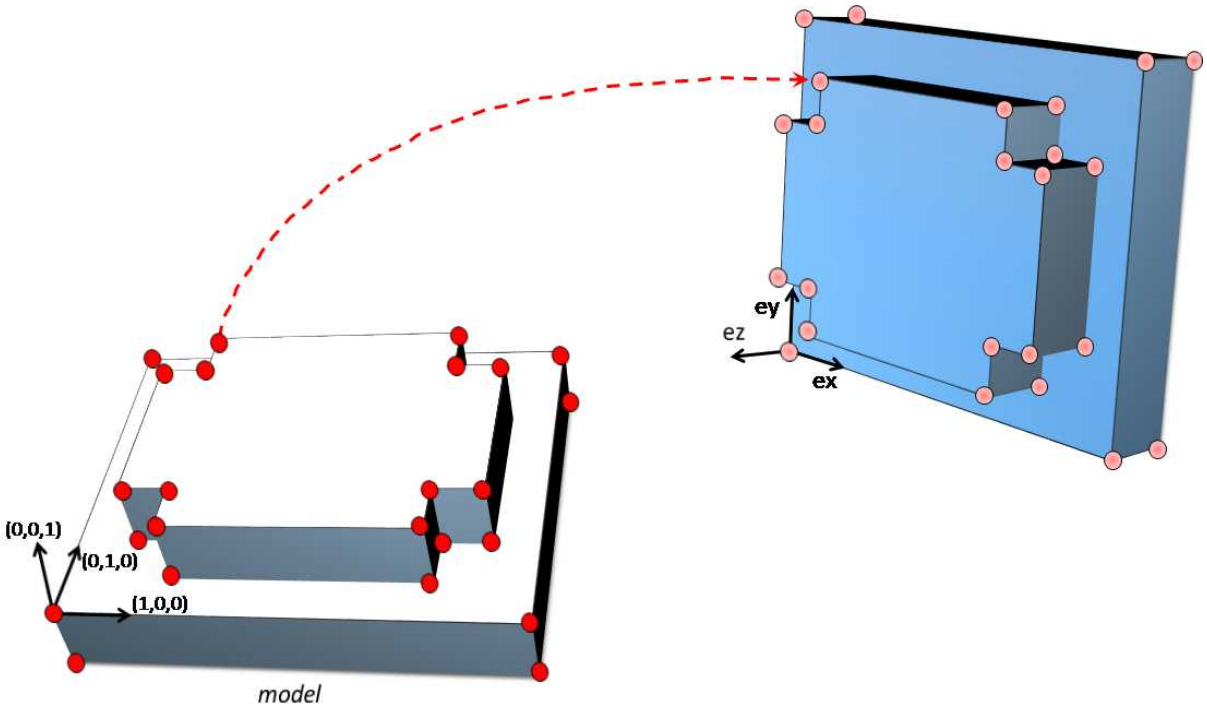
A `EFeaturesAligner` object finds the best transformation that maps a list of points to another list of points.

- The first list of points is called the "model". It is stored in the `EFeaturesAligner` object.
- The second list of points is called "measured points". It is passed as a parameter to the `Compute()` method. If successful, the result of this method is a `E3DTransformMatrix` object.
- The 2 lists should form matching pairs. In other words, the first point of the first list matches the first point of the second list, the second point of the first list matches the second point of the second list, and so on…

With the `Polarity` parameter, you can define which transformation is returned. It can be either:

- The one that moves one point from the first list (the model) to the second list of points (the measured points) if the polarity parameter is set to `EAlignmentPolarity_ModelToMeasured` (default).
- The one that moves a point from the second list (the measured points) to the first list (the model) if the polarity parameter is set to `EAlignmentPolarity_MeasuredToModel`.

The figure below illustrates the computation of the alignment transformation. In this example a model is aligned to an object using the coordinates of their corners.



Once the transformation is computed, use the method `GetOrthoBasis` of the `E3DTransformMatrix` object to get the basis (**ex**, **ey**, **ez**) and the center point **t** that defines the new basis.

You can also apply the computed transformation on any 3D point as illustrated in the code below.

```
E3DTransformMatrix alignBase;
E3DPoint ex, ey, ez, t;
std::vector<E3DPoint> model3d;
std::vector<E3DPoint> points3d;

// add points to model3d and points3d
// ...
AlignTool.SetModelPoints(model3d);
alignBase = alignTool.Compute(points3d);

// Get the orthogonal basis and store it in ex, ey, ez and t
alignBase.GetOrthoBasis(ex, ey, ez, t);

// Applying the transformation on point P►, results in point P►b
E3DPoint P► = E3DPoint(...);
E3DPoint P►b = alignBase*P►;
```

As you can see, the application of the transformation on a point is simply done by multiplying the transformation matrix by the point (as done in the example above).

On the other hand, if you need to transform a point cloud or a list of points, it is more efficient to use the `ApplyTransform()` method of an `EAffineTransformer` object.

Mesh

A mesh is a geometric representation of a 3D surface. The surface is defined by a triangle mesh connecting the 3D points. Like a point cloud, a mesh is expressed in the metric space.

Like a point cloud, you can generate a mesh from a depth map and use it to produce a ZMap.

Generation

An `EMesh` object is generated from a depth map using the `EDepthMapToMeshConverter` class.

Like `EDepthMapToPointCloudConverter`, this class uses a calibration model to transform the depth map pixels to 3D world positions. In addition, the depth map pixel connectivity is used to build the triangle mesh. Adjacent pixels produce surface triangles.

Use `SetCalibrationModel()` to select a calibration model and the method `Convert()` to generate an `EMesh` from an 8 bits or 16 bits depth map.

Access and usage

In an `EMesh` object the 3D world positions are stored as an `EPointCloud` (accessible through the method `GetPointCloud()`). The triangle mesh is stored as an array of point indexes, where 3 consecutive indexes define a triangle. The method `GetTriangleIndexes()` provides a read-only access to the triangle mesh.

You can use either the Open eVision proprietary format to save and load `EMesh` objects using the `Save()` and `Load()` methods, or use the STL standard file format (https://en.wikipedia.org/wiki/STL_(file_format)) using the `SaveSTL()` and `LoadSTL()` methods which respectively write to and read from ASCII or binary STL files.

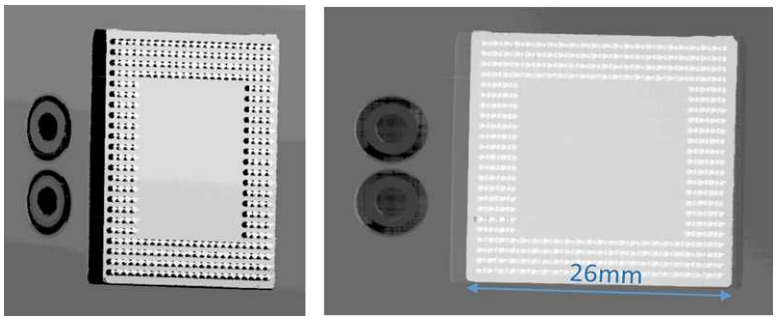
You can use an `EMesh` to produce a ZMap (see "Generating a ZMap" on page 57). Because an `EMesh` represents a surface, the so generated ZMap can show better continuity and less undefined pixels.

ZMap

Generating a ZMap

A ZMap is the projection of a point cloud or a mesh on a reference plane, with the distance coded as grayscale values:

- They are grayscale images, compatible with all Open eVision 2D libraries.
- They are distortion free, with affine transformation from/to metric coordinate system.



A depth map (left) and the corresponding ZMap (right), with default generation parameters and undefined pixel filling enabled

All Open eVision 2D processing are available on ZMaps: filtering, thresholding, blob extraction, measuring with EasyGauge, model matching with EasyFind or EasyMatch…

The `EPointCloudToZMapConverter` class implements the conversion from a point cloud to a ZMap (`EMeshToZMapConverter` converts a mesh to a ZMap). With all parameters at default value, the `Convert` method automatically chooses the projection plane, the orientation, the map size and the resolution.

Several methods are available to further control the conversion:

- `SetReferencePlane` defines a world space projection plane. The values of the ZMap pixels are the distance of the point cloud to that reference plane.

  By default, the reference plane crosses the origin and is perpendicular to the world Z axis. The plane is defined as a `E3DPlane` object.

- `SetOrientationVector` sets a world space vector representing the expected direction of the X (width) axis of the ZMap.

  The orientation vector allows you to “rotate” the object around the normal of the reference plane.

- `SetOrigin` specifies the world position that is on the ZMap lower left pixel (0, 0).

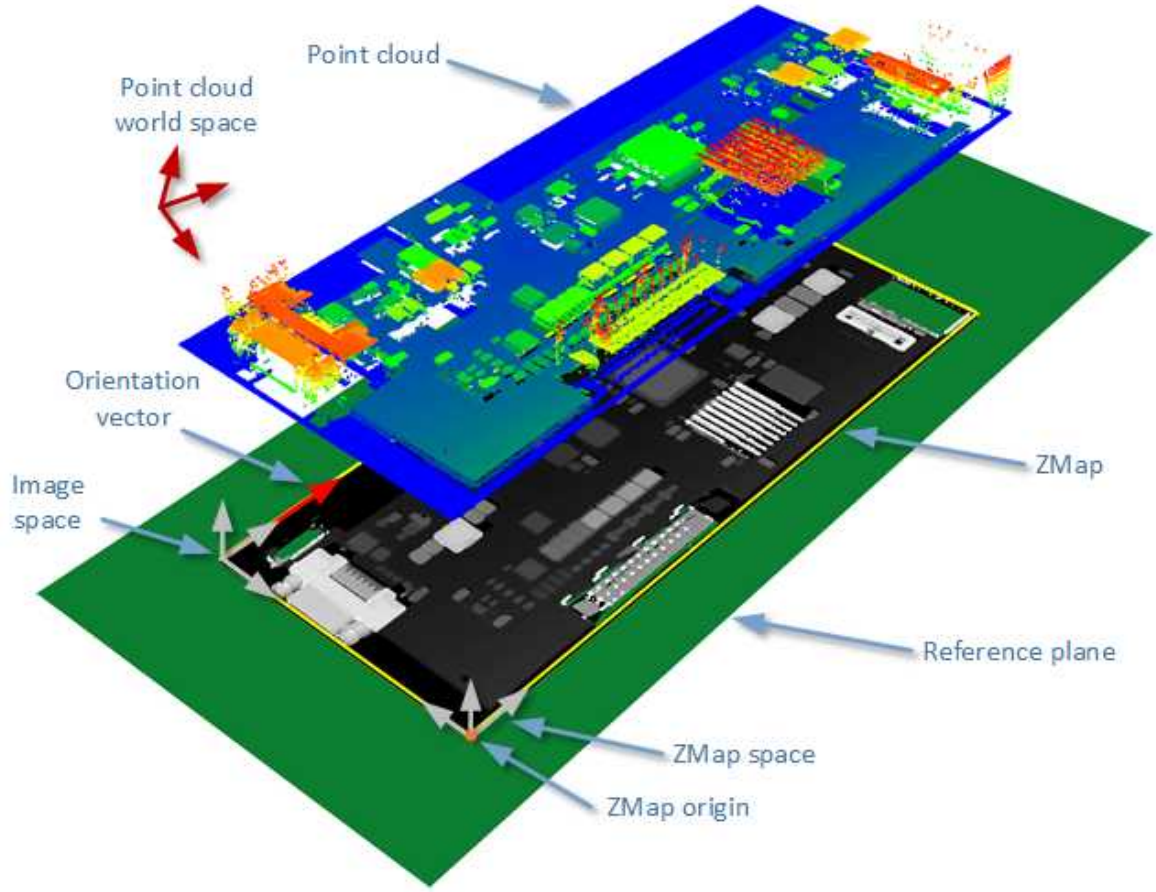
- `SetMapSize` defines the resolution (number of pixels in X and Y axis) of the generated ZMap.

- `SetMapXYResolution` adjusts the X and Y resolution of the ZMap pixels, in world space unit per pixel (for example mm/pixel). This value is used to compute the ZMap size (width and height), depending on the projected size of the point cloud on the reference plane.

- `SetMapZResolution` sets the Z resolution, in world space unit per pixel unit (gray value). The Z resolution is used to compute the transformation of the distance to the reference plan to the integer 8, 16 or 32 bits pixel value.
- `EnableFillMode` and `SetFillMode` control the options used to fill the "hole" in the ZMap. A hole exists when no 3D point is projected in the ZMap at a pixel position.

The methods `SetReferencePlane`, `SetOrientationVector` and `SetOrigin` are used to set up the transformation between the world space and the ZMap space. This transformation is rigid (distances are kept).

Alternatively, it is possible to directly set that transformation with the method `SetWorldToZMapTransform` using a rigid matrix as parameter. In that case, the reference plane, the orientation vector and the origin parameters are ignored.

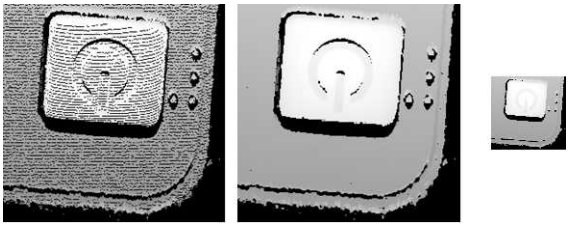


**The projection of a point cloud on a ZMap,
showing 3 coordinate systems: the world space, the ZMap space and the pixel space.**

The `Convert` method performs the effective projection of a point cloud (`EPointCloud`) or a 3D object (`EMesh`) to the 8, 16 or 32 bits ZMap.

When generating a ZMap from a point cloud, only individual points are projected on the ZMap. Depending on the point cloud density and the ZMap resolution, some regions of the ZMap may remain “undefined”. To get around this problem, adjust the resolution of the ZMap (`SetMapXYResolution` method) to remove “holes” on the ZMap.

By default, the point cloud to ZMap converter performs a filling algorithm. This process tries to replace undefined pixels with locally interpolated values.



Left: high resolution ZMap, the pixel scale exceeds the point cloud density
Center: the same generator parameters with the filling enabled
Right: a reduced ZMap scale/resolution, without filling

As a mesh defines a surface, its triangles are projected onto the ZMap plane. Thus, the generated image shows better continuity and less undefined pixels. However, the generation of a ZMap from an `EMesh` is slower than from an `EPointCloud`.

Creating a Point Cloud from a ZMap

To generate a point cloud from a ZMap, use the `EZMapToPointCloudConverter` class.

The `Convert()`method takes:

- A ZMap source
- A `EPointCloud` destination.
- 2 optional parameters:
  - An `ERegion` that defines the domain of the ZMap to convert.
    By default, Open eVision uses all the defined pixels of the ZMap generate the point cloud.
  - A parameter to select the world space (by default) or the ZMap space to store the resulting positions in the point cloud.

Managing the Coordinates

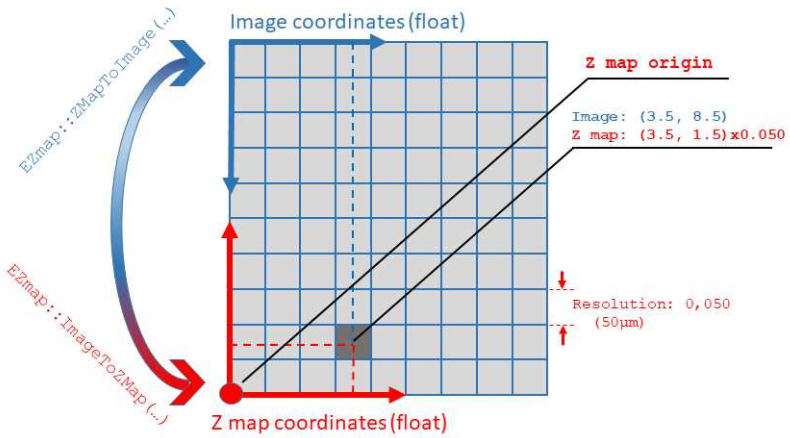
Coordinate systems on a ZMap

A ZMap has multiple coordinate systems:

- The **world space** system is the original, metric space from which the ZMap has been generated. Point clouds and meshes are expressed in the world coordinate system.
- The **ZMap space** is defined by a rigid transformation of the **world space**. The basis linked to this transformation is attached to the lower left corner of the ZMap.
- The **image space** is the system attached to the image representation of the ZMap. Its origin is the upper left corner of the ZMap and its unit length is one pixel along the X and Y axis.

The transformations between:

- The **image space** and the **ZMap space** include a scale factor.
- The **ZMap space** and the **world space** are solid transformations.



EZMap

The `EZMap` object exposes a set of methods to convert coordinates between world, ZMap and image spaces:

- `ImageToZMap` converts a 2D position in the image to ZMap coordinates.
- `ZMapToImage` is the reciprocal operation and converts a ZMap position to an image position.
- `ZMapToWorld` is a method to transform positions from the 3D ZMap space to the 3D world space. The world space is the original point cloud or mesh space.
- `WorldToZMap` is the reciprocal operation, converting from world space to ZMap.
- `ImageToWorld` and `WorldToImage` combine the functions above to transform directly from image space to world space (or the other way).

These methods only perform geometric transformations between the various coordinate systems and do not access the actual ZMap gray scale values.

The functions that access the pixel values are:

- `GetWorldPositionFromPixelPosition()` is a method transforming the actual pixel value at integer position (u, v) to the original world space. This method queries the ZMap internal representation to get the pixel value w and transform the pixel space (u, v, w) coordinates to a world space position.
- `GetPixelPositionFromWorldPosition()` is a method to get a pixel value from a world position. The world position is projected on the ZMap and the pixel value is returned. If the world position is outside the ZMap domain, the method returns `FALSE`.

3D Viewer

The class `E3DViewer` is an interactive 3D viewer for point clouds, ZMaps and meshes.

- It features multiple sources display, color ramps, 3D point picking and text label display.
- It is compatible with Windows and Linux and can be integrated to Win32, MFC and QT frameworks.

Creating a 3D viewer

- The general constructor of a 3D viewer is:
  `E3DViewer(EUIAPI uiApi, int orgX, int orgY, int width, int height, int parent)`
- The way to use it depends on the Operating System and the User Interface API.

Windows only

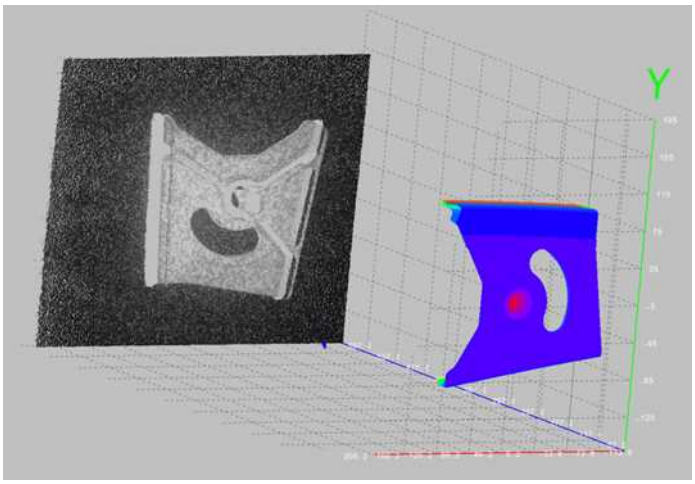
- To create a 3D viewer stand-alone window:
  - Use `E3DViewer(EUIAP::EUIAPI_Win32, orgX, orgY, width, height)`
- To create a 3D viewer as a part of another window in an MFC application:
  - Use `E3DViewer(EUIAP::EUIAPI_Win32, orgX, orgY, width, height, handle to the parent window)`
  - See the MsVc 3DViewer sample.

Windows and Linux

- To create a 3D viewer in a Qt application:
  - Use `E3DViewer(EUIAP::EUIAPI_Qt, orgX, orgY, width, height)`
  - You must instance the class inside a `QOpenGLWidget` object.
  - See the 3DViewer Qt sample.

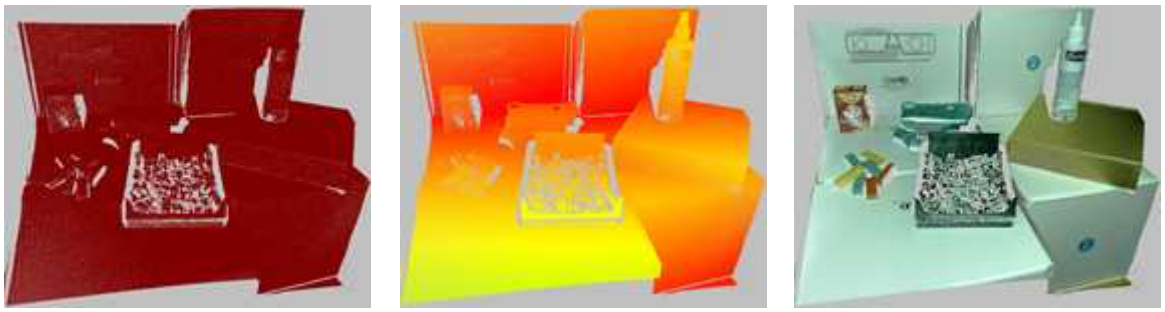
Managing the render sources

- A render source is a displayed entity. It can be an `EPointCloud`, an `EZMap` or an `EMesh`. You can display one or several render sources simultaneously in the 3D viewer.

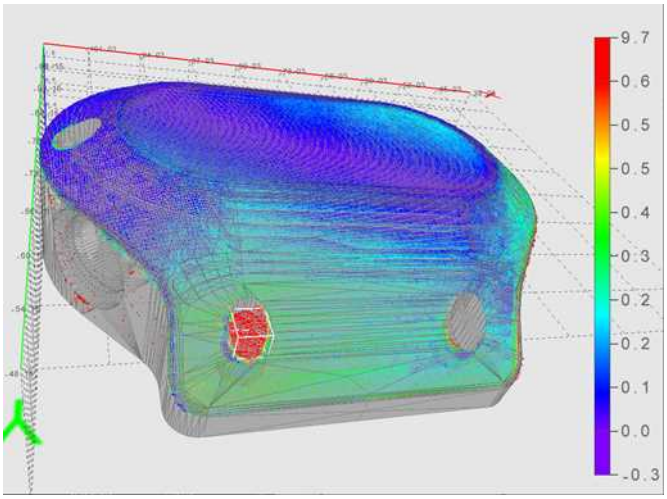


A point cloud displayed in gray scale and a mesh in false colors in the 3D viewer

- To manage the list of render sources, use the methods:
  - `AddRenderSource` to add another render source to the current list. The render source has a name for further reference.
  - `SetRenderSource` to change the content of the render source.
  - `RemoveRenderSource` to remove a render source from the current list.
- The render sources API exposes several display attributes:
  - Visibility (controlled by `ShowRenderSource`/ `HideRenderSource`)
  - Color mode (`SetRenderSourceColorMode`): choose between constant color, color ramp or point cloud color attributes.
  - Opacity (`SetRenderSourceOpacity`)
  - Point size (`SetRenderSourcePointSize`): applies to point clouds and ZMaps only.
  - Wire frame (`SetRenderSourceWireFrame`): applies to meshes only.



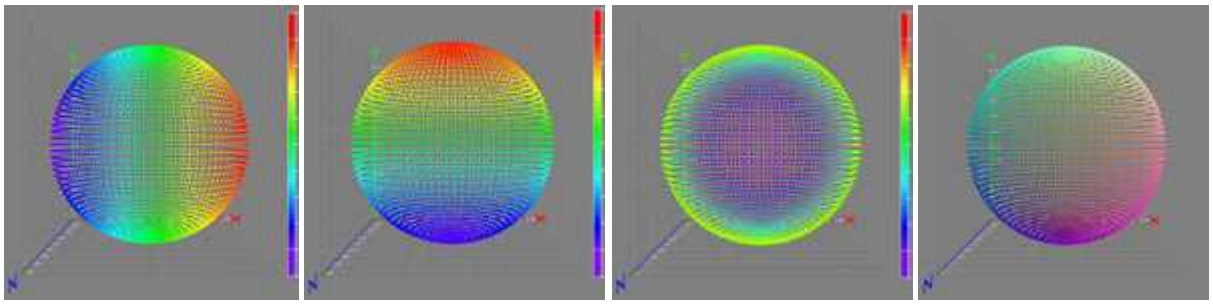
A point cloud displayed with constant color, color ramp or color attributes (data courtesy of Zivid)



A mesh with wireframe and transparency, combined with a point cloud with color ramp

Using a color ramp

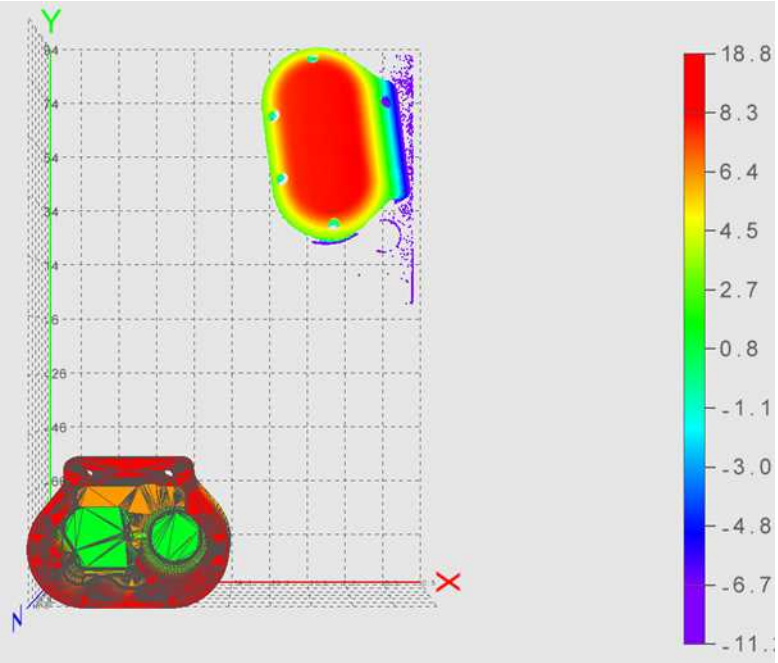
- When the color mode of a render source is `ESourceColorMode_Ramp`, the color of each point is calculated from the position or the attribute of the point.
- Use `SetColorRampMode` to choose the color ramp:
  - `EColorRampMode_HueFromX/Y/Z` computes the colors from respectively X/Y/Z point coordinates (`EColorRampMode_HueFromZ` is the default color ramp mode).
  - `EColorRampMode_RGBCube` computes the colors by mixing X,Y,Z point coordinates.
  - `EColorRampMode_HueFromIntensity` computes the colors from the intensity attribute of the point.
  - `EColorRampMode_HueFromConfidence` computes the colors from the confidence attribute of the point.
  - `EColorRampMode_HueFromDistance` computes the colors from the distance attribute of the point.



Color ramp modes Hue from X/Y/Z and RGB cube

- When a color ramp is defined, you can display a legend at the right side of the window (default position). To control the color ramp legend aspect, use the methods `Show`/`HideColorRampLegend`, `SetColorRampGraduationColor` and `SetColorRampLocation`.

- When the “Smart color ramp” is enabled with the method `SetEnableSmartColorRamp`, an outlier filtering processing is applied to remove the noise and spread the colors on the main part of the object. The outliers are then displayed with constant red or blue colors.



A color ramp EColorRampMode_HueFromZ with outlier removal process:
- The extreme points with Z coordinate between 8.3 and 18.8 are drawn in red
- The Z coordinate of 98% of the points are between -6.7 and 8.3

Interactive controls

On Windows, the interactive controls are built in the class `E3DViewer`.

- The following interactions are possible:

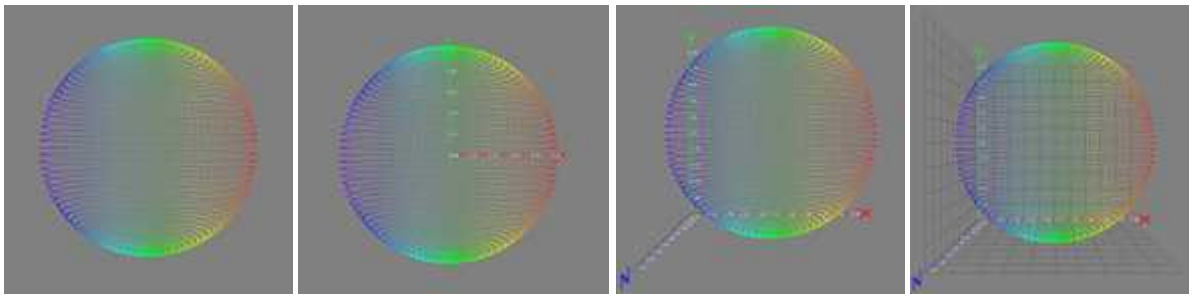
Intercation	Control
Rotate the view	left-click + mouse move
Translate the view	right-click + mouse move
Change the view distance	mouse wheel
Reset the view	**r**
View along the positive / negative X axis	**x** / **shift+x**
View along the positive / negative Y axis	**y** / **shift+y**
View along the positive / negative Z axis	**z** / **shift+z**
Show / hide the axis	**a**
Enable / disable the wireframe mode	**w**
Increase / decrease the point size	plus sign (**+**) / minus sign (**-**)

- Use the following methods to implement custom view controls:
  - `LockRotationInitialPosition`, `UpdateRotationPosition` and `LockRotationFinalPosition` correspond to the sequence click-drag-release to change the viewpoint by rotation.
  - `LockTranslationInitialPosition`, `UpdateTranslationPosition` and `LockTranslationFinalPosition` correspond to the sequence click-drag-release to change the viewpoint by translation.
  - `UpdateViewDistance` changes the view distance, usually controlled by the mouse wheel.
  - `ResetView` restores the default viewpoint.

  See the `Qt 3DViewer` sample for a use case of this view control API.
- You can also directly configure the view position with the methods:
  - `SetViewTarget` (by default, it is the center of the object).
  - `SetViewAngle` to choose the orientation of the view.
  - `SetViewDistance` to choose the distance to the view target.

View parameters

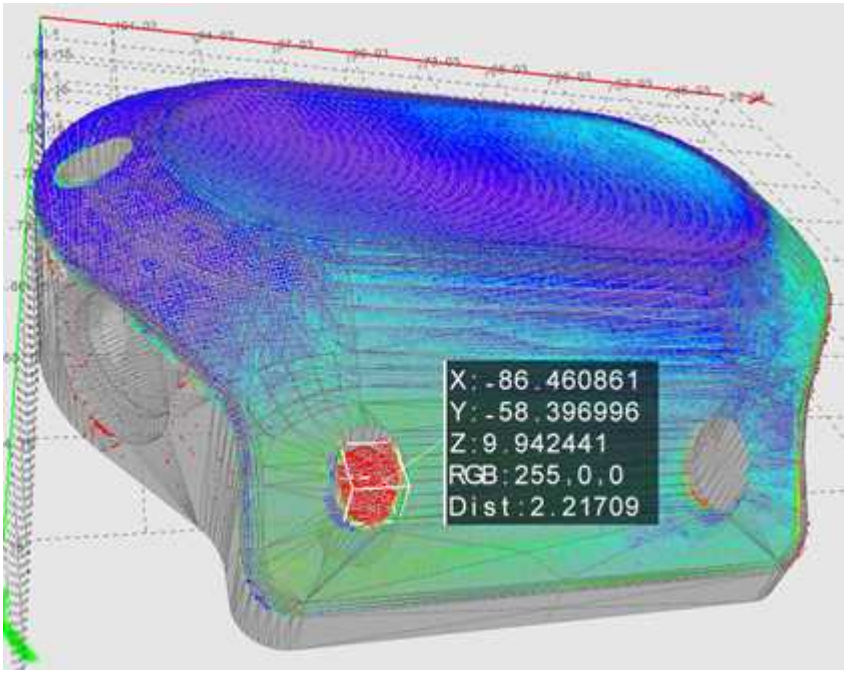
You can customize the 3D view and:
- Change the field of view with `SetFieldOfView`.
- Switch between the perspective and the orthographic view with `SetProjectionType`.
- Enable or disable the display of the X, Y and Z axis with `SetRenderAxis`.
- Switch the axis origin between the world origin and the object center with `SetAxisOrigin`.
- Enable or disable the display of a grid with `SetRenderGrid`.
- Activate an auto rotate animation with `SetAutoRotate`.
- Use a decimation level (remove some points to speed up the rendering) with `SetRenderDecimationLevel`.



No axis / world centered axis / bounding box axis / axis with grid

Picking a 3D point

- Picking a point means detecting the point closest to the given coordinates in a `E3DViewer` window. You can then display the detected 3D point, with attributes, as a text label.

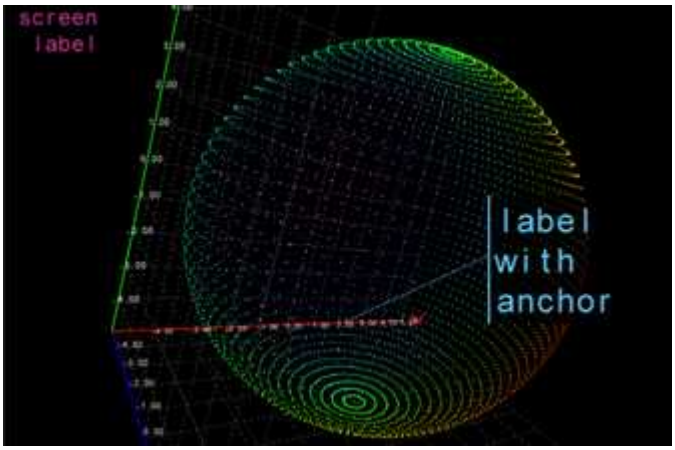


Displayed coordinates and attributes of a picked point on the 3D view

- The distance threshold used to select a picked point is defined by `SetPickingDistanceThreshold`. There is no picked point if the point cloud distance to the picked position is greater than this threshold.
- On the Win32 interface framework, the built-in control for the picking is **ctrl + left-click**. You can also control the picking with the methods: `Pick3DPoint`, `GetLastPickedPoint` and `ResetPicking`.
- To configure the display of the picking label, use `SetPickingDisplay`, `SetPickingLabelSize`, `SetPickingLabelColor` and `SetPickingLabelFixed`.

Text labels and 3D objects

- You can add custom text labels and 3D objects to the current view of the 3D viewer.

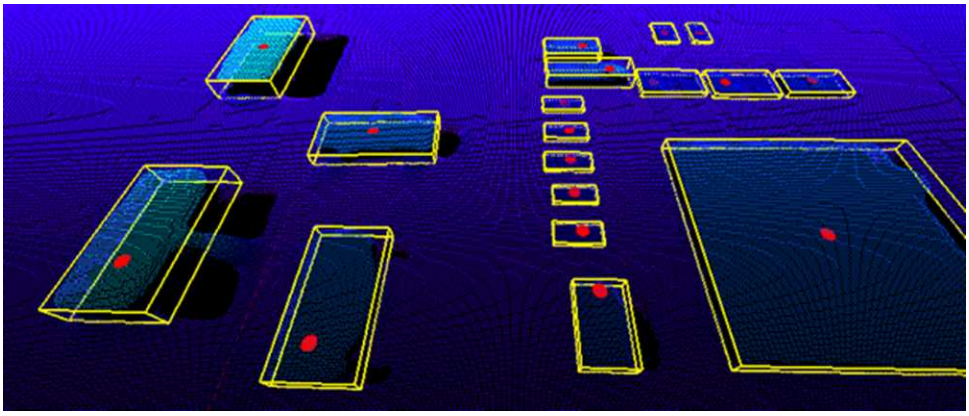


A screen label in the top left corner and a text label with 3D anchor

- To control the text label display, use:
  - `AddTextLabel` to add a text label with or without a 3D anchor. `AddTextLabel` returns an ID used for further reference.
  - `EditTextLabel` to change the position, color, size or text of a label.
  - `GetTextLabel` to get the attributes of a label.
  - `RemoveTextLabel` to remove a label.
  - `ClearTextLabels` to remove all labels.
- The class `E3DViewer` can also display `E3DObject` over a point cloud, a ZMap or a mesh. Use the tools Easy3DObject and Easy3DMatch to create the `E3DObjects`.
- Use the methods `Register3DObjects` and `RemoveCurrent3DObjects` to manage the list of `E3DObjects` that you want to display.

  An `E3DObject` contains several features (center point, bounding box, base plane…). Use the methods `Show` / `HideFeatureFor3DObject` and `Show` / `HideFeatureForAll3DObjects` to select the displayed features.

  See the `3DObjectExtraction` MSCV sample as an example for the display of `E3DObjects`.



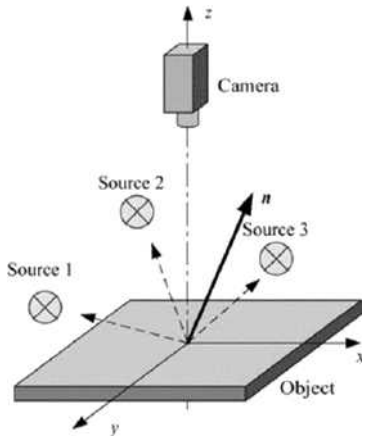
3D objects drawn with a point cloud displaying the bounding boxes and the top positions

Photometric Stereo

Photometric Stereo and Process

Introduction

The Photometric Stereo is a technique used to estimate the normals at the surface of an object.



Photometric stereo setup

Source: https://www.researchgate.net/figure/Principle-of-photometric-stereo_fig7_222422584

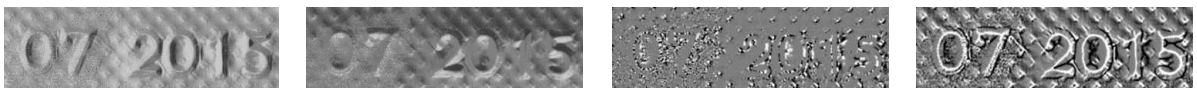
- It takes at least 3 images of the same object taken under different known light directions.

Inputs: images with different light directions

- It produces an image containing the fraction of light reflected (called *albedo*) and the normal of the surface at each pixel.

Outputs: albedos - normals

- The normals are processed to compute gradients and curvatures, allowing to easily see bumps and holes.

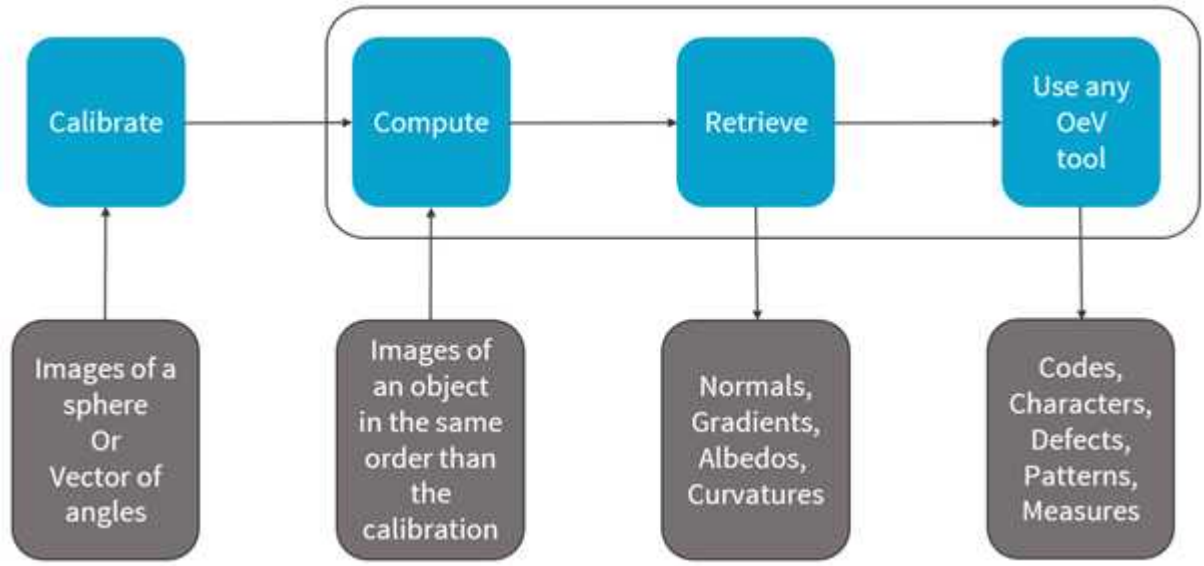


Outputs: gradients X - gradients Y - gaussian curvatures - mean curvatures

Process

You can use the object `Easy3D::PhotometricStereoImager` in a 4-step process:

1. Calibrate the setup from a sphere or from predefined angles (once per setup).
2. Perform the photometric stereo computation on the object images.
3. Retrieve the results.
4. Use and apply the Open eVision tools on the results.



Photometric stereo process

Resources

- The example described here demonstrates how to perform photometric stereo with Open eVision 3D libraries and tools.
- A sample application is also distributed with the source code. You can find it in `···\Sample Programs\MsVc samples\PhotometricStereo`.
- This example and the sample application are based on the following resources:
  - Open eVision 2.15
  - Microsoft Visual Studio 2017

> **NOTE**
> The license for Easy3D is necessary to use the photometric stereo tools.

Calibration

- You can perform the calibration either:
  - By setting the calibration angles.
  - By computing the calibration angles from images of a (hemi)sphere.

Azimuth and elevation

- To define a light direction, two angles are necessary, the azimuth and the elevation.
- When facing the image, the X-axis points right, Y points top and Z points towards the camera.
- The azimuth angles are oriented trigonometrically around the Z-axis.
  - A light source on the right of the image has an azimuth of 0°.
  - A light source on the top of the image has an azimuth of 90°.
- The elevation is the angle formed by the base plane and the light source.
  - A light source on the horizon has an elevation of 0°.
  - A light source on the camera has an elevation of 90°.

Code snippet

- The following code snippet shows how to perform the calibration from a (hemi)sphere.

```
EPhotometricStereoImager photometricStereo;

std::vector<EImageBW8> calibrationImages;
// Load calibration images (Todo)

std::vector<EROIBW8> calibrationROIs;
// Set the calibration ROIs (Todo)// Calibrate
float score = photometricStereo.CalibrateFromSphere(calibrationROIs);
```

- If the sphere is not detected, the calibration fails and generates an EException (EError EError_SphereDetectionFailed).

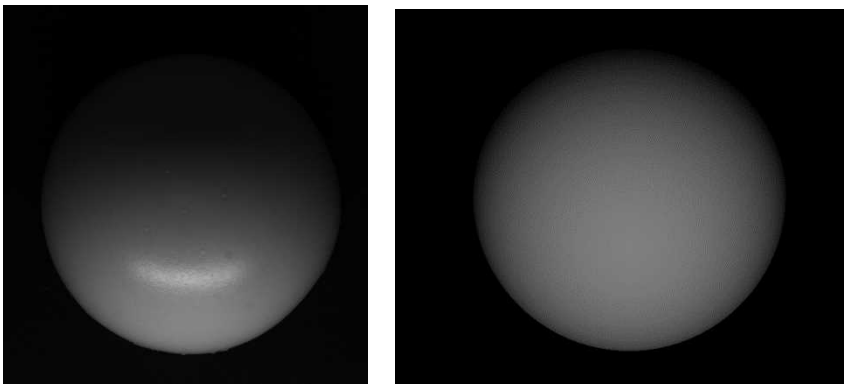
  In that case, you can pass the position of the circle to the method:

```
ECircle circle;

// Define circle (Todo)

photometricStereo.CalibrateFromSphere(calibrationROIs, circle)
```

- The method returns a score that indicates the reliability of the calibration.
  - The higher the value, the better the calibration.
  - The score range is [0, 1].
  - The scores above 0.75 are considered as good.
  - The scores below 0.50 are considered as bad.
  - The scores in between are considered as acceptable.
  - The method never fails. A bad score does not mean that you will not get good results on your images. It means that, if you do not, it is probably due to the calibration.

- The score is composed of 2 factors:
  - The lambertian (matte) of your sphere (the more lambertian the better).
  - The plausibility of the detected light directions.

  The following figure shows the scores for 2 examples.



2 images from different spheres:
left: a high reflection and a score of 0.70 - right: perfectly lambertian and a score of 0.96

- You can also directly set the calibration angles and retrieve them.

  Use `Easy::SetAngleUnit` to define the angle unit.

```
Easy::SetAngleUnit(EAngleUnit_Degrees);

std::vector<float> azimuths, elevations;

// Define the values of the angles (Todo)

photometricStereo.SetCalibrationAngles(azimuths, elevations);
```

Computation and Results

Computation

- Once the calibration is done, you can perform the photometric stereo computation on the object images.

```
std::vector<EImageBW8> objectImages;

// Load object images in the same order than the calibration images/angles (Todo)

std::vector<EROIBW8> objectROIs;

// Set the object ROIs (Todo)

// Compute
photometricStereo.Compute(objectROIs);
```

- You can also use an ERegion.

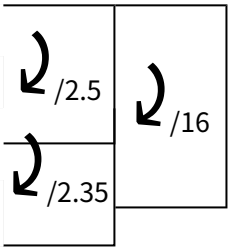
```
ECircleRegion circle;

// Define the ERegion (Todo)

// Compute
photometricStereo.Compute(objectROIs, circle);
```

- The computation time is proportional to the number of pixels in the image.

  To reduce this time, you can:
  - Set a smaller ROI.
  - Use an ERegion.
  - Use several threads.

  The following table shows the computation time in different configurations (when computing albedos, mean and gaussian curvatures with high contrast, see below).

Number of lights	Image size	Number of threads	Computation time (s)
4	4096 × 3072	1	1.473
		4	0.596
4	1024 × 768	1	0.092
		4	0.039



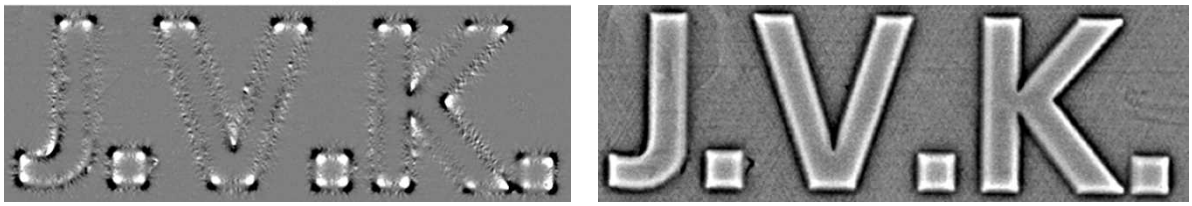
Retrieving the results

- Use the method Get··· or Compute··· of PhotometricStereoImager to retrieve your results.

```
// Retrieve the results
EImageC24 normals = photometricStereo.GetNormals();

EImageBW8 albedos = photometricStereo.GetAlbedos(Easy3D::EPhotometricStereoContrast_HighContrast);

EImageBW8 gradientsX = photometricStereo.GetGradientsX();
EImageBW8 gradientsY = photometricStereo.GetGradientsY();

EImageBW8 gaussianCurvatures = photometricStereo.ComputeGaussianCurvatures(Easy3D::EPhotometricStereoContrast_
HighContrast);

EImageBW8 meanCurvatures = photometricStereo.ComputeMeanCurvatures(Easy3D::EPhotometricStereoContrast_
HighContrast);
```

- The normals EImageC24 represents the x,y,z normals of the surface at each pixel.
  - A RGB pixel intensity of (0, 128, 255) corresponds to a x,y,z normal of (-1, 0, 1)
- The albedos EImageBW8 represents the fraction of light reflected at each pixel.
  - Compared to the input image, the albedo is independent of the lighting direction and intensity.
  - The albedos are normalized to the full image range.
- The gradientsX and the gradientsY EImageBW8 represent the gradients of the surface along the X- and Y-axis.
  - The gradients are clipped to +/- 3.715 before being mapped to the full image range.

- The gaussianCurvatures and the meanCurvatures EImageBW8 represent the local curvature of the surface at each pixel.
  - The gaussian curvatures are important when the curvature of the object is big in 2 orthogonal directions.
  - The mean curvatures only need an important change in 1 direction.
  - You can think of the gaussian and the mean curvatures as a corner detector and an edge detector.



The gaussian curvature highlights the corners and the mean curvature highlights the edges

GetAlbedos, ComputeMeanCurvatures and ComputeGaussianCurvatures

Most of the computations are done in the method Compute, however:

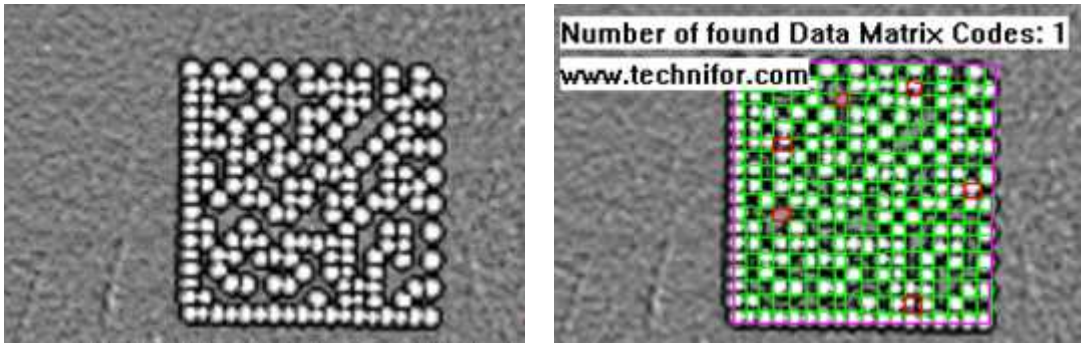
1. The last computations required for mean and gaussian curvatures are only performed when retrieving these maps to avoid computing them unnecessarily.
   - This is why these methods are named ComputeXXX instead of GetXXX.
   - The results are cached to avoid computing them several times.
2. Albedos, mean and gaussian curvatures are intrinsically floating point images. To convert them to EImageBW8, you can choose between several arguments:
   - EPhotometricStereoContrast_HighContrast to ignore outliers and produce images with a high contrast.
   - EPhotometricStereoContrast_FullRange to produce images where no data is ignored.
   - EPhotometricStereoContrast_FixedRange to produce images where the range is specified using an additional argument. This is especially useful when processing several different objects with a fixed threshold.

Processing the Results with Open eVision Tools

As the computation results are `EImageBW8`, you can process them with the various tools of Open eVision.

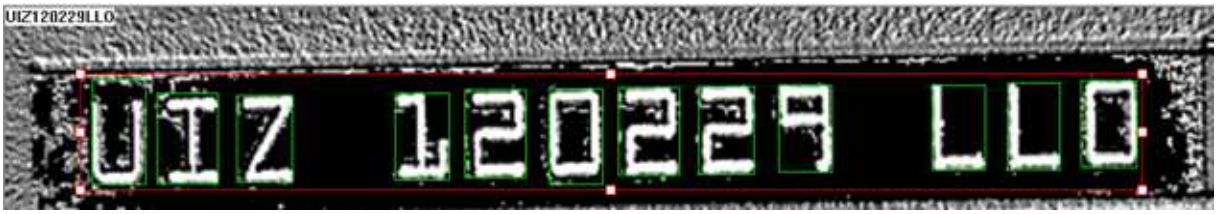
Here are some examples:

- Reading an embossed code with EasyBarCode2, EasyMatrixCode and EasyQRCode.



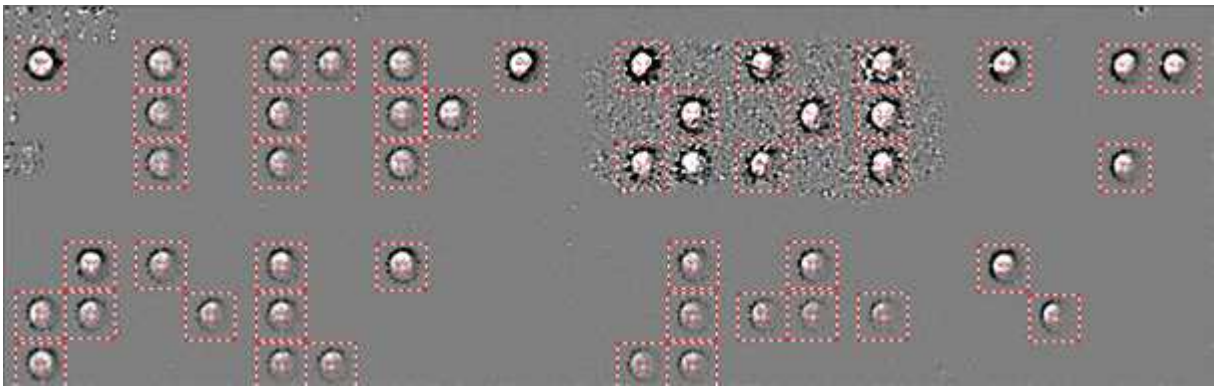
Mean curvatures of an engraved matrix code and EasyMatrixCode2 reading

- Reading an engraved text with EasyOCR2.



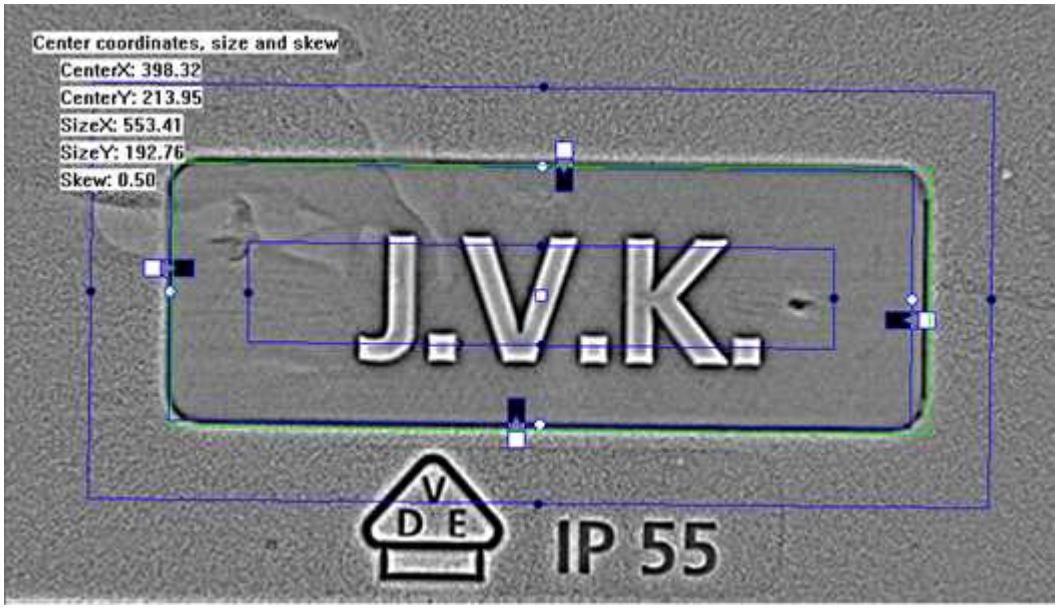
EasyOCR2 reading on the mean curvatures

- Finding patterns on embossed surfaces with EasyFind, EasyMatch and EasyObject.



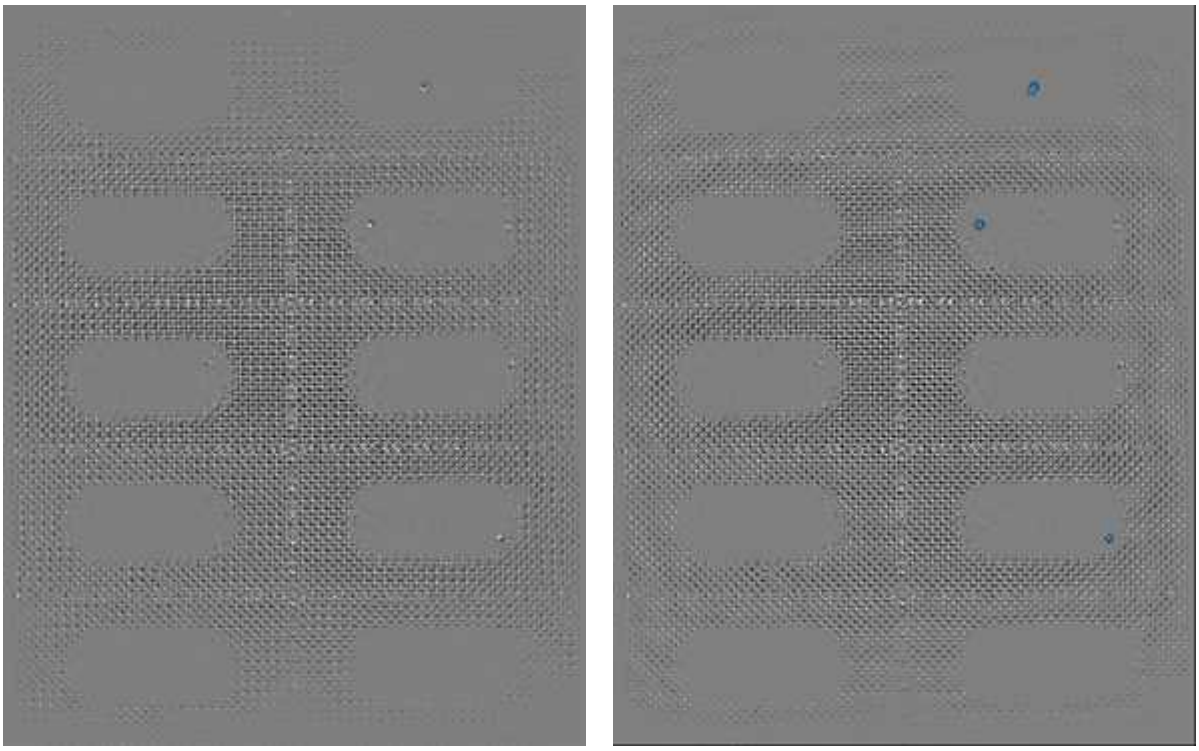
EasyFind results on the gaussian curvatures to detect braille characters

- Measuring shapes with EasyGauge.



Rectangle measurement with EasyGauge on the mean curvatures

- Finding defects in objects with EasySegment.



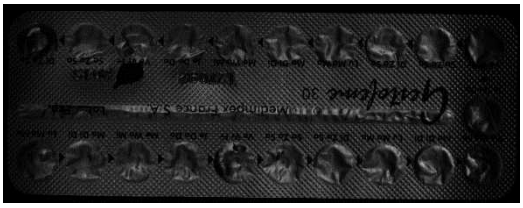
Gaussian curvatures of a blister pack with 3 holes and EasySegment supervised potential results

Improving the Results

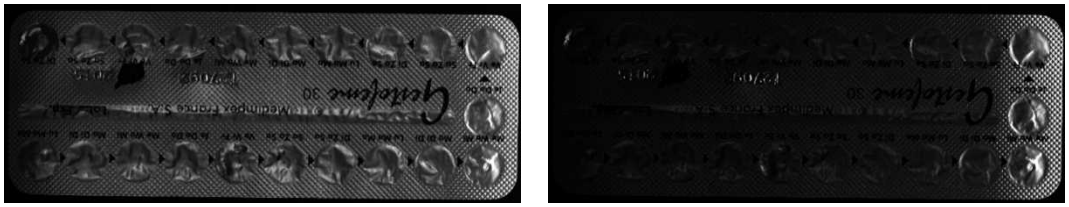
Using a dark image to account for ambient lighting

The photometric stereo assumes that each image is lit from a single light source.

- This assumption is not valid if the setup is exposed to (non-negligible) ambient lighting.
- To handle this issue, the `EPhotometricStereoImager` provides an `EImageBW8` dark image to the methods `Calibration` and `Compute`.
  - This dark image is an image of the object under ambient light only (all setup lights are off).



The dark image



The object image: raw (left) and after correction with the dark image (right)

Using flat images to correct non-uniform lighting

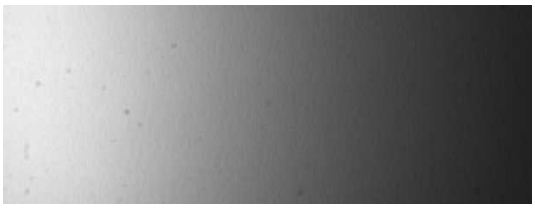
Photometric stereo assumes that each image is lit from an intensity uniform light source.

- This means that each pixel is lit by the same quantity of light.
- This assumption is not valid in physical setups using leds, where the part of the image closest to the leds receives more light.
- To handle this issue, the `EPhotometricStereoImager` provides a method to register a flat image used by the method `Compute`.
  - This flat image is an image of a uniform background taken in the same lighting configuration.

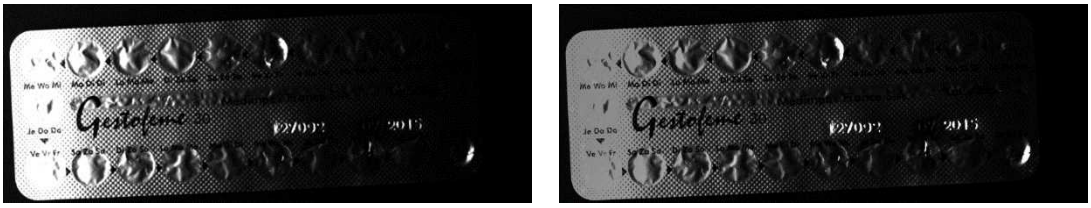
```
// calibrate imager or sets its angles (Todo)

std::vector<EImageBW8> flatImages;

// Load flat images in the same order than the calibration images/angles (Todo)

std::vector<EROIBW8> flatROIs;
```

```
// Set the flat images ROIs (Todo)

// Configure flat images, this could optionally be done with a dark image as well
photometricStereo.ConfigureNonUniformLightingCorrection(flatROIs);

// Perform one or more computations, each will use the flat images (Todo)
photometricStereo.Compute(objectROIs);

// Optional: non uniform lighting correction could be disabled or (re-)enabled
// using SetEnableNonUniformLightingCorrection
```

- The following example illustrates the effect of a non-uniform lighting correction on the object images.
  - The proximity of the light source generates a lighting effect on the left of the image that is visible on both the flat and the raw images.
  - This effect is corrected on the last image, where the brightest pixels are those oriented towards the surface.



The flat image

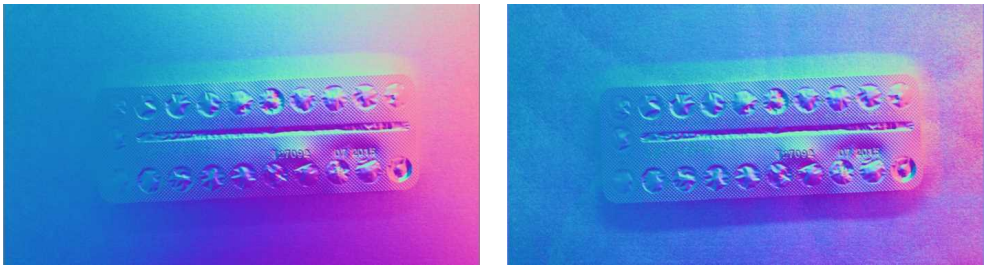


The object image: raw (left) and after correction with the flat image (right)

- The following examples illustrate the effects of a non-uniform lighting correction on 2 albedos images.
  - The corrected albedos show less burning on the extremities of the images.

The albedos images: raw (left) and after correction with the flat images (right)

- The following examples illustrate the effects of a non-uniform lighting correction on a normals images.
  - The normals fields is more uniform.



The normals image: raw (left) and after correction with the flat image (right)

Effect of the distance between lights and object

There is a tradeoff in the distance between the light and the object (that is the elevation angle).

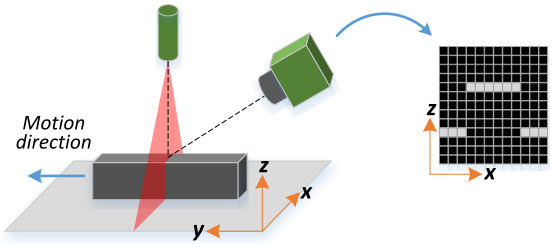
- When the elevation angle is high, the lighting is more uniform. This means that:
  - The “burning” effects visible on some images is less important.
  - The shadows are also less of a problem.
- When the lighting source is close, the lighting directions are more diverse. This means that:
  - The quantity of information used to build the photometric stereo is higher.

TIP
We recommend using elevation angles between 30 and 70°.
We achieve our best results around 40°.

3.2. Easy3DLaserLine - Laser Line Extraction and Calibration

Laser Triangulation

In a laser-line triangulation system, a laser line is projected on the object to measure. A camera is looking at the laser line from a different point of view. The line deformation observed by the camera contains the shape information of the measured object.



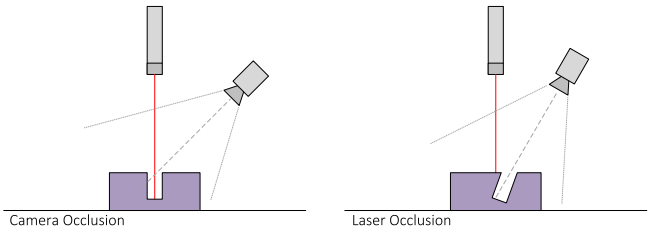
The scanning of the object consists in moving it under the laser line and recording multiple images.

From the scanning you can reconstruct its 3D shape.

Occlusions

Using the laser triangulation method, the laser may be unable to reach some parts of the object or the camera may be unable to view them. This is called occlusion.

- On the left illustration, the camera does not see the bottom of the hole, inducing camera occlusion.
- On the right illustration, the laser does not reach the bottom of the hole, inducing laser occlusion.



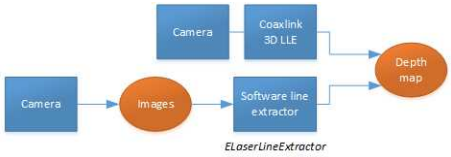
TIP
You can limit or avoid occlusions by using advanced scanning methods, for example by using two cameras or two lasers.

The Laser Line 3D Acquisition Pipeline

The 3D acquisition pipeline starts with the acquisition of a laser line profile and ends up with the point cloud, mesh or ZMap.

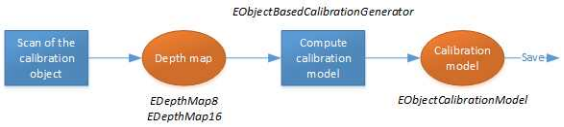
The source material for 3D processing is the depth map, coming from a Coaxlink Quad 3D-LLE or generated from a list of images.

3 types of depth map are available, one for each different pixel coding scheme (8, 16 or 32 bits).



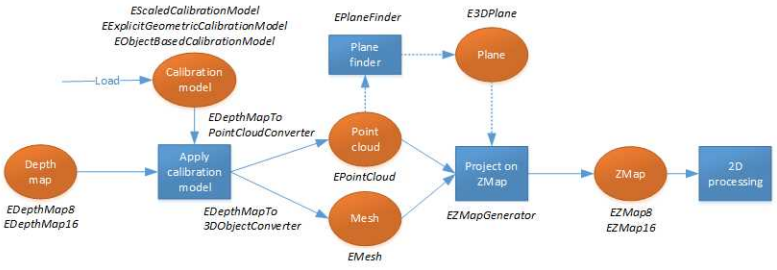
The generation of a depth map, from a hardware or a software source

Some processing methods can use the depth map directly, but most measurement and matching processes need metric, distortion-free representations. Calibration of the laser triangulation setup is therefore required. Calibration is used to turn the depth map into a point cloud or mesh expressed in a metric space that we call “world space”.



The generation of an object based calibration model, from a scan of the reference object

A point cloud is a list of 3D points, expressed in a world space coordinate system. The point cloud can be projected on a plane, producing a ZMap, which is a convenient and effective representation for 2D processing with a metric scale.



The workflow from the depth map to the ZMap

The following sections describe the classes and methods useful for a 3D workflow. The "Measuring a Remote Controller" on page 133 goes through this processing pipeline.

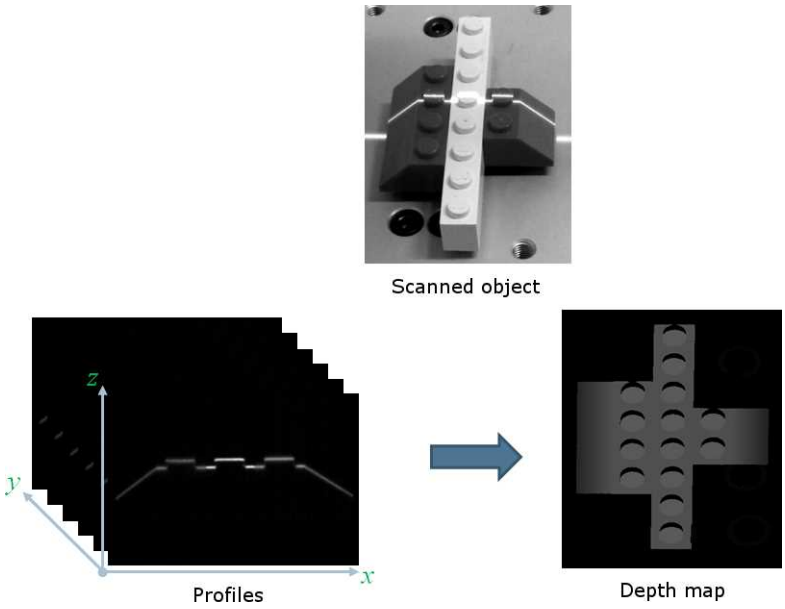
Laser Line Extraction

A Laser Line Extraction (LLE) algorithm is required to create a depth map from a sequence of profiles of the object captured by the camera sensor.

The objective of an LLE algorithm is to measure the line position along a vertical profile in every column of a sensor frame, within a user-defined region of interest (ROI).

For every step of the object position, the detection analyzes each column of a frame individually and produces a row of output positions, stored as gray values.

The figure below illustrates a depth map generation.

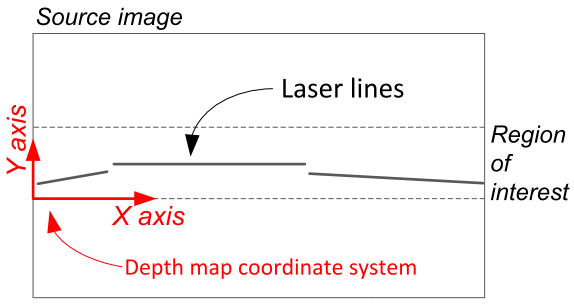


The `ELaserLineExtractor` class provides the laser line extraction functionality in Open eVision. It implements several algorithms to extract the laser line (see below for more details):

- **Maximum detection** returns the position of the pixel of maximum intensity. It's the fastest method but it doesn't support sub-pixel precision.
- **Peak detection** approach detects local maxima. If several maxima are detected, the one with the highest intensity is returned. The position is returned with sub-pixel precision.
- **Center of gravity** algorithm is suitable when the laser line is spread over several pixels. The position is returned with sub-pixel precision.

> **TIP**
> You can also set a threshold to exclude pixels with low intensity.

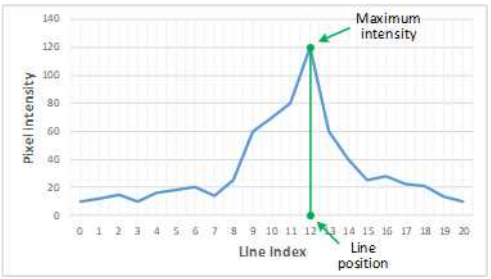
The line position returned by the laser line extraction algorithms is relative to the bottom of the region of interest. So, values in the depth map range from 0 (bottom of the ROI) to the height of the ROI.



Laser line extraction methods

Maximum detection

The maximum detection algorithm analyzes all the pixels in a ROI column to determine the one with the maximum intensity. The figure below shows the laser line position on a given ROI column.



Maximum detection on a ROI profile

We also recommend to include in the processing chain:

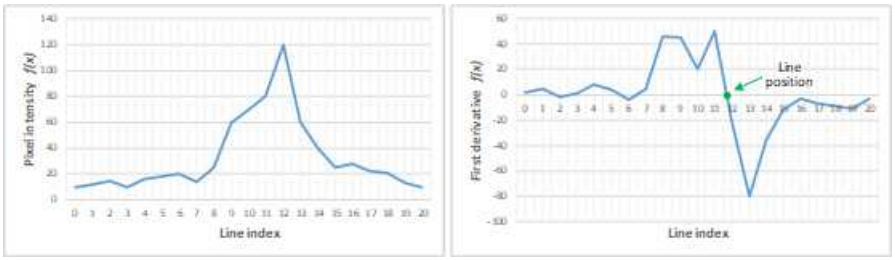
- A low-pass filter to reduce the high frequency variations in the image.
- A threshold to eliminate the background noise from the sensor.

Peak detection

The peak detection algorithm relies on a discrete simplification of the first derivative function.

$$\frac{df}{dx} = f(x+1) - f(x-1) = f'(x)$$

The $f'(x)$ outputs the slope of a given $f(x)$ along the x.



$f(x)$ and $f'(x)$ plots

We compute the line position by detecting where $f'(x)$ changes its signal based on the two-point form line equation:

$$y - y_1 = \frac{y_2 - y_1}{x_2 - x_1}(x - x_1)$$

where (x_1, y_1) and (x_2, y_2) are two points on the line with $x_2 \neq x_1$, we obtain the following equation for $y = 0$:

$$x = \frac{x_1 y_2 - x_2 y_1}{y_2 - y_1}$$

Center of gravity

The center of gravity (CoG) method uses an algorithm that calculates the center of mass of an image object. Also known as "centroid of plane figures", the CoG is obtained by the following equations:

$$\overline{X} = \frac{\sum ax}{\sum a} \quad \overline{Y} = \frac{\sum ay}{\sum a}$$

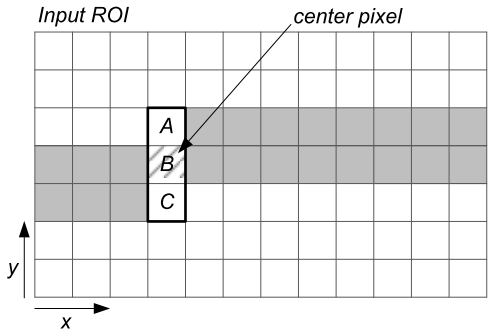
where $\overline{X}$ and $\overline{Y}$ are the coordinates of the CoG and a is the pixel intensity along the x and y axes.

Center of gravity on a ROI profile

Low-pass linear filter

Optionally, you can apply a low-pass linear filter in front of the line extraction in order to reduce noise and high frequencies in the image.

The low-pass filter applies a convolution operator on a 1 x 3 sliding window. The 3 elements of the convolution kernel (A, B and C) are configurable, accepting any positive integer. The figure below illustrates the positioning of the convolution kernel elements within a given ROI.



You can activate the low-pass filter for any of the laser line extraction methods with the method `ELaserLineExtractor::SetEnableSmoothing(true/false)`. Parameters A, B and C are set with `ELaserLineExtractor::SetSmoothingParameters(A, B, C)`.

Calibration

The calibration is used to apply the transformation between a depth map and a point cloud or a mesh.

There are 3 ways to set up this conversion:

- Apply a simple scale on the pixel coordinates of the depth map (`EScaleCalibrationModel` class)
- Use the explicit geometric model (`EExplicitGeometricCalibrationModel` class)
- Use the object-based calibration approach (`EObjectBasedCalibrationModel` class)

These models share the same base class `ECalibrationModel` and exposes the method `Apply()`, which is used to apply the conversion between a depth map pixel and a 3D point. It takes as input the coordinates of one point in a depth map and it returns the coordinates of the corresponding point in the 3D space.

The method `Apply` is not aware of the possible mirroring of the corresponding depth map and cannot make use of `EDepthMap::AxisSystemType` (see below). If necessary (when the corresponding depth map is vertically mirrored) the y coordinates should be flipped before calling the `Apply` method.

- The class `EDepthMapToPointCloudConverter` generates a point cloud from a depth map, using one of the calibration models.
- The class `EDepthMapToMeshConverter` generates a mesh from a depth map, using one of the calibration models.

By convention:

- The origin of the referential is the lower-left corner of the depth map.
- The center of the first pixel at the lower-left corner is at x = 0.5 and y = 0.5.
- The center of the pixel at the upper-right corner is at x = width - 0.5 and y = height - 0.5 where width is the width of the depth map and height is its height.

Mirrored depth maps

By default, Easy3D considers that the origin of the 3D axis of the depth map is the bottom left of the internal image buffer, and the Y axis is pointing up. This means that the depth map image is not seen as vertically mirrored compared to the real world image of the scanned object.

Nevertheless, depending on your acquisition setup this mirroring can happen (for example if the direction of the scan is inverted).

If this is your case, you can set the `EDepthMap::SetAxisSystemType` to `EAxisSystem_UpperLeftCorner`, meaning that the origin of the 3D axis is on the upper left corner and the Y axis is pointing down.

This value changes the behavior of the methods :

- `EObjectBasedCalibrationGenerator.Compute`
- `EDepthMapToPointCloudConverter.Convert`
- `EDepthMapToMeshConverter.Convert`

Scale calibration

The scale model (`EScaleCalibrationModel`) only applies a simple factor on the X, Y and Z axis. These factors are the only parameters of `EScaleCalibrationModel`.

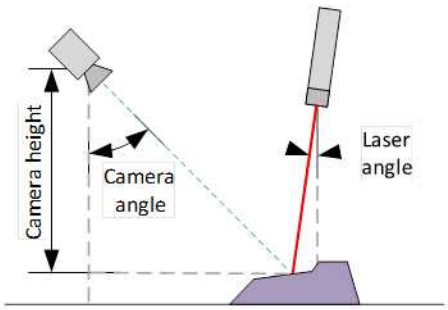
For depth maps coming from laser triangulation setup, this transformation does not produce corrected, metric points. It's main use is to display depth maps as 3D data with the `E3DViewer` class.

Explicit geometric calibration

The explicit geometric model (`EExplicitGeometricCalibrationModel`) defines a simple and ideal laser triangulation setup. The explicit calibration makes some strong assumptions on the setup geometry and can only be used when a minimum set of parameters are known:

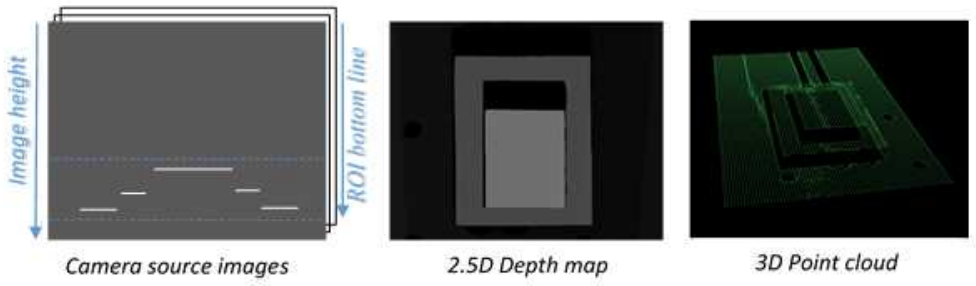
- The angles of the camera and the laser plane, in the counter clockwise direction. The camera angle must be positive.
- The height of the camera above the scanned object.
- The field of view of the camera defined by the sensor size (mm) and the optical focal length (mm).
- The physical distance between two line scans of the depth map (depends on acquisition rate and motion speed).
- The size of the image and the ROI origin used in laser line extraction (between the top (0) and the bottom (height) of the image).

TIP
Use the "Easy3D_Setup_Configuration.xlsx" spreadsheet to compute and check your setup configuration and parameters.



Explicit calibration setup with camera angle, laser angle and camera height

The setup of an explicit geometric calibration uses the constructor of the `EExplicitGeometricCalibrationModel` class.



Object-based calibration

Object-based calibration gives real world, metric, coordinates from an arbitrary laser triangulation setup. From the scan of a reference object, the calibration process tries to calculate all the parameters required for the transformation to the world space (position and attributes of the camera, position of the laser plane, relative motion of the object, optical distortion…).

For more details, please refer to the "Object-Based Calibration Guidelines" on page 87 section.

Object-Based Calibration Guidelines

Easy3D calibration is a powerful process that uses a single scan of a calibration object to calibrate a laser triangulation setup.

1. The calibration process generates a calibration model.
2. Easy3D uses this calibration model to transform the laser profile scans (or depth maps) into metric, distortion free point clouds.

- The calibration model includes all the geometric parameters required for this transformation:
  - The relative position of the laser and the camera.
  - The projection and the distortion model of the camera.
  - The relative motion of the object.

This document explains all the steps involved in the calibration process, from the design of the calibration object to the Open eVision API.

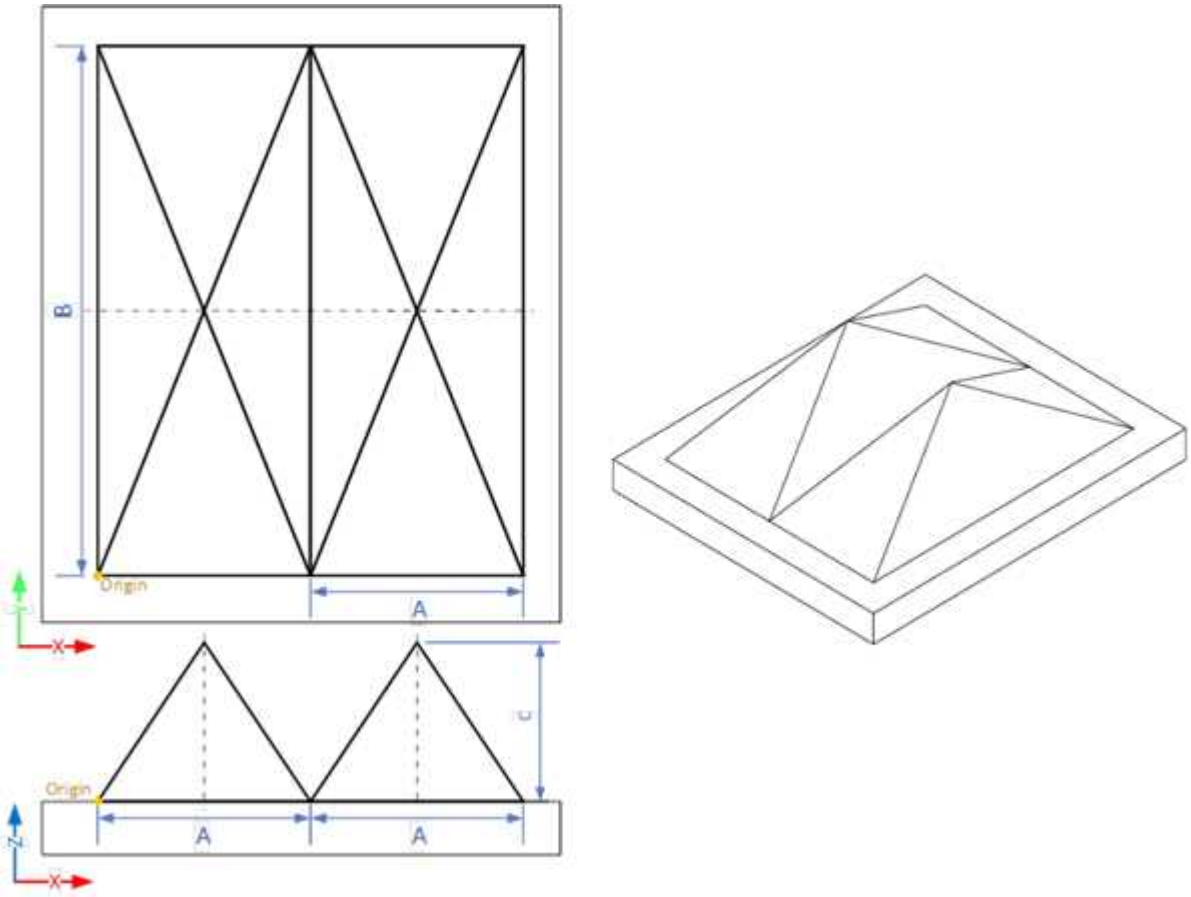
The calibration object

The general principle of Easy3D calibration is to match a scan of a known calibration object to its true geometric dimensions.

The double pyramid

TIP
In Open eVision 2.7 the “double truncated pyramid” calibration object is recommended over the "double pyramid" model.

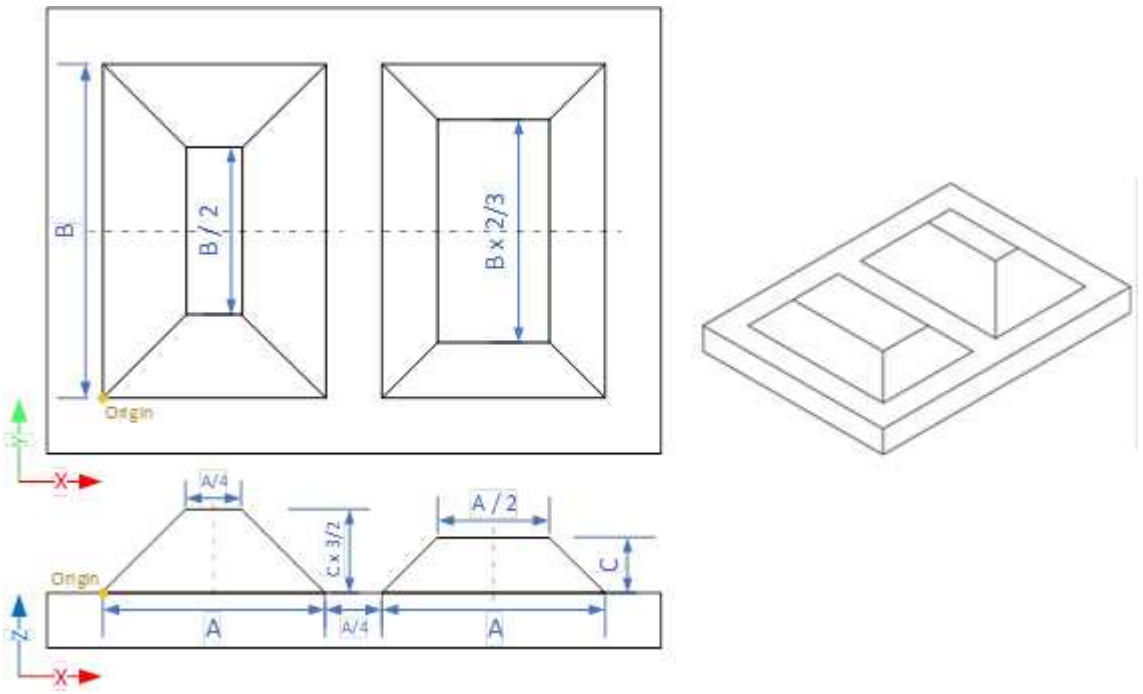
The dimensions of the “double pyramid” calibration object along the X-, Y- and Z-axes are named A, B and C respectively.



The "double pyramid" calibration model

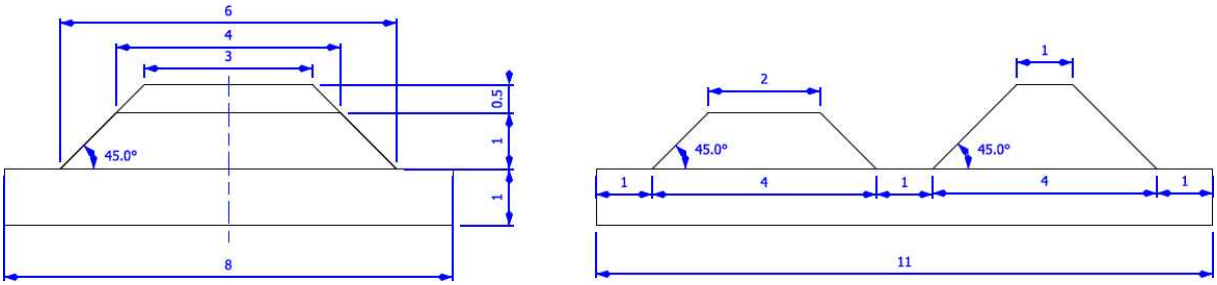
The truncated double pyramid

- The dimensions of the “double truncated pyramid” calibration object the X-, Y- and Z-axes are named A, B and C respectively.
- The design of the double truncated pyramid must follow the ratios given in the illustration below.



The "double truncated pyramid" calibration model (recommended)

- For example, the provided CAD files of the calibration object use A = 4 cm, B = 6 cm and C = 1 cm. The Calibration Object Size, required for the calibration process, are the values A, B and C.



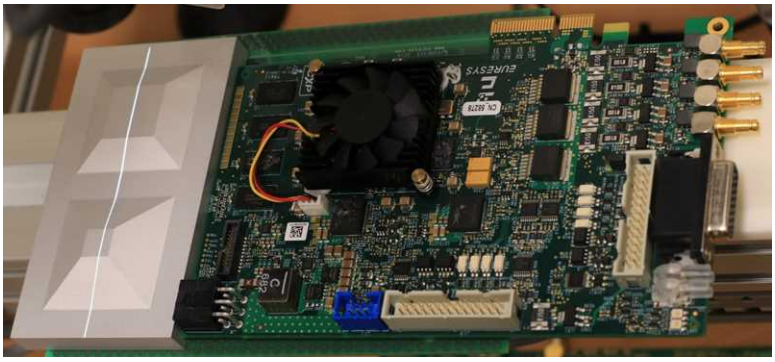
The "double truncated pyramid" calibration model with A = 4, B = 6 and C = 1

Building a calibration object

Overall dimensions

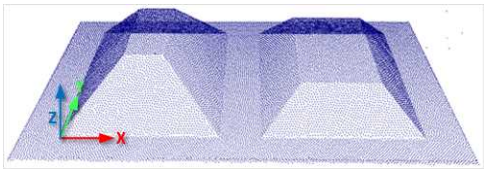
- Manufacture a calibration object that fits the working area of the project.
- For example, if the project targets the inspection of a PCB (a printed circuit board as illustrated), design your calibration object with:
  a. The dimension A or B (it does not matter) similar to the width of the PCB.
  b. The height (C) of only several millimeters.

> **TIP**
> This is not a strict requirement, if the scanned object is slightly larger or smaller than the calibration object, the calibration process is still valid.



A PCB scanning setup with the associated calibration object
The calibration object dimensions (A, B and C) match the width and the height of the PCB

> **TIP**
> There is no constraint on the orientation of the calibration object during the scan:
> - The X-axis can be aligned with the motion direction or with the laser line.
> - After the calibration process, the origin and axes of the 3D calibrated point cloud follow the conventions of the reference design.

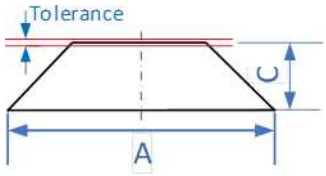


A calibrated point cloud with the origin and the axis of the coordinates system
The 3D origin is located at the external corner of the higher pyramid

Precision and tolerance

The relevant dimensions of the calibration object are the width, the length and the height of the pyramids (called A, B and C in the illustrations).

- The relative dimensions to A, B and C (B/2, A/4⋯) are important and you must execute them with the same precision.
- The dimensional tolerances are related to the overall expected precision.
  If you want to achieve measurements on the point cloud with a precision of 0.01 mm, the manufacturing of the calibration object must have the same precision.
- These tolerances only apply to the pyramids geometry, the calibration process does not use the dimensions of the support.
- The planar surfaces must be flat between 2 parallel planes separated by the target tolerance, as illustrated.



The tolerance of the pyramids sides is defined as the smallest distance between two parallel planes that contain the entire surface

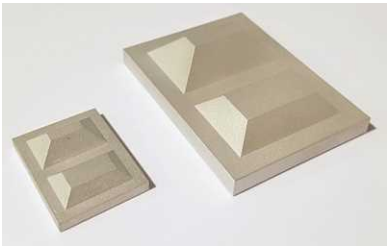
Material and surface finishing

TIP
The goal is to obtain the laser profile as thinnest as possible over the whole object surface with the largest reflected energy.

The build material and the surface finishing are also important and must have:

- A good reflectance, with diffuse reflection (no specular reflections).
- No transmission and limited diffusion inside the material.

TIP
You can obtain a good surface finishing using aluminum material and blasting. Blasting gives the surfaces a satin gray finish.

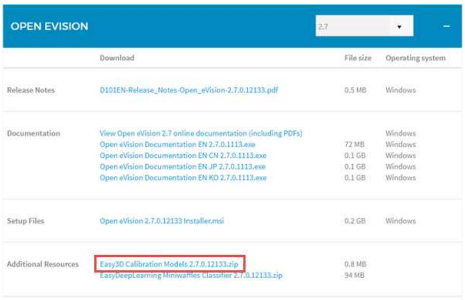


2 aluminum machined calibration objects with a micro-abrasive blasting surface treatment

3D CAD models

The calibration object models are available in various 3D CAD format like STEP, OBJ and STL.

Download these files from the Open eVision download area in the `Additional Resources` section (www.euresys.com/Support).



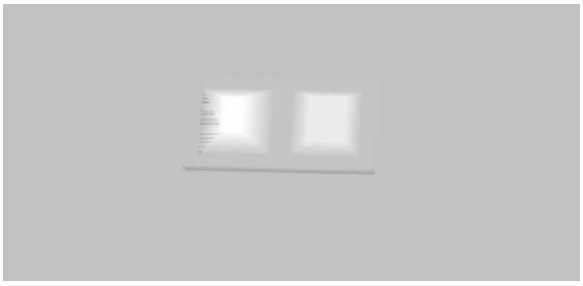
Download the calibration object models

Scanning the calibration object

- The scan of the calibration object produces a depth map.
- To ensure a correct detection of the calibration object and a precise calibration model, you must fulfill the following criteria:
  - All faces of the calibration object must be visible on the depth map (this affects the orientation of both the camera and the laser).
  - No other object can be higher than the calibration object in the depth map.
  - The depth map must have at least 200 x 200 pixels.
  - The calibration object must cover at least 50% of the defined pixels of the depth map.
- Examples of bad scans:

Missing pixels on the side faces

Not enough lines



The calibration object is too small on the depth map

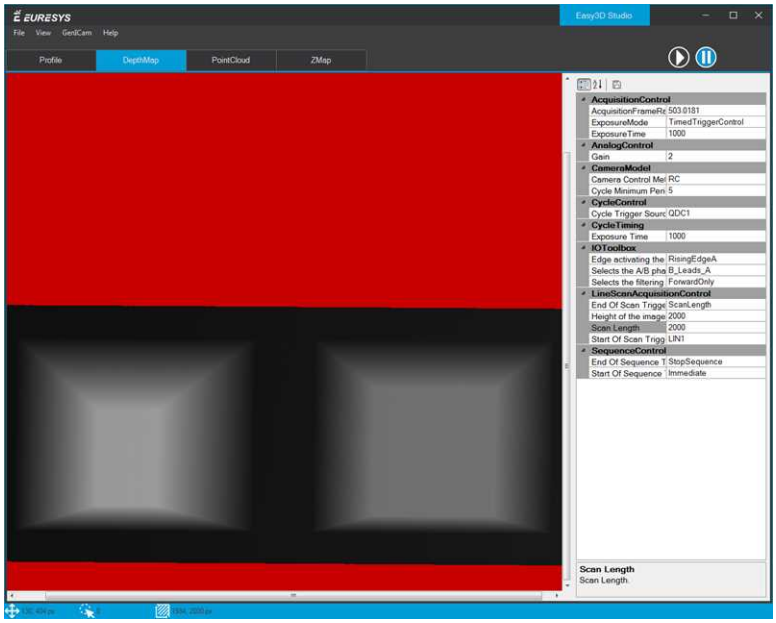
Calibration with Easy3D Studio

Easy3D Studio is a free application that helps you to set up a laser triangulation scanner. You can easily set the acquisition parameters of the Coaxlink Quad 3D LLE frame grabber and perform the calibration.

The DepthMap panel

This panel displays:

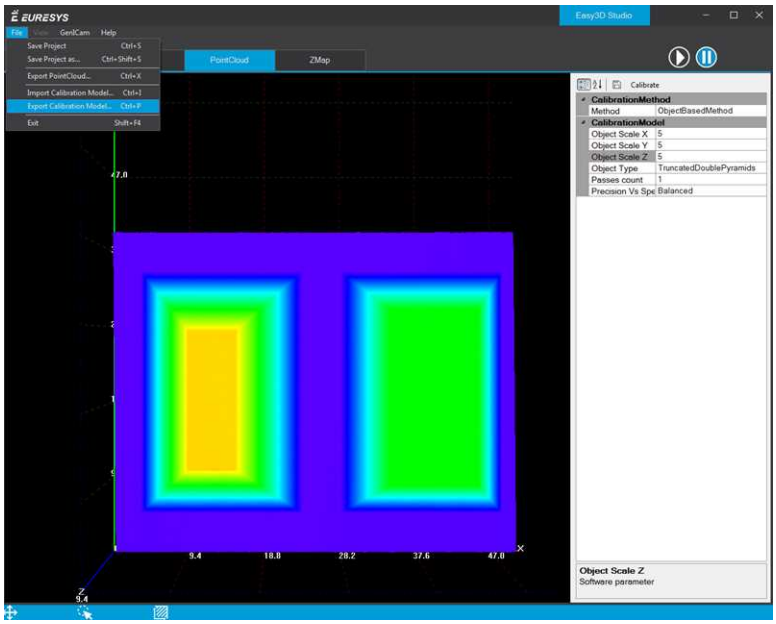
- The scanned image.
- The acquisition parameters on the right side.



The PointCloud panel

This panel displays:

- The depth map of the scanned image.
- The object-based calibration parameters on the right side.
- The Calibrate button computes the calibration model using the last scanned depth map.
- When the calibration model is ready, the depth map is transformed into a point cloud.
- You can export the calibration model for later use.



Required parameters

The calibration based on a calibration object requires several parameters:

- Set the Object Type as DoublePyramid or TruncatedDoublePyramid.
  - The DoublePyramid object type is deprecated and not recommended.
- Set the Object Size to represent the real size of the calibration object.
  - If your calibration object has a base of 20 mm by 30 mm and a height of 5 mm, set these values in the Object Size A/B/C parameters.
  - The point cloud after the calibration uses coordinates in millimeters.
- Set the parameter Precision Vs Speed Trade Off to define the time spent on the calibration process.
  - The 3 possible values are Fast, Balanced and Precise.
- Set the parameter Passes count to define the number of iterations used to refine the calibration model.
  - Use 1 for the fastest processing.
  - Use up to 3 for slower but potentially better calibration model.

Using the calibration with Open eVision

- The class `EObjectBasedCalibrationModel` is the container for the object based calibration model.
- The class `EObjectBasedCalibrationGenerator` performs the computation of such a model using an EDepthMap8/16/32f as input.

The following code snippet illustrates the calculation of a calibration model:

```
                    // Initialize a depth map from an image of a double truncated pyramid

                    EDepthMap►6 depth_map;
depth_map.LoadImage("ctx►calibration object.png");      // from Easy3D sample images
depth_map.SetZResolution(►.f / (► << 5));               // ►►.5 fixed point pixel format
// Initialize the calibration generator
EObjectBasedCalibrationGenerator calib_generator;
calib_generator.SetCalibrationObjectType(EObjectBasedCalibrationType_TruncatedDoublePyramid, 40.f, 60.f, ►0.f);
// Type and size of the calibration object

// Compute the calibration modelEObjectBasedCalibrationModel calib_model;
calib_model = calib_generator.Compute(depth_map);
float error = calib_model.GetCalibrationError();

// Save the calibration model
calib_model.Save("calib.model");.
```

The following code snippet illustrates the use of a saved calibration model:

```
                    // Load the calibration model
                    EObjectBasedCalibrationModel calib_model;
calib_model.Load("calib.model");

// Load a depth map (captured in the same context)EDepthMap►6 depth_map;
depth_map.LoadImage("ctx►shapes.png");
depth_map.SetZResolution(►.f / (► << 5));

// Initialize a converter, use the loaded modelEDepthMapToPointCloudConverter converter;
converter.SetCalibrationModel(calib_model);

// Convert the depth map to a metric point cloud and save itEPointCloud point_cloud;
converter.Convert(depth_map, point_cloud);
point_cloud.SavePCD("point_cloud.pcd");.
```

To experiment and learn about the Easy3D calibration, a C++ sample called `3DCalibration` is provided with the source code in the Open eVision distribution.

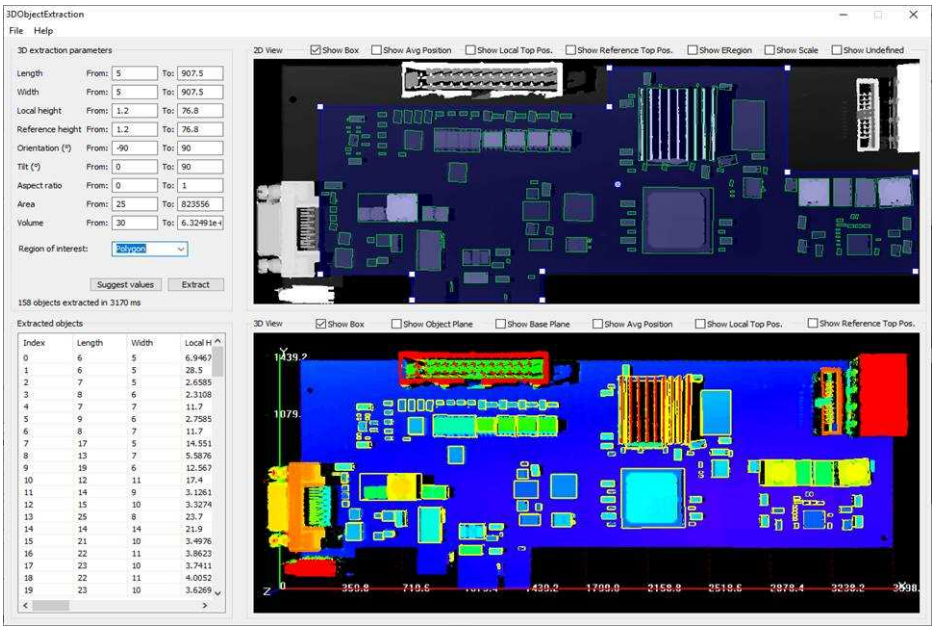
3.3. Easy3DObject - Extracting 3D Objects

Purpose and Workflow

Introduction

- The `Easy3DObject` tool extracts objects and their features from a ZMap.
  - The `E3DObjectExtractor` class uses a set of criteria to select the objects to extract.
  - The extracted objects are instances of the `ED3Object` class.
- Open eVision provides a demo application with C++ source code and 2 C++ / C# samples:

  This demo application exposes most of the features of the Easy3DObject tool.



Library workflow

1. Load or build a ZMap (from an image or a point cloud).
2. Construct an `E3DObjectExtractor` instance.
3. Set the selection criteria of the `E3DObjectExtractor` instance.
4. Extract the 3D objects, with or without an `ERegion`.
5. Get and process the extracted objects list.

Load or build a ZMap

A ZMap is a grayscale image with a metric coordinate system. It is sometimes referred to as a “height map”.

You can create a ZMap from an 8- or a 16-bit image or generate it from a point cloud.

- Before using an image as a ZMap, set the resolution.

> **TIP**
> The resolution is the metric size of a pixel (for example in mm / pixel) and the height difference between 2 consecutive grayscale levels.

- From a point cloud, use the `EPointCloudToZMapConverter` class to generate a ZMap. Choose the target ZMap resolution according to the point cloud sampling.
- Depending on the 3D scan precision, you can use a ZMap with 8- or 16-bit per pixel.

> **TIP**
> A 16-bit processing is more accurate but slower than an 8-bit processing.

Object Features

Units

Both the `E3DObjectExtractor` parameters and the `E3DObject` features are expressed in metric units.

- For example: if the resolution of the input `EZMap` is expressed in mm / pixel, the length parameter is expressed in mm.
- Use the `Resolution` accessors of the `EZMap` to query and change its resolution.

Angles are expressed in the unit defined by `Easy.AngleUnit`.

> **TIP**
> In this documentation, we use the default setting and all angles are expressed in degrees.

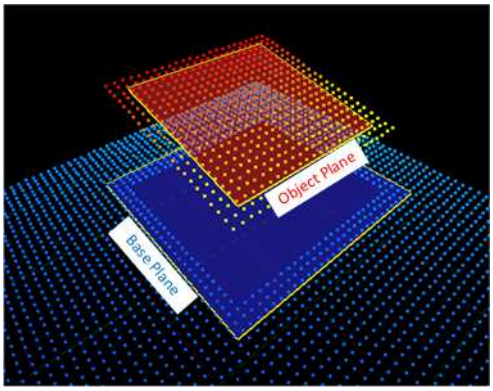
Object plane and base plane

The E3DObjectExtractor fits a plane to the pixels of each E3DObject output:

- Use E3DObject.Plane to access this plane.

The E3DObjectExtractor also tries to fit a plane to the pixels surrounding an E3DObject

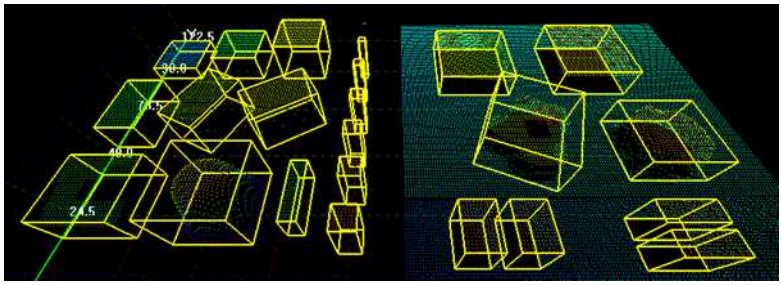
- This plane is called the *base plane*.
- It is an estimation of the local background around the object.
- If there are too many undefined pixels in this area, the base plane is equal to the reference plane of the input EZMap.



Bounding box

The *bounding box* is the minimal enclosing rectangle for all the object positions.

- It is oriented in the XY plane of the ZMap space (rotation around the Z axis of the ZMap).
- Its rotation is used as the orientation of the object (see E3DObject.GetOrientation).
- Its X and Y sizes are the object length and width (see E3DObject.GetLength and E3DObject.GetWidth).
- Its Z size is always in the Z axis of the ZMap direction.

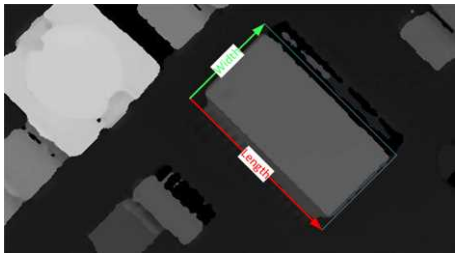


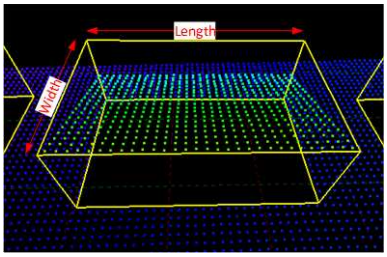
Length and width

The *length* of an object is the largest dimension on the XY plane in the ZMap space. It is the same as the size of the major axis of the bounding box.

The *width* of an object is the smallest dimension on the XY plane in the ZMap space. It is the same as the size of the minor axis of the bounding box.

Use the `E3DObjectExtractor.LengthRange` and the `E3DObjectExtractor.WidthRange` accessors to set the ranges of allowed values for the length and the width.





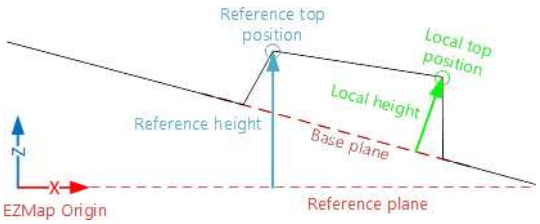
Local and reference top positions and heights

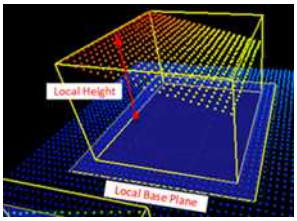
The *local top position* of an object is the position (3D coordinates) of the point in the `E3DObject` that is the furthest from the base plane.

The *local height* of an object is the distance between the local top position and the base plane.

The *reference top position* of an object is the position (3D coordinates) of the point in the `E3DObject` that is the furthest from the reference plane.

The *reference height* of an object is the distance between the reference top position and the reference plane.





If there are too many undefined pixels in the object surroundings:

- The base plane is equal to the reference plane of the input `EZMap`.
- The local top position is equal to the reference top position.
- The local height is equal to the reference height.

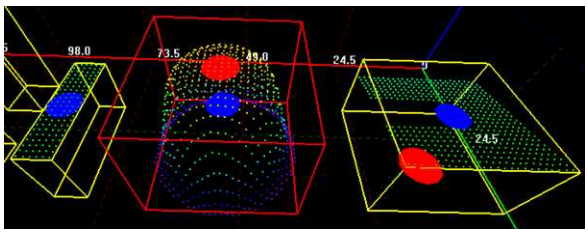
Use the `E3DObjectExtractor.LocalHeightRange` and the `E3DObjectExtractor.ReferenceHeightRange` accessors to set the ranges of allowed values for the local and the reference height.

Average position

The *average position* is the arithmetic mean of the 3D positions of the object, also known as the barycenter.

In the illustration below:

- The average position is displayed in blue.
- The top position is displayed in red.
- On the left object, the average and the top positions are at the same place.
- On the center object the average position is “inside” the object.

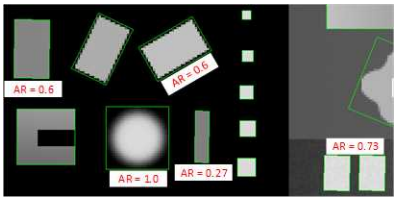


Aspect ratio

The *aspect ratio* is the width (the smallest dimension on the XY plane) divided by the length (the largest dimension).

- It lies between 0 and 1.
- The smaller the ratio, the more elongated the object is.
- A square has an aspect ratio of 1.

Use the `E3DObjectExtractor.AspectRatioRange` accessor to set the range of allowed values for the aspect ratio.

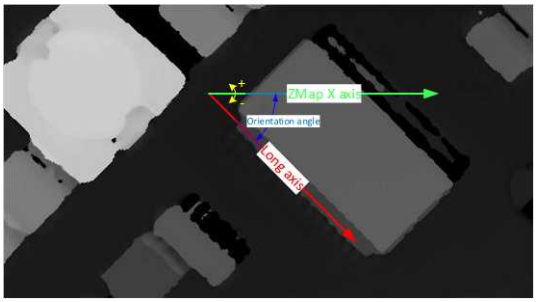


Orientation angle

The *orientation angle* is the angle between the X axis of the `EZMap` and the longest axis (the length) of the object.

- The angle is measured in the clockwise direction.
- The value must lie between -90° and +90°.

Use the `E3DObjectExtractor.OrientationRange` accessor to set the range of allowed values for the orientation angle.



Local and reference tilt angles

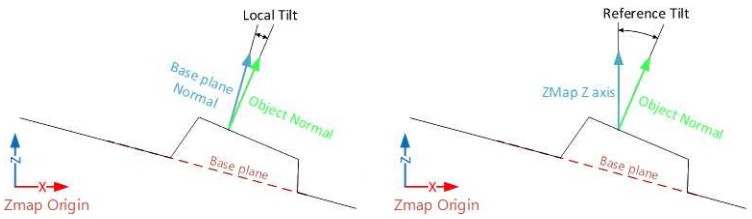
The *local tilt angle* is the angle between the base plane and the object plane.

- A value of 0 means that the object top surface is parallel to its base.
- The value must lie between 0° and +90°.

The *reference tilt angle* is the angle between the object plane and ZMap XY plane.

- A value of 0 means that the object top surface is parallel to its base.
- The value must lie between 0° and +90°.

Use the `E3DObjectExtractor.LocalTiltRange` and the `E3DObjectExtractor.ReferenceTiltRange` accessors to set the range of allowed values for the tilt angles.

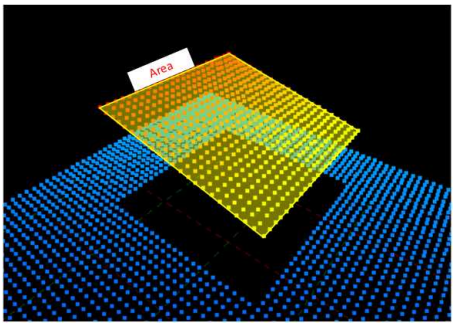


Area

The object *area* is the area of the top surface of the object projected on the reference plane of the `EZMap`.

- It is equal to [the number of pixels in the object] × [the x-resolution of the `EZMap`] × [the y-resolution of the `EZMap`].

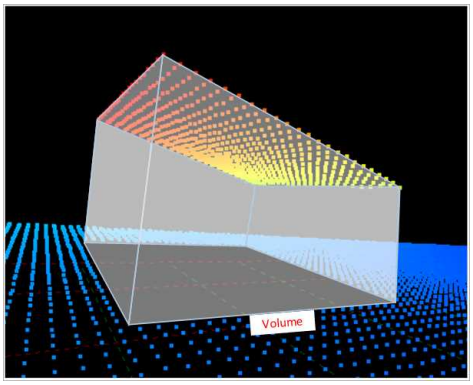
Use the `E3DObjectExtractor.AreaRange` accessor to set the range of allowed values for the area.



Volume

The object *volume* is the volume that lies between the top surface and the base plane of the object.

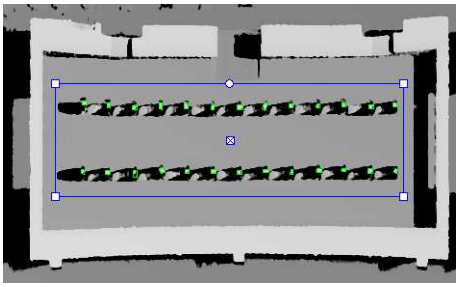
Use the `E3DObjectExtractor.VolumeRange` accessor to set the range of allowed values for the volume.



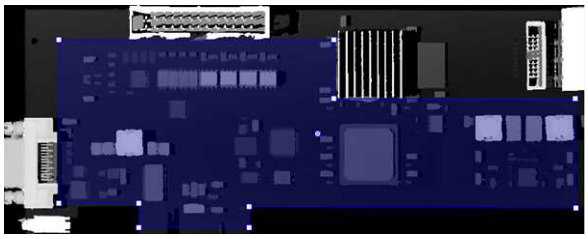
Extracting and Using Objects

Extracting the objects

Use the `E3DObjectExtractor.Extract` method to perform the objects extraction.



You can limit the extraction to an `ERegion`, for example to ignore parts of the ZMap that are not interesting and/or to speed up the extraction process.



The processing speed of the extraction depends directly on:

- The number of pixels in the ZMap or in the ERegion.
- The number of segmented objects.

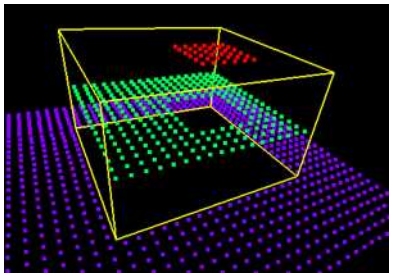
TIP
Adjust the extraction ranges to reduce the number of objects and speed up the extraction process.

Overlapped objects

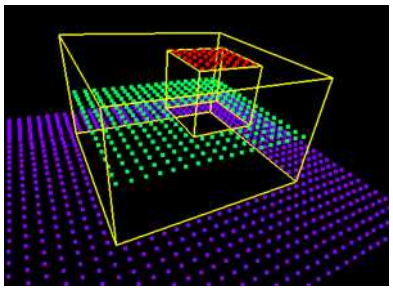
By default, the extraction does not produce objects that overlap on the ZMap. You must enable the `SetOverlappedObject` option to extract “stacked” objects.

The *area ratio* and the *height difference* parameters control how overlapped objects are extracted:

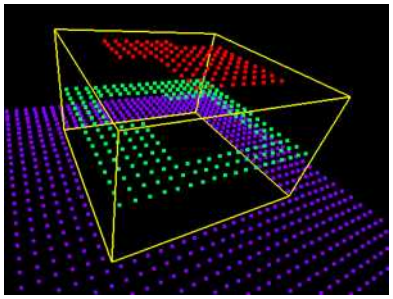
- The *area ratio* is configured by `SetOverlappedAreaRatio`. The area of the bottom object divided by the area of the top object must be larger or equal than that ratio.



Overlapped extraction is disabled.

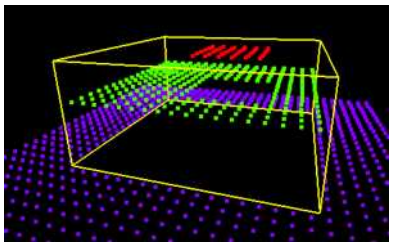


Overlapped extraction is enabled, with `OverlappedAreaRatio` = 4.

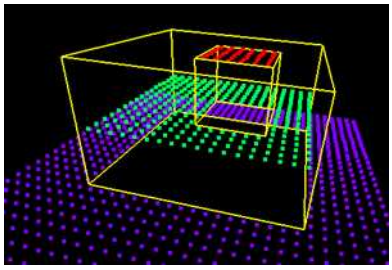


Overlapped extraction is enabled, with `OverlappedAreaRatio` = 4.
The top object is too large to be extracted, the ratio of the areas is lower than 4.

- The *height difference* is configured by `SetOverlappedHeightDifference`. This represent the minimum height difference between the top and the bottom object



Overlapped extraction is enabled, with `OverlappedHeightDifference` = 2.
The height of the top object (red) from the bottom object (green) is too small, the object is not extracted.

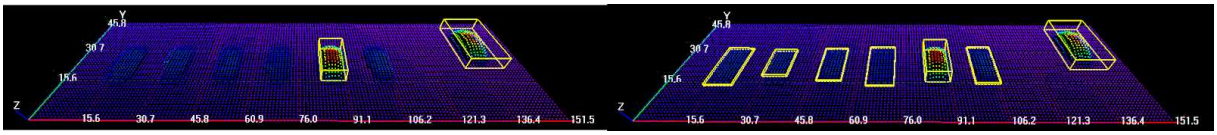


Overlapped extraction is enabled, with `OverlappedHeightDifference` = 2.
The height of the top object from the bottom object is larger than 2, the object is extracted.

Controlling the object detection

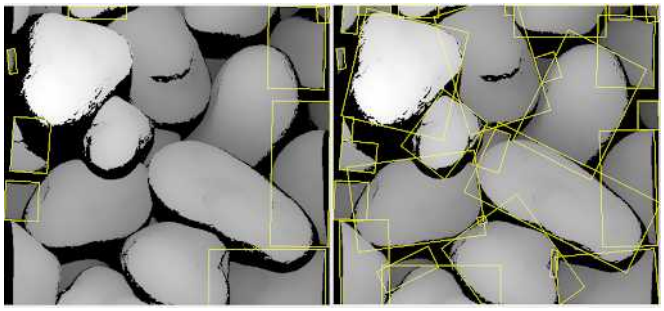
Two optional parameters affect the detection of the object:

- `SetExtractionSensitivity` controls the sensitivity of the extraction.
  - A higher value increases the ability to detect objects that are mixed with their surrounding, because their grey values are close to the background or because the transition (the gradient) between the object and the background is smooth.
  - This parameter value ranges from 0 to 1 (the default value is 0.6).



Extraction sensitivity: 0.5 (left) and 0.8 (right)

- `SetContourReinforce` affects the extraction of the objects.
  - As the extraction can fail when objects are close or touch each other, this parameter enables a filter to enhance the frontiers between objects and enable the extraction of such objects.
  - The filter can affect the measurements.



Contour reinforcement: OFF (left) and ON (right)

Using the objects

The E3DObjectExtractor.Extract method populates a list of E3DObject fulfilling your set criteria.

- Each E3DObject is a collection of descriptive features of the associated 3D points in the EZMap, such as its oriented bounding box, its local height and its volume.
- Call the associated E3DObject method to access a feature.
- The E3DObject list is sorted from the smallest area to the largest area.

The code snippet below provides an example for extracting features from the E3DObject list.

```
// get the extracted objects and loop over them
std::vector<Easy3D::E3DObject> objects = extractor.GetObjects();
int nObjects = objects.size();
for (int index = 0; index < nObjects; ++index)
{
  // inspect bounding box dimensions
  E3DPoint bbCenter = objects[index].GetBoundingBox().GetCenter();
  float bbHeight = objects[index].GetBoundingBox().GetXSize();
  float bbLength = objects[index].GetBoundingBox().GetYSize();

  // inspect object plane and base plane
  Easy3D::E3DPlane opjPlane = objects[index].GetPlane();
  Easy3D::E3DPlane basePlane = objects[index].GetBasePlane();

  // inspect the ERegion that exactly contains the object
  ERegion objRegion = objects[index].GetRegion();
}
```

Visualizing the objects

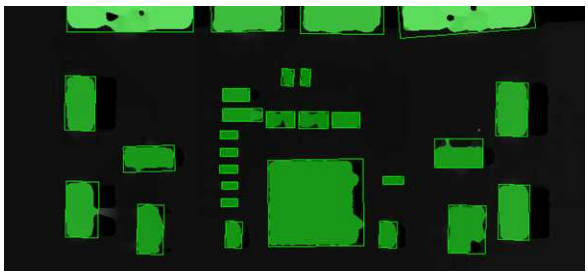
To visualize some of these features in 2D or 3D:

- Use the E3DObject.Draw method.
- Or submit a list of E3DObject to an E3DViewer.

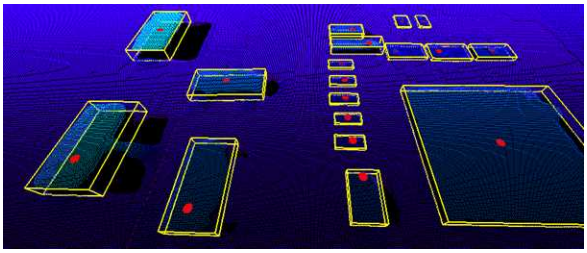
> **TIP**
> In an E3DViewer, use the ERenderStyle structure to choose your rendering style.

The following code snippets illustrate how to draw some object features:

- In a 2D graphic context: Drawing a 2D Feature from the List of E3DObjects



- In a 3D viewer: Drawing 3D Features from a List of E3DObjects

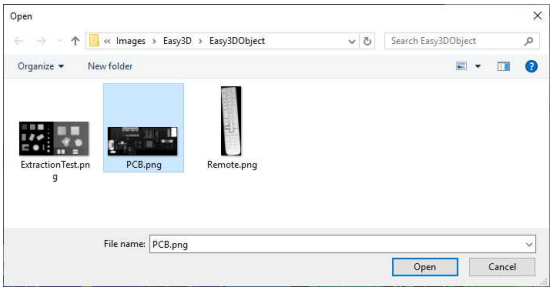


Use Case - Inspecting a PCB

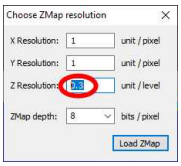
The purpose of this use case is to test if all the components are present and correctly placed on the PCB.

TIP
This example uses the sample image `Sample Images\Easy3D\Easy3DObject\PCB.png` and the illustrations are based on the Easy3DObject demo application.

1. Load the PCB image.



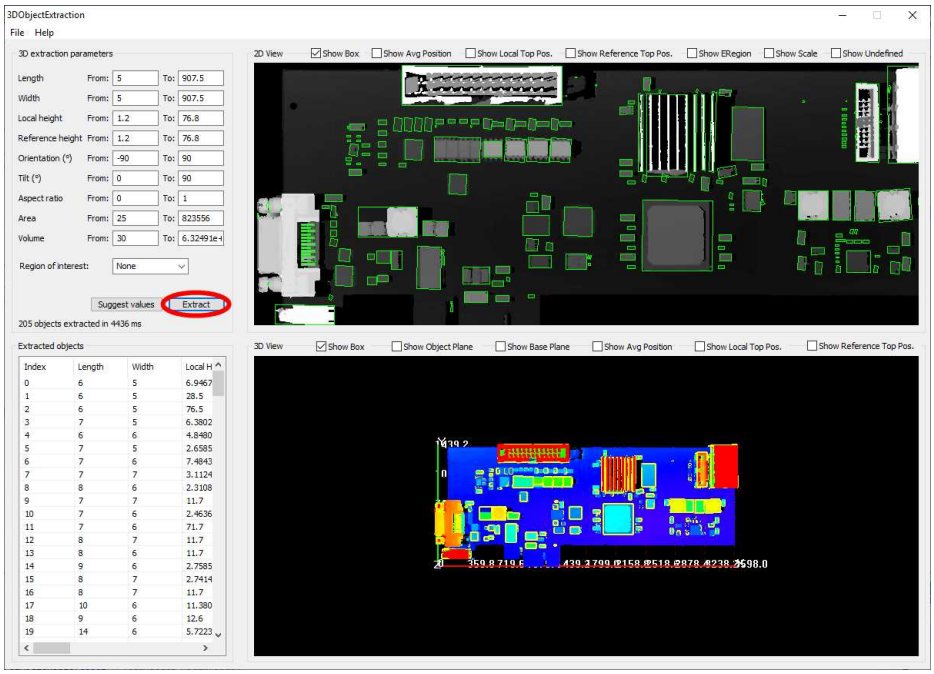
2. Set the resolution.
   - The provided PCB sample is an 8-bit gray scale image.
   - Use a Z resolution of 0.3 metric unit per gray scale level for a realistic proportion.



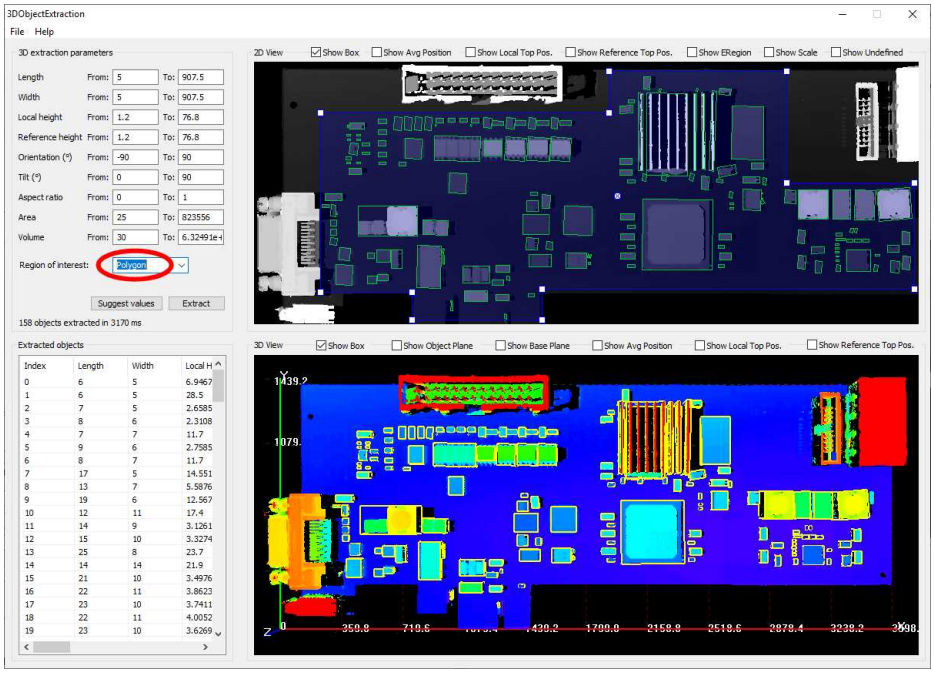
3. Keep the suggested parameters for a first extraction.
   - The suggested parameters are set from the ZMap width, height and resolution.

4. Click on the `Extract` button to perform the extraction.

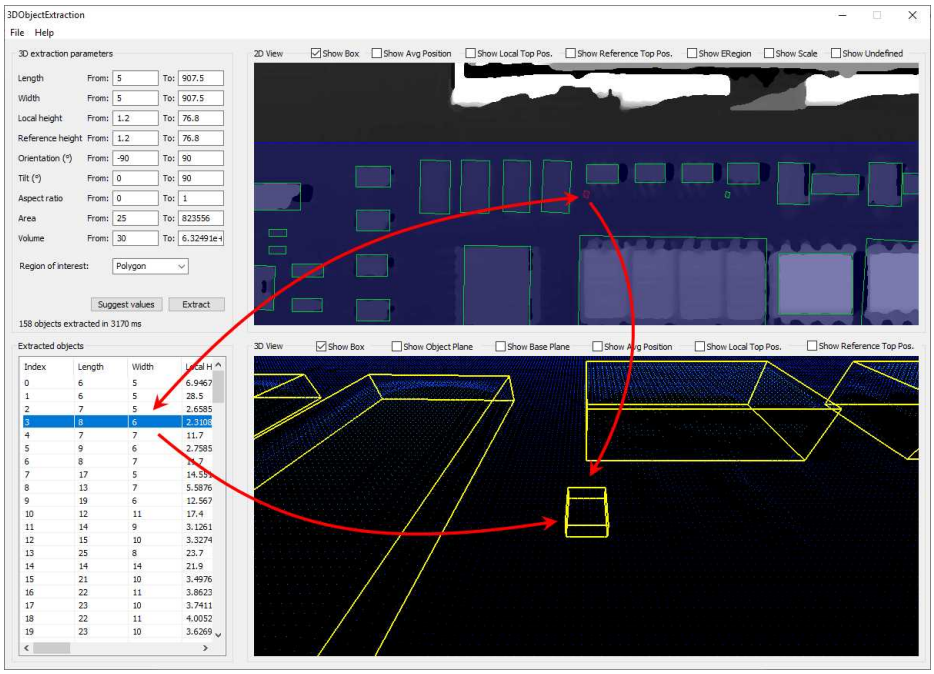
   When the extraction is done:
   - The object list is filled.
   - Click on a column title to sort the object list.
   - The various measures are displayed.
   - The 2D View and the 3D View show the extracted object bounding boxes.



5. Use a polygon region of interest to restrict the searched area.
   - You can limit the extraction to a region defined as a rectangle, a polygon or an ellipse in the demo application.
   - Use the Open eVision API, to define and use any `ERegion`.



6. Press again the `Extract` button to generate a new list of objects. Now, only the objects located inside the region are extracted.
7. The 2D View and 3D View automatically focus on the object selected in the list. You can also select an object by clicking on a bounding box in the 2D View.

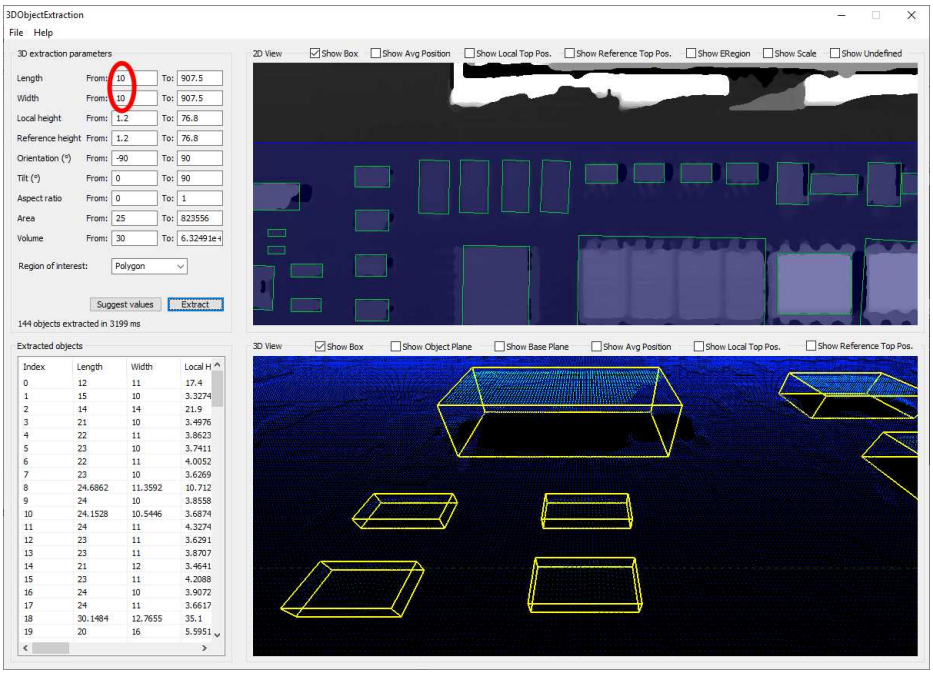


8. Use the size ranges to discard the smaller components.

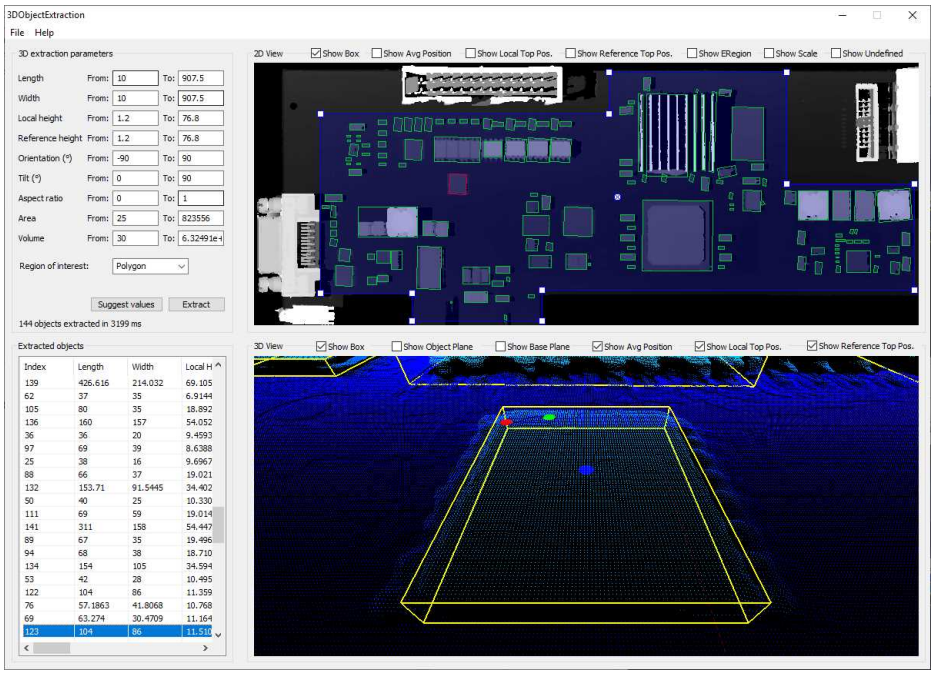
To add or remove objects:

- Change the extraction parameters, like the length and width ranges.
- In the illustration below, objects smaller than 10x10 metric unit are not extracted.

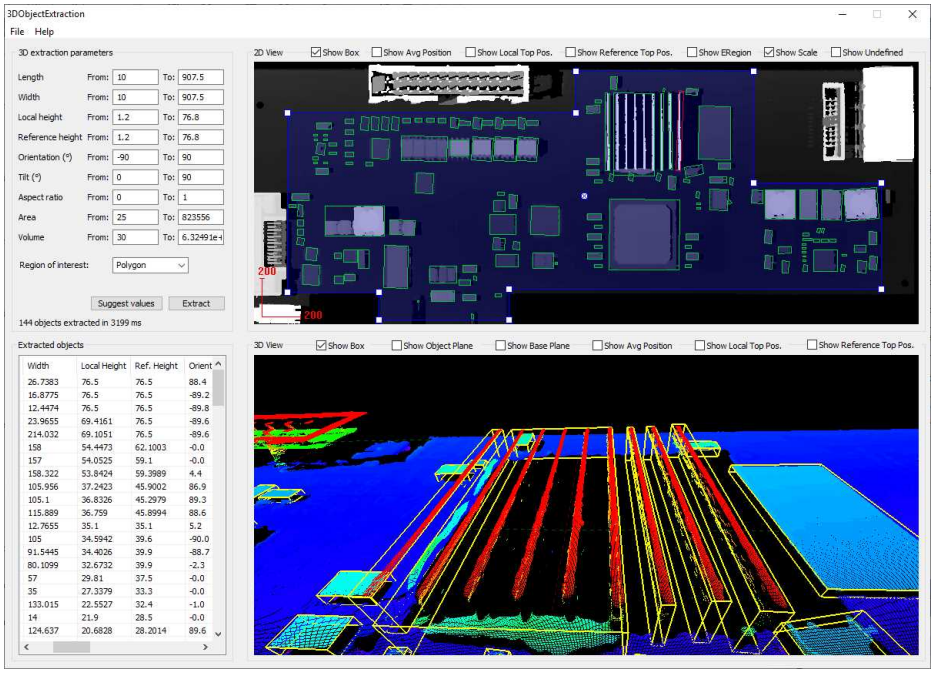
NOTE
After changing a parameter, press the `Extract` button to perform a new extraction.



9. Check or uncheck the boxes at the top of the views to toggle the display of most of the object features, either in the 2D View or the 3D View.
   - In the illustration below, the object list is sorted by local height.
   - The first object is selected and displayed in both views.

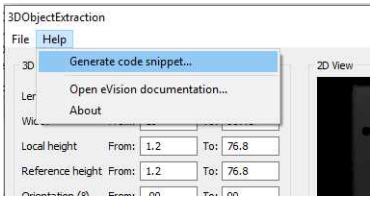


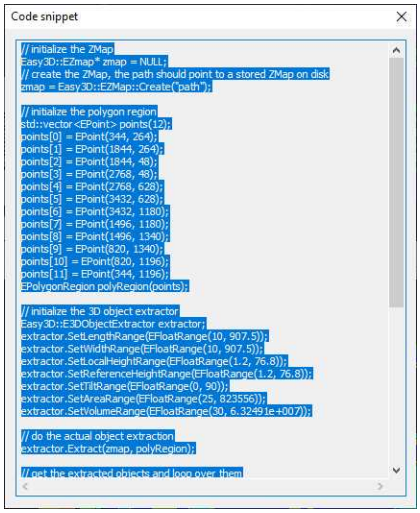
10. Adjust the extraction parameters to accept or reject objects based on the results.



11. Open the `Help` menu and click on `Generate code snippet` to generate the C++ code corresponding to the current configuration.

    The generated code illustrates how you can:
    - Load a ZMap.
    - Define a region.
    - Set the configuration parameters of the extraction.
    - Start the extraction process.
    - Iterate through the resulting objects list.





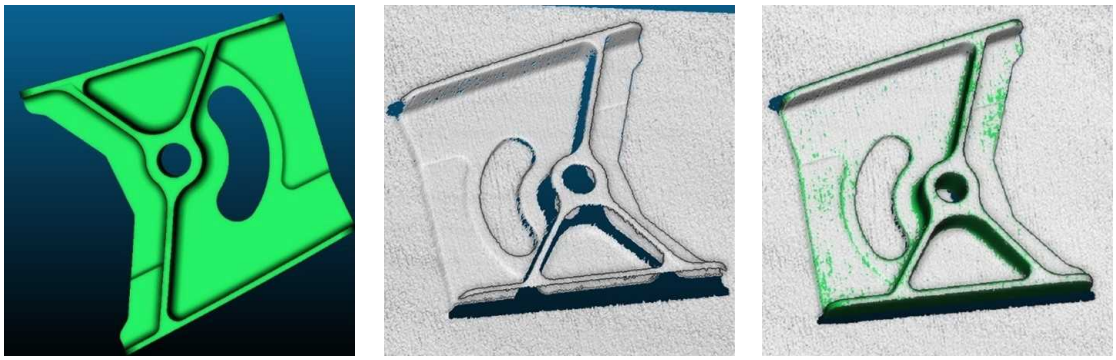
3.4. Easy3DMatch - 3D Alignment and Comparison

Purpose and Workflow

Purpose

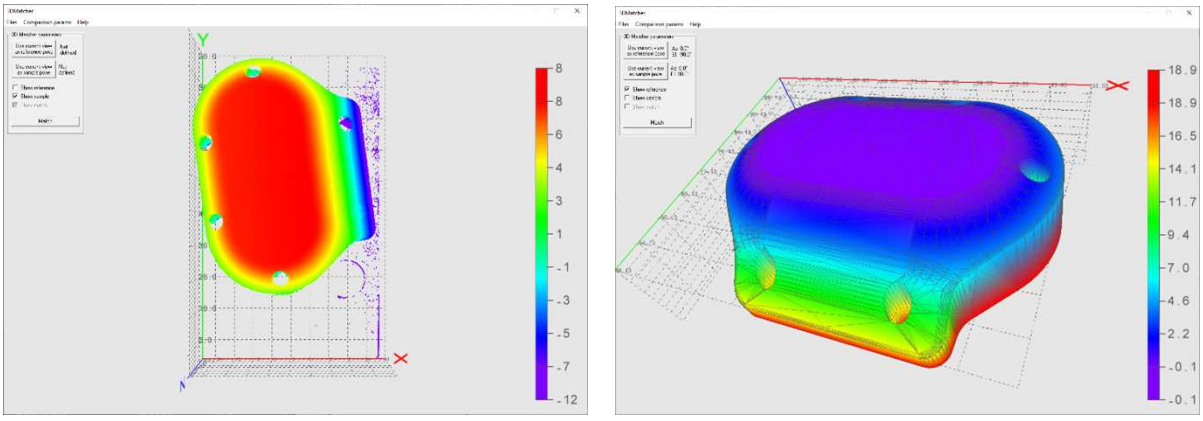
Easy3DMatch allows you to:

- Align a scanned object with another scan or with a reference mesh.
  - The Easy3DMatch tool features alignment functions to find the exact pose (position and orientation) of acquired 3D objects using a reference model.
  - You can specify this model as a reference point cloud or as a 3D mesh from CAD software.

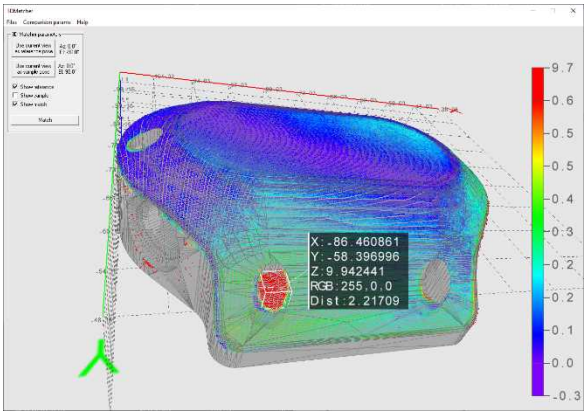


CAD model — sample point cloud — model and sample aligned
(3D models courtesy of Direct Dimensions)

- Compare an aligned scan with a reference model or mesh:
  a. Compute the local distances between 3D scans and a golden sample or a reference mesh.
  b. Detect anomalies such as misplaced features, geometric distortions, gaps and bumps.



Reference — sample
(3D CAD models courtesy of Direct Dimensions)



Result of the comparison

Workflow

1. Load a reference as:
   - A mesh (define its viewpoints)
   - A point cloud (with one viewpoint)
   - A ZMap
2. Load a sample, either as:
   - A point cloud (with one viewpoint)
   - A ZMap
3. Perform alignment and/or matching:
   - Optionally, align the sample and get its `E3DAlignment` with respect to the reference (`E3DAligner`).
   - Optionally, compare the sample to the reference by defining ROIs as `3DBox` (`E3DComparer`).
   - Align the sample and compare it directly to the reference by defining ROIs as an `ERegion` (`E3DMatcher`).
4. Use the transformation from sample to model to locate the sample and/or process the detected `E3DAnomalies`.

Resources

- The example described here demonstrates how to use Easy3DMatch with Open eVision 3D tools.
- You can also find a sample application, with its source code, in `…\Sample Programs\MsVc samples\3DMatcher`. Most of the illustrations are screenshots from this sample.
- The example and the sample application are based on the following resources:
  - Open eVision 2.16
  - Microsoft Visual Studio 2017
- You need the Easy3DMatch license to use it.

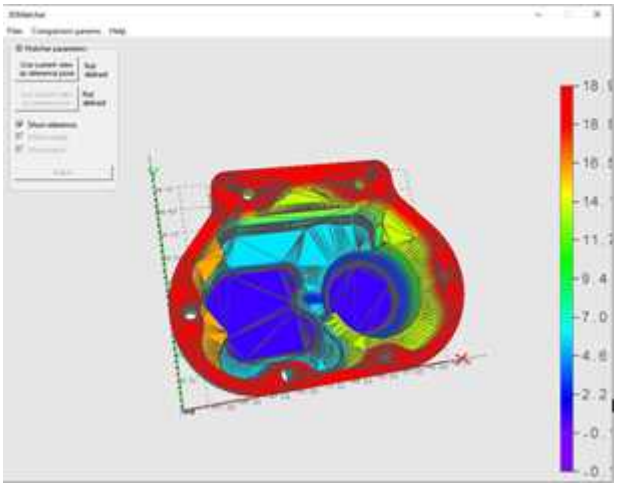
Alignment (E3DAligner)

Base case

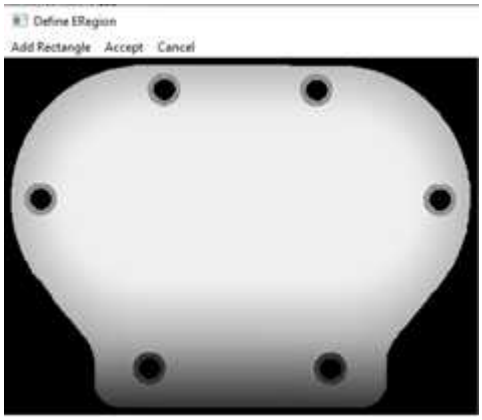
Use the class `E3DAligner` to load a reference and a sample and to find the transformation from the sample to the reference.

1. The first step is to set the reference using the method `SetReference`.
   - In addition to the mesh or the cloud, this method also takes one or several `E3DPlane` or azimuth and elevation angles (see "Calibration" on page 69 for a definition of the azimuth and the elevation).
   - The angles are used to compute the plane and are just an easier way to specify it.
2. The goal of the plane is to specify the face(s) of the object that can be visible on the sample.
   - You must do this only once for the reference and once for the sample(s), assuming they are all taken with the same scanner.

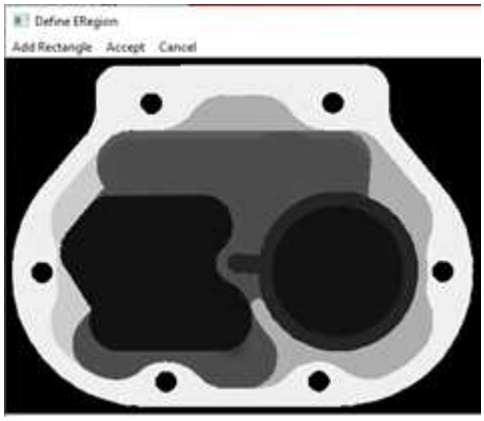
   Here is an illustration of the process:



View of the CAD



Bottom face, corresponding to the plane of the normal (0, 0, -1) and equation z = 15 or an azimuth of 0° and an elevation of -90°



Top face of the object, corresponding to the plane of the normal (0, 0, 1) and equation z = -15
or an azimuth of 0° and an elevation of 90°.

3. Call the method `Align` with a point cloud or a zmap and get an object `E3DAlignment` that contains:
   - The pose, an `E3DTransformMatrix` mapping the sample to the reference.
   - The error, indicating the quality of the matching.
   - The index of the reference pose that was matched. This is useful when several poses are defined (in the example above, there are 2 poses defined).

Defining a reprojection plane to improve the results

Ideally, the sample (and the point cloud or the ZMap used as reference) should be aligned on the viewpoint. This is however not always true, for example when the scanner does not lay on top of the object. In these cases, the user may specify the plane on which the object lays, either by giving an `E3DPlane` or a flat scan on which only the plane is visible.

In both cases, the plane normal must have the correct orientation (pointing upwards or downwards), that is if the plane is above the normal (z object > z plane), the z coordinate of the normal should be positive. This is specified either directly in the `E3DPlane` or by a boolean argument `objectAbovePlane` when giving a flat scan.

Code samples

Base sample

```
////////////////////////////////////////////////
// This code snippet shows how to compute the     //
// alignment between a sample and a cad reference.//
////////////////////////////////////////////////

// load the reference mesh and define the pose
Easy3D::E3DAligner aligner;
Easy3D::EMesh cad;
cad.Load("…");
float azimuthReference = 0.f, elevationReference = 90.f;
aligner.SetReference(cad, azimuthReference, elevationReference);

// load the sample
```

```
Easy3D::EPointCloud sample;
sample.Load("…");
float azimuthSample = 0.f, elevationSample = 90.f;

// perform alignment
Easy3D::E3DAlignment alignment = aligner.Align(sample, azimuthSample, elevationSample);
```

Use a reprojection plane

```
////////////////////////////////////////////////
// This code snippet shows how to set the     //
// reprojection plane when performing alignment.  //
////////////////////////////////////////////////

// load the reference mesh and define the pose
Easy3D::E3DAligner aligner;
Easy3D::EMesh cad;
cad.Load("…");
Easy3D::E3DPlane refPlane(Easy3D::E3DPoint(0, 0, ⌙), 0);
aligner.SetReference(cad, refPlane);

// define the reprojection plane
bool userKnowsPlaneAZEl = false; // depending on the user
if (userKnowsPlaneEquation)
{
  Easy3D::E3DPlane reprojectionPlane(Easy3D::E3DPoint(0, 0, -⌙), -⌙5);
  aligner.SetScanReprojectionPlane(reprojectionPlane);
}
else
{
  Easy3D::EPointCloud cloud;
  cloud.Load("…");
  bool objectAbovePlane = true; // is the object above the plane on the cloud
  aligner.SetFlatScan(cloud, objectAbovePlane);
}

// load the sample
Easy3D::EPointCloud sample;
sample.Load("…");
float azimuthSample = 0.f, elevationSample = 90.f;

// perform alignment
Easy3D::E3DAlignment alignment = aligner.Align(sample, azimuthSample, elevationSample);
```

Use `E3DAlignment` to align a sample on the reference

```
////////////////////////////////////////////////
// This code snippet shows how to apply the   //
// transformation of the E3DAlignment to the  //
// sample to overlap it on the reference      //
////////////////////////////////////////////////

// perform alignment (see previous examples)
Easy3D::E3DAlignment alignment;
EPointCloud sample;

// align sample on reference
Easy3D::EPointCloud alignedSample;
Easy3D::EAffineTransformer::ApplyMatrix(alignment.GetPose(), sample, alignedSample);
```

Computation Time

The following table shows the computation time on a representative object. The first step of an alignment is to decimate the given `EPointCloud` (a very large cloud may explain important computation times).

Number of threads	Computation times
1	811 ms
2	618 ms
4	570 ms

Comparison (E3DComparer)

Base case

Use the class `E3DComparer` to load a reference and an already aligned sample (for example by using `E3DAligner`) and to find the distance map between both as well as anomalies.

- To use the `E3DComparer`:
  - Use the method `SetReference` to specify the reference with either an `EMesh` or an `EPointCloud`.
  - Set the options of the comparison (ROIs and thresholds).
  - Call the method `Compare` with the sample `EPointCloud`.
  - Use `ComputesAnomalies` to retrieve the list of `E3DAnomaly`.
  - Use `GetComparisonPointCloud` to retrieve the `EPointCloud` containing the distances.
- An `E3DAnomaly` represents a specific area in which the discrepancies between the sample and the reference are important. They are represented by:
  - An `EPointCloud` containing all the points of the anomaly and their distance to the sample.
  - The area of the anomaly.
  - Its center of gravity.
  - A bounding box around the anomaly.

  Note that the `E3DAnomaly` represents points on the reference (except on `NoExtraMaterial` regions and when the distance mode is set to `EComparisonDistanceMode_Advanced` for `E3DMatcher`).
- Use `GetComparisonPointCloud` to retrieve an `EPointCloud` containing distance and/or colors that represent the distance to the sample or the reference for each of these points.

`SetROI` and `SetDontCare`

- The class `E3DComparer` can perform the comparison on only a subset of the object. This has two benefits: it is faster and it allows to ignore false-positives when detecting anomalies.
  - Use `SetROI` with a vector of `E3DBox` to define the zones on which to perform a comparison.
  - Use `SetDontCare` to specify areas that are excluded from the comparison.
  - A point belonging to `SetROI` and `SetDontCare` boxes is not compared. By default, all points are compared.

SetNoExtraMaterial

- The class `E3DComparer` checks, for each point of the reference (in the ROI), the distance to its nearest neighbor in the sample.
  - This avoids false positives, where we would use points of the sample that are not part of the object (the plane on which the object lays for example).
  - This allows to detect missing points on the sample.
  - A drawback of this approach is that extra material, that is points that should not be in the sample (for example, a hole that is filled) are not detected. You can solve this problem by specifying a list of `E3DBox` containing the areas that should not contain extra material.

SetAnomalyThresholds

- An anomaly is a sufficiently large contiguous area of points whose distance to the scan is above a threshold.
  - To specify the two thresholds (distance and area), use the method `SetAnomalyThresholds`.
  - By default, these two thresholds are set relatively to the model size.
  - Aa a more advanced anomaly detection method, use `SetAnomalyHysteresis`.

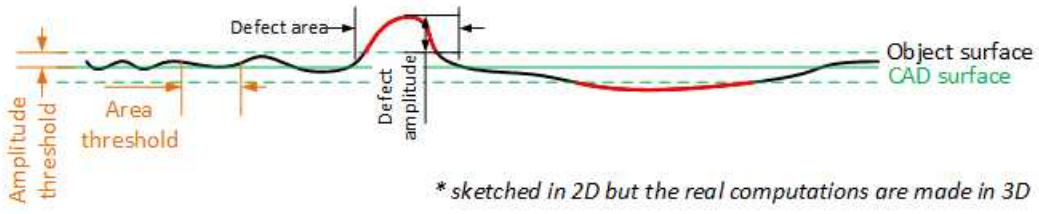


Illustration of the thresholds

SetAnomalyHysteresis

- You can use the method `SetAnomalyHysteresis` that is a more specific anomaly detection method.
  - With this method, a cluster of points should have a large enough subset of its points with an even larger distance to the sample to be an anomaly.
  - This may be useful if you do not want to consider as an anomaly the points with a medium distance unless they are close to points with a high distance.

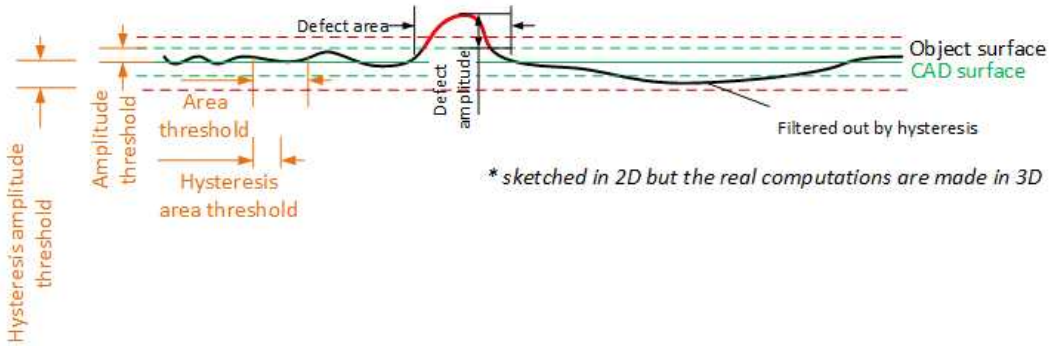


Illustration of the hysteresis thresholds

SetEnableAutomaticDecimation

- By default, the clouds are automatically decimated in such a way that the decimation error does not impact the anomalies detection.
  - This has the benefit of speeding up processing.
  - If the resolution of your point clouds is small with respect to your distance threshold, calling `SetEnableAutomaticDecimation(false)` could improve the speed as it will avoid useless decimation.

SetEnableAutomaticCrop

- By default, the sample clouds are automatically cropped around the reference to avoid computing distance for points that are not on the object (for example, the plane on which the object lays).

Prepare the reference

- If not called explicitly, the first call to `Compare` automatically computes the internal data structures.

Code samples

Minimal code

```
////////////////////////////////////////////////////
// This code snippet shows how to compare a sample //
// with a golden scan reference.                   //
////////////////////////////////////////////////////

// load the reference golden scan and set reference
Easy3D::E3DComparer comparer;
Easy3D::EPointCloud cloud;
cloud.Load("…");
comparer.SetReference(cloud);

// set thresholds
float distanceThresh = .2f, areaThresh = ⌙.f;
comparer.SetAnomalyThresholds(distanceThresh, areaThresh);

// prepare data structures (optional)
comparer.PrepareReference();

// load the sample and perform comparison
Easy3D::EPointCloud sample;
sample.Load("…");
comparer.Compare(sample);

// compute anomalies
std::vector<Easy3D::E3DAnomaly> anomalies = comparer.ComputesAnomalies();

// TODO: if (anomalies.size() != 0u): an anomaly was detected: inspect the sample manually? throw it away?

// get cloud to inspect it manually
Easy3D::EPointCloud visualisationCloud;
comparer.GetComparisonPointCloud(visualisationCloud);
```

Advanced code

```
////////////////////////////////////////////////
// This code snippet shows how to set the options //
// when comparing two elements with E3DComparer.  //
////////////////////////////////////////////////

// load the reference golden scan and set reference
Easy3D::E3DComparer comparer;
Easy3D::EPointCloud cloud;
cloud.Load("…");
comparer.SetReference(cloud);

// set thresholds
float distanceThresh = .2f, areaThresh = ⬐.f;
float hystDistanceThresh = ⬐.5f, hystAreaThresh = .5f;
comparer.SetAnomalyThresholds(distanceThresh, areaThresh);
comparer.SetAnomalyHysteresis(hystDistanceThresh, hystAreaThresh);  // defined relatively to base thresholds

// set ROIs
std::vector<Easy3D::E3DBox> rois = { Easy3D::E3DBox(⬐5, ⬐5, ⬐5) };
comparer.SetROI(rois);
std::vector<Easy3D::E3DBox> dontCare = { Easy3D::E3DBox(5, 5, 5) };
comparer.SetDontCare(dontCare);
std::vector<Easy3D::E3DBox> noExtraMaterial = { Easy3D::E3DBox(Easy3D::E3DPoint(⬐0, ⬐5, 20), 0, 0, 0, 5, 5, 5) };
comparer.SetNoExtraMaterial(noExtraMaterial);

// prepare data structures (optional)
comparer.PrepareReference();

// load the sample and perform comparison
Easy3D::EPointCloud sample;
sample.Load("…");
comparer.Compare(sample);

// compute anomalies
std::vector<Easy3D::E3DAnomaly> anomalies = comparer.ComputesAnomalies();

// TODO: if (anomalies.size() != 0u): an anomaly was detected: inspect the sample manually? throw it away?

// get cloud to inspect it manually
Easy3D::EPointCloud visualisationCloud;
comparer.GetComparisonPointCloud(visualisationCloud);
```

Computation time

The following table shows the computation time on a representative object. The first step of a comparison is to decimate the given `EPointCloud` (a very large cloud may explain important computation times).

If you are using a mesh as reference without a specific ROI, the mesh contains many points that have no correspondence in the scan (hidden faces), this can increase processing time a hundred-fold.

Number of threads	Computation times
1	686 ms
2	484 ms
4	395 ms

Alignment and Comparison (E3DMatcher)

Base Case

Use the class E3DMatcher to load a reference and a sample and to align and compare them at the same time.

E3DMatcher inherits from E3DAligner (see "Alignment (E3DAligner)" on page 115)and implements an API close to the one of E3DComparer (see "Comparison (E3DComparer)" on page 118)with some extra capabilities due to the usage of the reference points of view used in E3DAligner.

To use the E3DMatcher:

1. The first step is to set the reference using the method SetReference.
   - In addition to the mesh or the cloud, this method also takes one or several E3DPlane or azimuth and elevation angles (see "Calibration" on page 69 for a definition of the azimuth and the elevation).
   - The angles are used to compute the plane and are just an easier way to specify it.
2. Set the options of the comparison (ROIs, thresholds, mode...) and optionally a reference plane.
3. Call the Match method with the sample point cloud and its reference plane.
   - This returns an E3DMatch object containing the anomalies and the E3DAlignment (E3DMatch inherits from E3DAlignment)
4. Optionally, use GetComparisonPointCloud to retrieve an EPointCloud that contains the distances.

- You can perform all these steps interactively in the E3DMatch sample.
- The main difference between E3DMatcher and E3DComparer is that the ROIs are defined using ERegion on the EZMap corresponding to the projection of the reference on the given E3DPlane.

  This also allows for more advanced comparisons (see ComparisonDistanceMode and SetEnableMissingPointAsAnomaly).

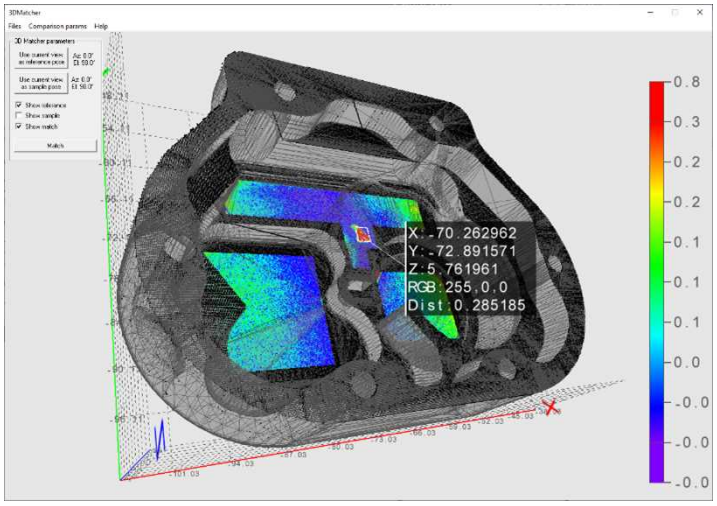
SetComparisonDistanceMode

Use SetComparisonDistanceMode to select one of the methods available in the class E3DMatcher to compute the distances:

- EcomparisonDistanceMode_Fast: the fastest method but less precise on the edges.
- EcomparisonDistanceMode_Normal: the default method.
- EcomparisonDistanceMode_Advanced: the slowest method that penalizes more bumps.

SetAllComparisonROI

- The class E3DMatcher can perform the comparison on only a subset of the object. This has two benefits: it is faster and it allows to ignore false-positives when detecting anomalies.
  - Use SetAllComparisonROI with one on several Eregion to define the zones on which to perform a comparison.
  - These Eregion should be interpreted as a masking part of the object on a projected view. Use RetrieveReferencePoses to retrieve the corresponding view.



Only the areas on the ROI are compared

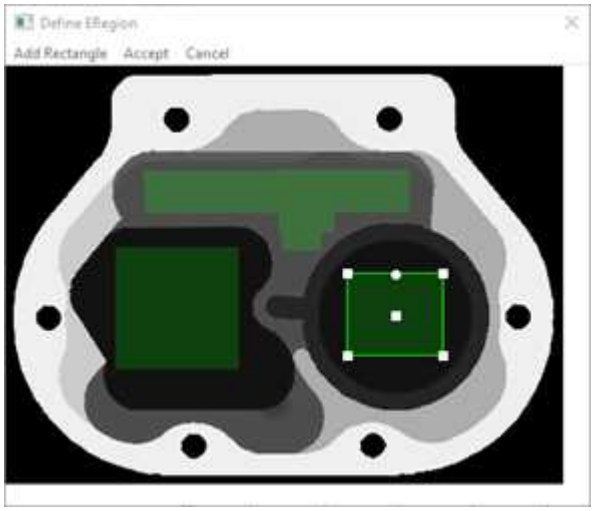
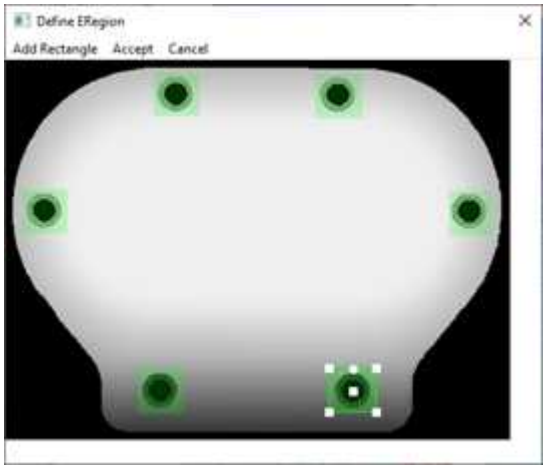


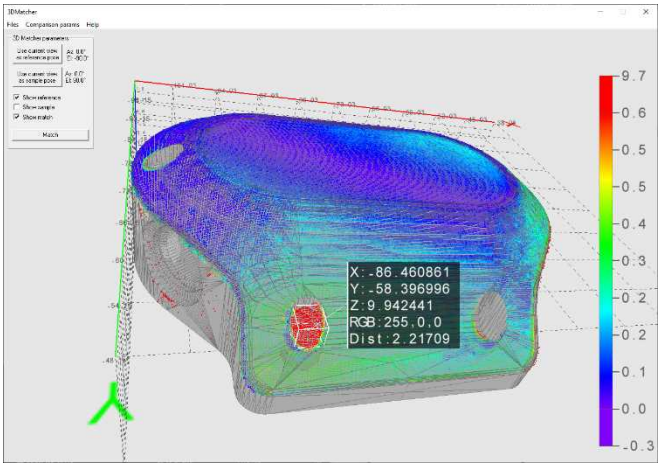
Illustration of setting ROI on a projection of the reference

SetAllComparisonNoExtraMaterial

- The class E3DMatcher checks, for each point of the reference (in the ROI), the distance to its nearest neighbor in the sample.
  - This avoids false positives, where we would use points of the sample that are not part of the object (the plane on which the object lays for example).
  - This allows to detect missing points on the sample.
  - A drawback of this approach is that extra material, that is points that should not be in the sample (for example, a hole that is filled) are not detected. You can solve this problem by specifying a list of E3DBox containing the areas that should not contain extra material.



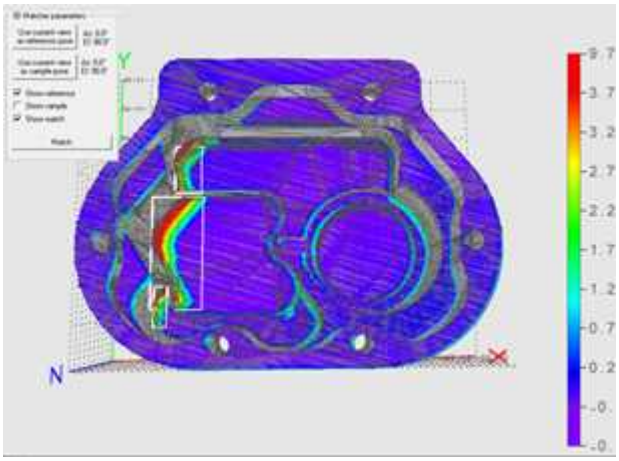
We do not want the holes to be filled



A filled hole is reported as an anomaly

SetEnableMissingPointAsAnomaly

- By default, the points missing on the scan are considered as defaults.
  - In some case this may lead to false positives (a shadow on the sample is not necessarily a default, just the absence of information).
  - In other cases these points should be taken into account (for example, a deep hole in the object can result in the absence of points instead of the presence of misplaced points).
  - Use the method `SetEnableMissingPointAsAnomaly` to select one of these behaviors.



False anomalies due to shadows in the sample

SetAnomalyThresholds

- An anomaly is a sufficiently large contiguous area of points whose distance to the scan is above a threshold.
  - To specify the two thresholds (distance and area), use the method `SetAnomalyThresholds`.
  - By default, these two thresholds are set relatively to the model size.
  - Aa a more advanced anomaly detection method, use `SetAnomalyHysteresis`.

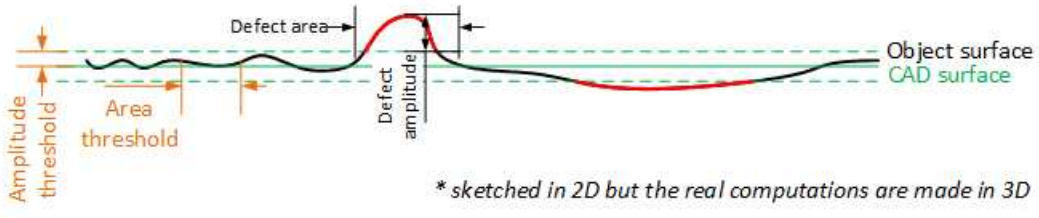


Illustration of the thresholds

SetAnomalyHysteresis

- You can use the method `SetAnomalyHysteresis` that is a more specific anomaly detection method.
  - With this method, a cluster of points should have a large enough subset of its points with an even larger distance to the sample to be an anomaly.
  - This may be useful if you do not want to consider as an anomaly the points with a medium distance unless they are close to points with a high distance.

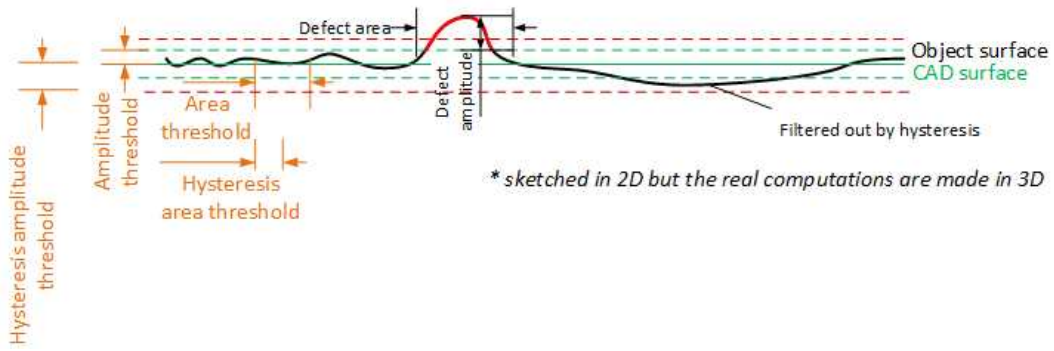


Illustration of the hysteresis thresholds

SetEnableAutomaticDecimation

- By default, the clouds are automatically decimated in such a way that the decimation error does not impact the anomalies detection.
  - This has the benefit of speeding up processing.
  - If the resolution of your point clouds is small with respect to your distance threshold, calling `SetEnableAutomaticDecimation(false)` could improve the speed as it will avoid useless decimation.

SetEnableAutomaticCrop

- By default, the sample clouds are automatically cropped around the reference to avoid computing distance for points that are not on the object (for example, the plane on which the object lays).

Prepare the reference

- If not called explicitly, the first call to `Compare` automatically computes the internal data structures.

Code samples

Minimal sample

```
////////////////////////////////////////////////
// This code snippet shows how to match a sample  //
// with a golden scan reference.                  //
////////////////////////////////////////////////

// load the reference golden scan and set reference
Easy3D::E3DMatcher matcher;
```

```
Easy3D::EPointCloud reference;
float azimuthReference = 0.f, elevationReference = 90.f;
reference.Load("…");
matcher.SetReference(reference, azimuthReference, elevationReference);

// set thresholds
float distanceThresh = .2f, areaThresh = ⌙.f;
matcher.SetAnomalyThresholds(distanceThresh, areaThresh);

// prepare data structures (optional)
matcher.PrepareReference();

// load the sample and perform comparison
Easy3D::EPointCloud sample;
float azimuthSample = 0.f, elevationSample = -90.f;
sample.Load("…");
Easy3D::E3DMatch match = matcher.Match(sample, azimuthSample, elevationSample);
std::vector<Easy3D::E3DAnomaly> anomalies = match.GetAnomalies();

// TODO: if (anomalies.size() != 0u): an anomaly was detected: inspect the sample manually? throw it away?

// get cloud to inspect it manually
Easy3D::EPointCloud visualisationCloud;
matcher.GetComparisonPointCloud(visualisationCloud);
```

Advanced sample

```
////////////////////////////////////////////////
// This code snippet shows how to set the options //
// when matching two elements with E3DMatcher.    //
////////////////////////////////////////////////

// load the reference golden scan and set reference
Easy3D::E3DMatcher matcher;
Easy3D::EPointCloud reference;
float azimuthReference = 0.f, elevationReference = 90.f;
reference.Load("…");
matcher.SetReference(reference, azimuthReference, elevationReference);

// use advanced comparison mode
matcher.SetComparisonDistanceMode(EComparisonDistanceMode_Advanced);

// ignore shadows
matcher.SetEnableMissingPointAsAnomaly(false);

// set thresholds
float distanceThresh = .2f, areaThresh = ⌙.f;
float hystDistanceThresh = ⌙.5f, hystAreaThresh = .5f;
matcher.SetAnomalyThresholds(distanceThresh, areaThresh);
matcher.SetAnomalyHysteresis(hystDistanceThresh, hystAreaThresh);  // defined relatively to base thresholds

// retrieve reference poses (reference must have been set)
std::vector<Easy3D::EZMap8> referencePoseProjections;
matcher.RetrieveReferencePosesProjections(referencePoseProjections);

// set ROI on the left half of the object
ERectangleRegion roiRegion(0.f, 0.f, float(referencePoseProjections[0].GetWidth()) / 2.f, float
(referencePoseProjections[0].GetHeight()));
matcher.SetComparisonROI(&roiRegion);

// set No Extra material on the whole object
ERectangleRegion noExtraMatRegion(0.f, 0.f, float(referencePoseProjections[0].GetWidth()) / 2.f, float
(referencePoseProjections[0].GetHeight()));
matcher.SetComparisonNoExtraMaterial(&noExtraMatRegion);
```

```
// prepare data structures (optional)
matcher.PrepareReference();

// load the sample and perform comparison
Easy3D::EPointCloud sample;
float azimuthSample = 0.f, elevationSample = -90.f;
sample.Load("…");
Easy3D::E3DMatch match = matcher.Match(sample, azimuthSample, elevationSample);
std::vector<Easy3D::E3DAnomaly> anomalies = match.GetAnomalies();

// TODO: if (anomalies.size() != 0u):an anomaly was detected: inspect the sample manually? throw it away?

// get cloud to inspect it manually
Easy3D::EPointCloud visualisationCloud;
matcher.GetComparisonPointCloud(visualisationCloud);
```

Computation time

The following table shows the computation time on a representative object. The first step of an alignment is to decimate the given `EPointCloud` (a very large cloud may explain important computation times).

Number of threads	Computation times
1	1335 ms
2	1180 ms
4	1165 ms

4. Code Snippets

4.1. Basic Types

Loading and Saving Images

Functional Guide | Reference: Load, Save, SaveJpeg

```
////////////////////////////////////////////////////////
// This code snippet shows how to load and save an image. //
////////////////////////////////////////////////////////

// Images constructor
EImageBW8 srcImage;
EImageBW8 dstImage;

// Load an image file
srcImage.Load("mySourceImage.bmp");

// ...

// Save the destination image into a file
dstImage.Save("myDestImage.bmp");

// Save the destination image into a jpeg file
// The default compression quality is 75
dstImage.Save("myDestImage.jpg");

// Save the destination image into a jpeg file
// set the compression quality to 50
dstImage.SaveJpeg("myDestImage50.jpg", 50);
```

Interfacing Third-Party Images

Functional Guide | Reference: SetImagePtr

```
////////////////////////////////////////////////////////////
// This code snippet shows how to link an Open eVision image //
// to an externally allocated buffer.                        //
////////////////////////////////////////////////////////////

// Images constructor
EImageBW8 srcImage;

// Size of the third-party image
int sizeX;
int sizeY;

//Pointer to the third-party image buffer
EBW8* imgPtr;

// ...

// Link the Open eVision image to the third-party image
// Assuming the corresponding  buffer is aligned on 4 bytes
srcImage.SetImagePtr(sizeX, sizeY, imgPtr);
```

Retrieving Pixel Values

Functional Guide | Reference: GetImagePtr

```
////////////////////////////////////////////////////////////
// This code snippet shows the recommended method (fastest)  //
// to access the pixel values in a BW8 image                 //
////////////////////////////////////////////////////////////

EImageBW8 img;

OEV_UINT8* pixelPtr;
OEV_UINT8* rowPtr;
OEV_UINT8  pixelValue;
OEV_UINT32 rowPitch;
int x, y;

rowPtr = reinterpret_cast <OEV_UINT8*>(img.GetImagePtr());
rowPitch = img.GetRowPitch();

for (y = 0; y < height; y++)
{
    pixelPtr = rowPtr;

    for (x = 0; x < width; x++)
    {
        pixelValue = *pixelPtr;

        // Add your pixel computation code here

        *pixelPtr = pixelValue;
        pixelPtr++;
    }

    rowPtr += rowPitch;
}
```

ROI Placement

Functional Guide | Reference: Attach, SetPlacement

```
////////////////////////////////////////////////////////////
// This code snippet shows how to attach an ROI to an image  //
// and set its placement.                                    //
////////////////////////////////////////////////////////////

// Image constructor
EImageBW8 parentImage;

// ROI constructor
EROIBW8 myROI;

// ...

// Attach the ROI to the image
myROI.Attach(&parentImage);

//Set the ROI position
myROI.SetPlacement(50, 50, 200, ↵00);
```

Vector Management

Functional Guide | Reference: Empty, AddElement

```
////////////////////////////////////////////////////////////
// This code snippet shows how to create a vector, fill it   //
// and retrieve the value of a given element.                //
////////////////////////////////////////////////////////////

// EBW8Vector constructor
EBW8Vector ramp;

// Clear the vector
ramp.Empty();

// Fill the vector with increasing values
for(int i= 0; i < ►28; i++)
{
       ramp.AddElement((EBW8)i);
}

// Retrieve the ►0th element value
EBW8 value= ramp[9];
```

Exception Management

Functional Guide | Reference: GetPixel, What

```
//////////////////////////////////////////
// This code snippet shows how to manage  //
// Open eVision exceptions.               //
//////////////////////////////////////////

try
{
       // Image constructor
       EImageC24 srcImage;

       // ...

       // Retrieve the pixel value at coordinates (56, 73)
       EC24 value= srcImage.GetPixel(56, 730);
}

catch(Euresys::Open_eVision_►_►::EException exc)
{
       // Retrieve the exception description
       std::string error = exc.What();
}
```

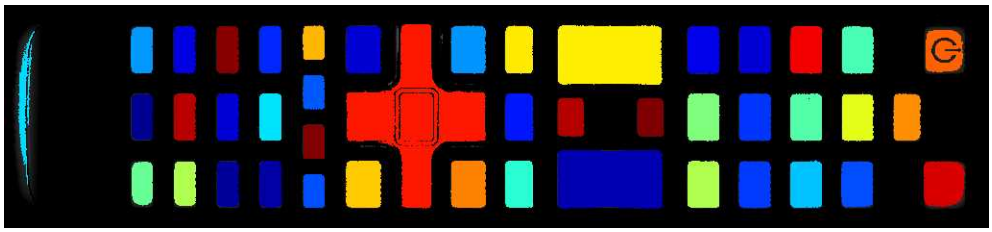
5. Application Examples

5.1. Measuring a Remote Controller

This topic presents a complete 3D processing workflow, featuring a TV remote controller as sample object.

Introduction

The remote controller on the laser triangulation acquisition setup



The remote controller after 3D processing and projection on a 2D image

The proposed process is the sequence of the following operations:

One time calibration process:

1. Load a depth map representing the calibration object.
2. Perform the calibration model computation.
3. Store the calibration model.

For each object:

1. Load the object depth map.

2. Apply the calibration model to get the world point cloud.
3. (Optional) Save the point cloud to a PCD file.
4. Search for a reference plane by either:
   - Choosing 3 points on the remote depth map to be used to compute a plane.
   - Using the `3DPlaneFitter` function.
5. Choose 2 points to define an orientation.
6. Build a ZMap using the reference plane and the orientation vector.
7. (Optional) Save the ZMap as an image.
8. Query the ZMap to get world space measurement.
9. Process the ZMap with 2D image function.

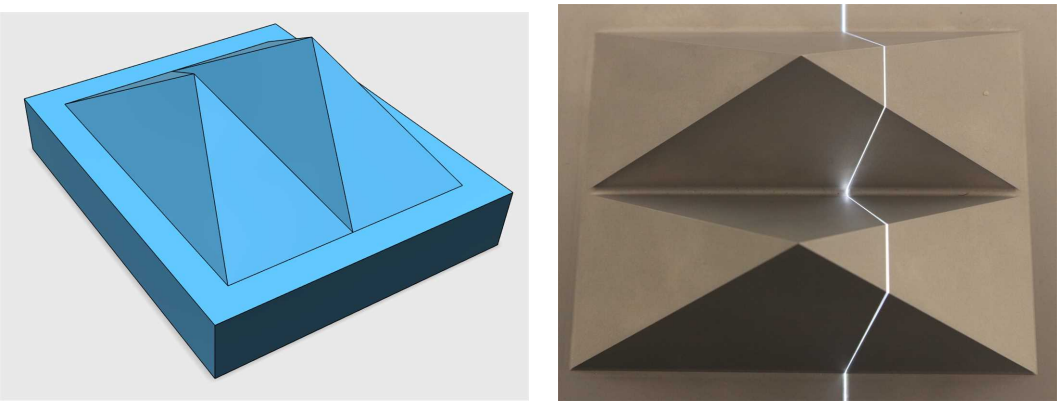
> **TIP**
> For easier reading, the code snippets in this example do not show exception catching and error checking.

Calibration

The calibration process is mandatory to find the exact transformation from the depth map to the real world, metric, coordinate system.

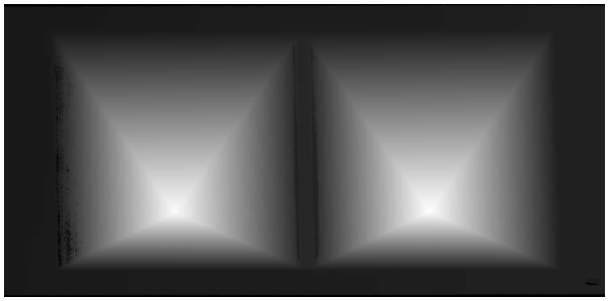
Open eVision features an object based calibration process: the scan of a reference object of known geometry is used in the calibration calculation.

> **TIP**
> The recommended calibration object is the double truncated pyramid.



CAD model of the double pyramid and calibration object scanned

Using a Euresys Coaxlink 3D LLE frame grabber, the captured image is directly a depth map. Depth maps are 8 bits or 16 bits grayscale images with the pixel values representing the height of the laser profile.



A depth map (gray scale image) of a double pyramid, used as the calibration object

The code snippet below shows how to load the depth map representing the double pyramid object, using it to compute a calibration model and save the result for later use.

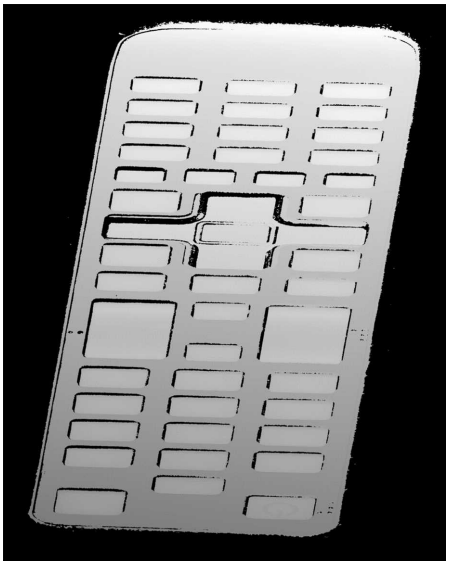
```
// Load the depthmap used for the calibration process
EDepthMap►6 calibration_depthmap;
calibration_depthmap.Load("calibration.tiff");
// Set the Z resolution from the number of bits for the fractional part, depends on the depth map acquisition
calibration_depthmap.SetZResolution(►.f / (►<<5));

// Declare the object based calibration generator
EObjectBasedCalibrationGenerator calibrator;
// set the real world scale of the scanned object
calibrator.SetCalibrationObjectType(EObjectBasedCalibrationType_DoublePyramid);
calibrator.SetCalibrationObjectScale(►0.f);

// Declare an object based calibration model
EObjectBasedCalibrationModel calibration_model;

// Perform the calibration process (can take some time, like ►0 seconds)
calibration_model = calibrator.Compute(calibration_depthmap);

// Check the calibration result
if(calibration_model.IsInitialized())
  {
     printf("Calibration succeeded with score: %g\n", calibration_model.GetCalibrationError());
     // Save the model for later use
     ESerializer* serializer = ESerializer::CreateFileWriter("calibration.model");
     calibration_model.Save(serializer);
     delete serializer;
  }
  else
  {
     printf("Calibration failed\n");
  }
```

Processing the object in 3D

This section exposes the 3D workflow, from the source depth map to metric measurement.

Acquiring and calculating the 3D point cloud

The calibration model previously calculated is used to transform the depth map data to real world 3D point cloud.



A depth map of the TV remote controller
(the object is distorted and scaled while black pixels represent undefined regions, that is parts of the object that were not seen by the camera or lit by the laser)

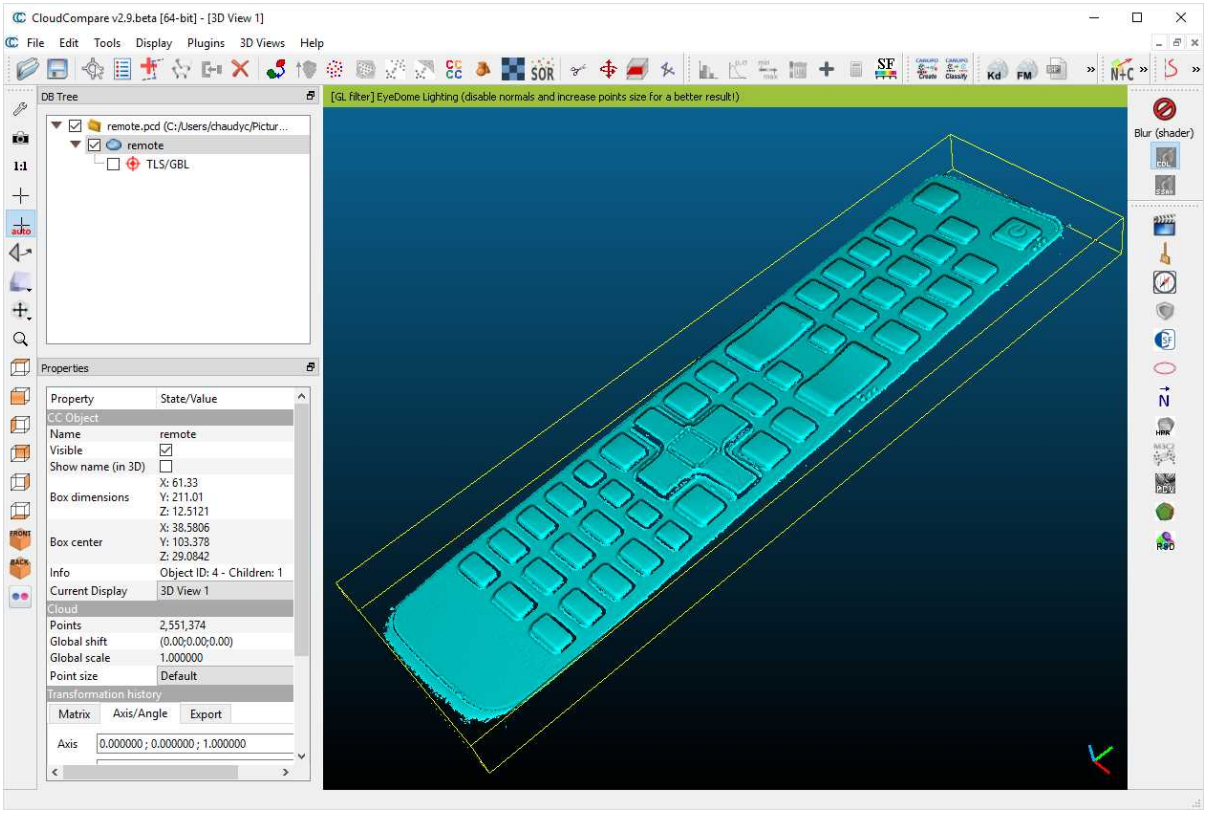
The code snippet below:

1. Loads a calibration model.
2. Transforms the depth map to a 3D point cloud.
3. Saves the point cloud to a PCD file.

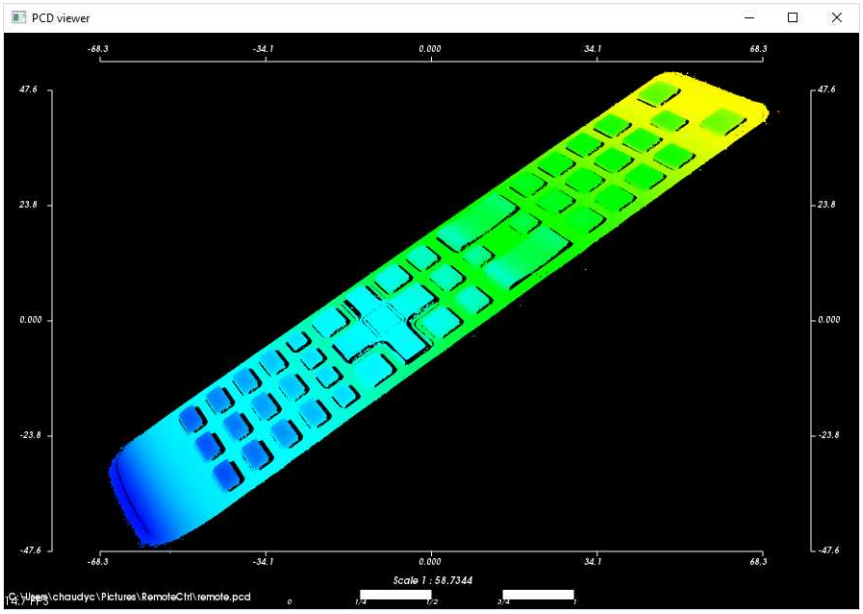
```
// Read an abstract calibration model from file
ECalibrationModel* calibration_model;
ESerializer* serializer = ESerializer::CreateFileReader("calibration.model");
// must be desallocated later
calibration_model = ECalibrationModel::Create(serializer);
delete serializer;

// Declare a depth map to point cloud converter
EDepthMapToPointCloudConverter dm2pc;
// attach a calibration model to the converter
dm2pc.SetCalibrationModel(*calibration_model);

// Generate the point cloud
EPointCloud point_cloud;
dm2pc.Convert(object_depthmap, point_cloud);

printf("Point cloud size : %d\n", point_cloud.GetNumPoints());

// Save to point cloud to a PCD file
point_cloud.SavePCD("point_cloud.pcd");
```

TIP
The PCD file is a simple 3D point container, used by the PCL framework (www.pointclouds.org). Such file can be loaded in the PCL viewer of other tools like Cloud Compare (www.cloudcompare.org).

As shown on the screen shots below, data in point cloud are in world coordinate system, expressed in the calibration object units. Distances and angles are correct and then metric measures are possible. However, processing on point clouds can be difficult and costly and then the ZMap representation is an alternative allowing 2D processing on metric world space.



The resulting point cloud viewed in the Cloud Compare application



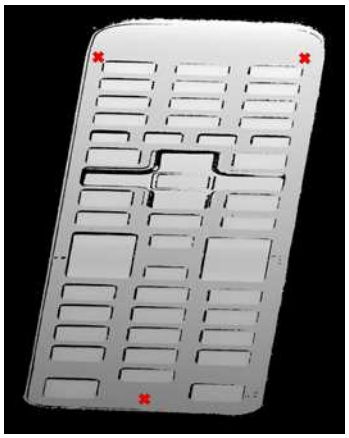
The resulting point cloud in the PCL viewer; the color ramp shows that the main body plane of the remote is not aligned with an axis

Searching for a reference plane

To perform measurements and processing, it is usually mandatory to transform the data to a reference frame. For the remote controller, we want to level to the main plane supporting the keys and orient the points along the remote edge.

If the depth map has been previously registered (by a consistent acquisition process or by the detection of fiducial markers), it may be possible to build the reference plane from 3 chosen points (points to be known as part of the reference plane).

```
// Use 3 known points to build the reference plane
E3DPoint p►(600.5, 450.5, object_depthmap.GetZValue(600, 450));
E3DPoint p2(►700.5, 470.5, object_depthmap.GetZValue(►700, 470));
E3DPoint p3(840.5, 2300.5, object_depthmap.GetZValue(840, 2300));

// convert these points from depth map space to world space, using the calibration model
E3DPoint w►, w2, w3;
w► = calibration_model.Apply(p►);
w2 = calibration_model.Apply(p2);
w3 = calibration_model.Apply(p3);

// build the world plane using 3 points
E3DPlane reference_plane(w►, w2, w3);
```

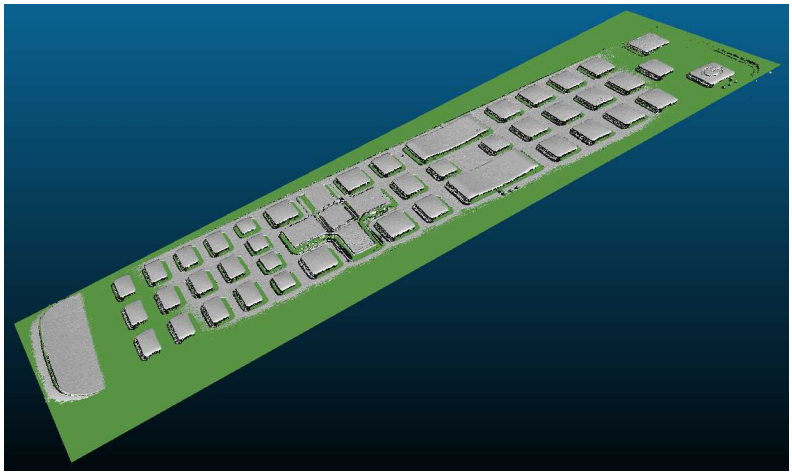


The original object depth map and the position of 3 points used for the reference plane calculation

Another option, if the depth map is not registered, is to use the `E3DPlaneFitter` class. This function tries to find the main plane from a point cloud using a probabilistic approach. It finds a subset of the point cloud that lies on a plane, given a user defined threshold tolerance.

The distance tolerance is a parameter of `E3DPlaneFitter` and must be adapted depending on the scale, noise and curvature of the plane in the point cloud.

```
// Use a E3DPlaneFinder with a distance tolerance of 0.► (world space coordinate)
float distance_tolerance=0.►f;
EPlaneFinder plane_finder(distance_tolerance);
E3DPlane reference_plane=plane_finder.Find(point_cloud);
```



The principal plane (in green) extracted from the point cloud by `E3DPlaneFinder` class

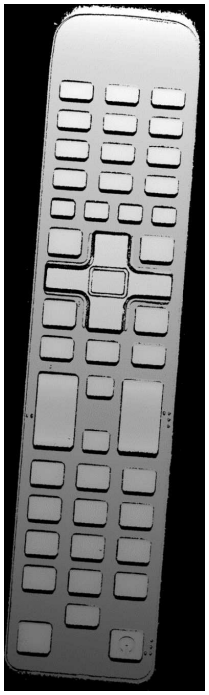
Building the ZMap

The ZMap is a gray scale 2D image, representing the projection of the 3D points to a reference plane. The value of the pixels of the ZMap is the distance of the 3D point to the reference plane, coded in a fixed point representation.

The ZMap also supports the “undefined pixel” specific value, when no point is projected on a pixel and there is no valid value at that position.

As shown below, the point cloud to ZMap conversion can be made using default values for all parameters: resolution and scale of the ZMap, reference plane, orientation, origin will all be chosen automatically.

```
// Create the converter
EPointCloudToZMapConverter pc2zmap;

// Create a ►6 bits ZMap and fill it with point cloud points
EZMap►6 zmap;
pc2zmap.Convert(point_cloud, zmap);

// Save the ZMap as a PNG image
zmap.SaveImage("zmap.png");
```

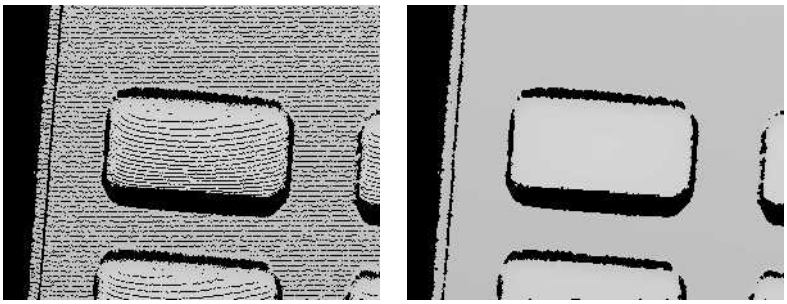


The generated depth map with default parameters

The body of the remote is not leveled and the object is not aligned. Nevertheless, comparing to the depth map, the ZMap is a calibrated representation of the object. Metric distances can be evaluated on the ZMap.

The current implementation of the ZMap converter simply projects 3D points on the ZMap image. Thus, depending on the point density and projection parameters, undefined pixels and region may appear in the ZMap.

The ZMap converter automatically perform a filling algorithm on undefined pixels. Disable it with the `EnableFillMode(false)`.

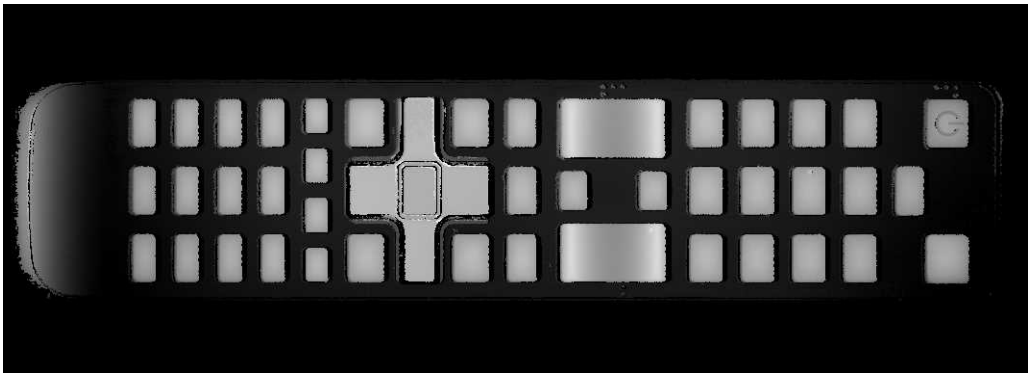


`EnableFillMode(false)` and `EnableFillMode(true)`

To avoid undefined pixels, choose a target scale for the ZMap. The method `SetScale()` changes the target X and Y resolution (in metric unit per pixel).

With the default configuration, the ZMap generator uses a horizontal reference plane. Use the `SetReferencePlane()` method to “level” the object and use the main body as the reference plane. `SetOrientationVector()` specifies the direction of the X (width) axis of the ZMap. The orientation vector allow to “rotate” the object around the reference plane normal.

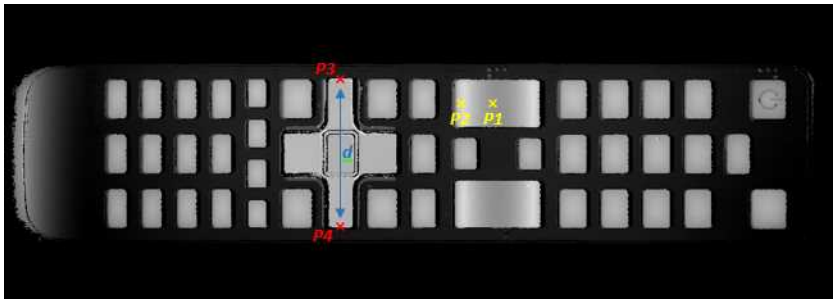
```
// level the object by defining a reference plane
pc2zmap.SetReferencePlane(reference_plane);

// align to the world Y axis
pc2zmap.SetOrientationVector(E3DPoint(-0.0750►, 0.9964, -0.0376►));

// choose a resolution of 0.2mm per pixel
pc2zmap.SetMapXYResolution(0.2f);

// generate the ZMap
pc2zmap.Convert(point_cloud, zmap);
```



The ZMap with a reference plane previously calculated, an orientation to align the object and a reduced resolution

Use queries on ZMap to retrieve metric coordinates (for example, to measure the size and/or the height of a feature). Useful functions are `GetWorldPositionFromPixelPosition(x,y)` and `GetZValue(x,y)`.

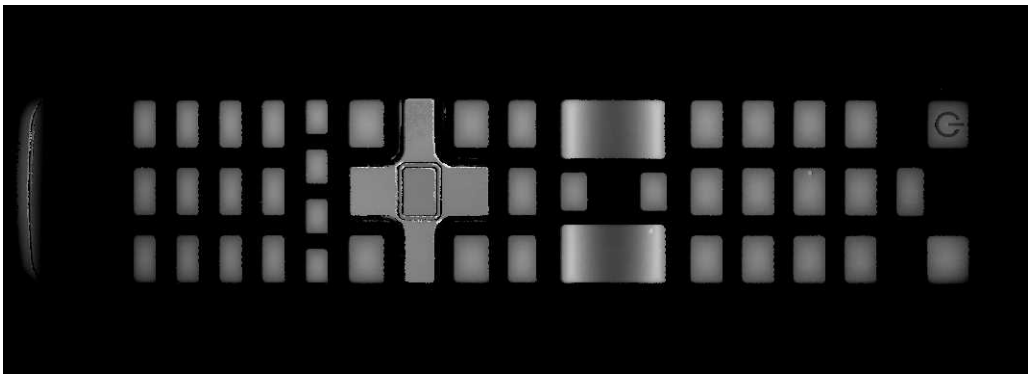
```
float h► = zmap.GetZValue(638, ►28);       // get "height" at position P►
float h2 = zmap.GetZValue(595, ►28);       // get "height" at position P2

E3DPoint p3 = zmap.GetWorldPositionFromPixelPosition(437, 98);  // get world position at p3
E3DPoint p4 = zmap.GetWorldPositionFromPixelPosition(437, 288); // get world position at p4
float d = p3.DistanceTo(p4);                     // world distance between p3 and p4
```



- h1 (1.15601) and h2 (1.83618) are distance above the ZMap reference plane. These are values in millimeters, the difference evaluates the "curvature" of the key.
- P1 (58.843, 84.7838, 32.1084) and P2 (20.9479,81.9271, 32.0041) are positions in the original 3D world space.
- The distance d (38.0028) represents the width of the remote keyboard in millimeters.

The reference plane can be shifted (translated) to remove the remote controller body and keep only the keys in the ZMap. An 8 bits ZMap must be used to be compatible the other Open eVision 2D libraries.

```
// shift the plane by 1mm in the normal direction
float d = reference_plane.GetSignedDistanceFromOrigin();
reference_plane.SetSignedDistanceFromOrigin(d + 1.f);
pc2zmap.SetReferencePlane(reference_plane);
// choose the scale for the Z axis (2mm for 256 grey scale values)
pc2zmap.SetMapZResolution(2.f / 256);
// convert the point cloud to a 8 bits ZMap
EZMap8 zmap8;
pc2zmap.Convert(point_cloud, zmap8);
```



ZMap with shifted reference plane: only the keys remain visible while other pixels are set to 0 (undefined value)

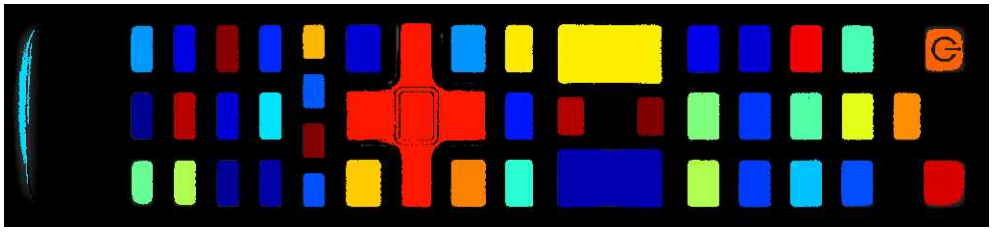
TIP
This image can be used in 2D libraries like EasyImage, EasyObject or EasyGauge.

Processing the ZMap

On a ZMap, the gray value of a pixel is the distance (height) above the reference plane. Threshold, filters, morphology and other image operators can be used directly.

Here is an example of a region segmentation using EasyObject:

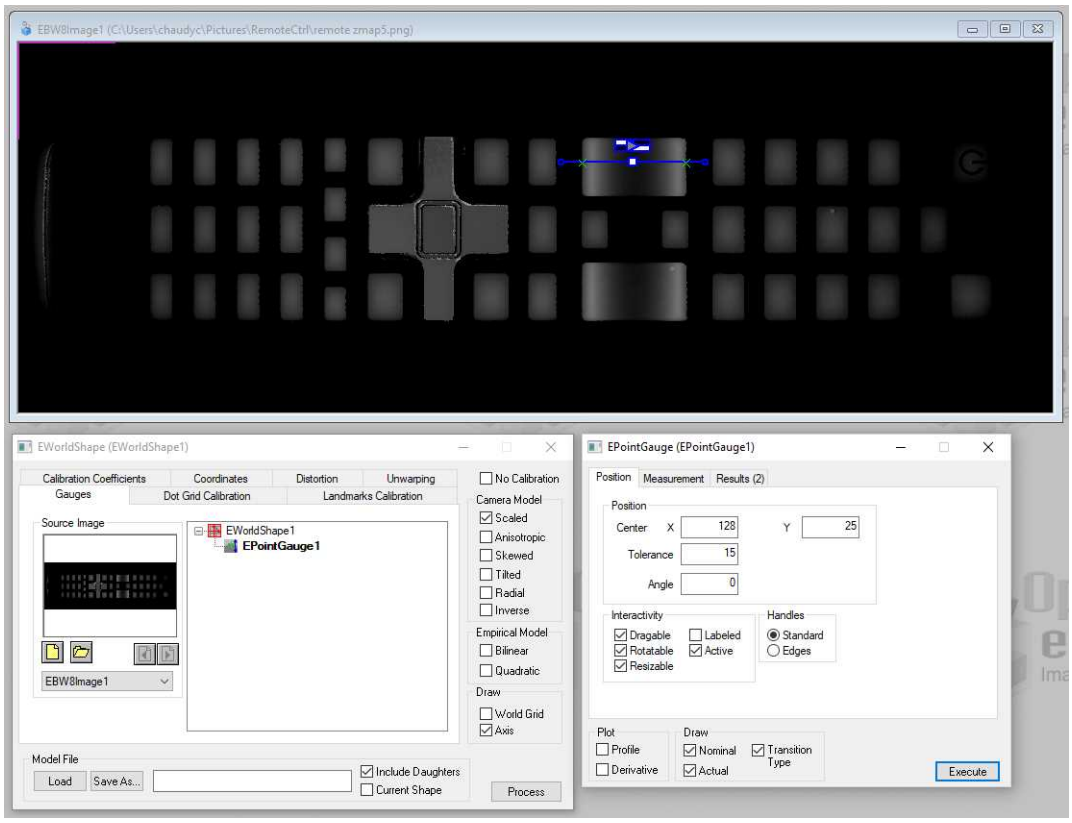
```
// segment the objects of the ZMap (default is Minimum Residue segmentation method)
ECodedImage2 coded_image;
EImageEncoder image_encoder;
image_encoder.Encode(zmap8.AsEImage(), coded_image);

// filter the object by area
EObjectSelection object_selection;
object_selection.AddObjects(coded_image);
object_selection.RemoveUsingUnsignedIntegerFeature(EFeature_Area, 100, ESingleThresholdMode_Less);
```



The extracted objects with EasyObject on the ZMap image

The ZMap includes a `EWorldShape` object that you can use for EasyGauge measurement. The `EWorldShape` class represents the scale between the image space and the world space.

```
// get the world shape from the ZMap
const EWorldShape& world_shape = zmap8.GetWorldShape();

// setup a point gauge using that world shape
EPointGauge pointGauge;
pointGauge.Attach(&world_shape);

// set gauge center point and tolerances in world space (mm)
pointGauge.SetCenterXY(►28.f, 25.f);  // ►28mm and 25mm from the upper left corner
pointGauge.SetTolerances(►5.f, 0.f);  // ►5mm, half gauge size

// perform the measurement on the ZMap
pointGauge.Measure(&zmap8.AsEImage());

// get the 2 points and calculate the length of the key, values are in millimeters
EPoint p► = pointGauge.GetMeasuredPoint(0);
EPoint p2 = pointGauge.GetMeasuredPoint(►);
float length = p►.Distance(p2);      // return 2►.6►9mm
```



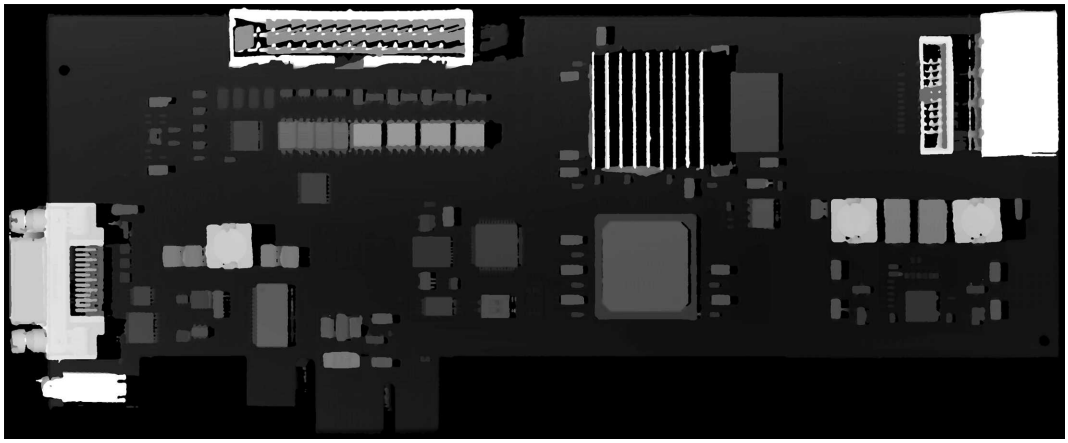
A point gauge on a ZMap in Open eVision Studio: the parameters are the same as the code snippet above

5.2. Inspecting a PCB

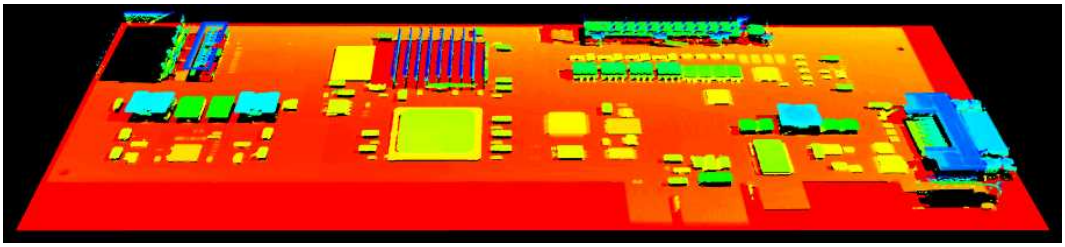
With Easy3D, it is possible to use depth maps for PCB inspection. This section presents a simple detection of missing or misplaced components on a PCB. The processing is done entirely with 2D images but use depth maps as inputs.

The workflow is as follow:

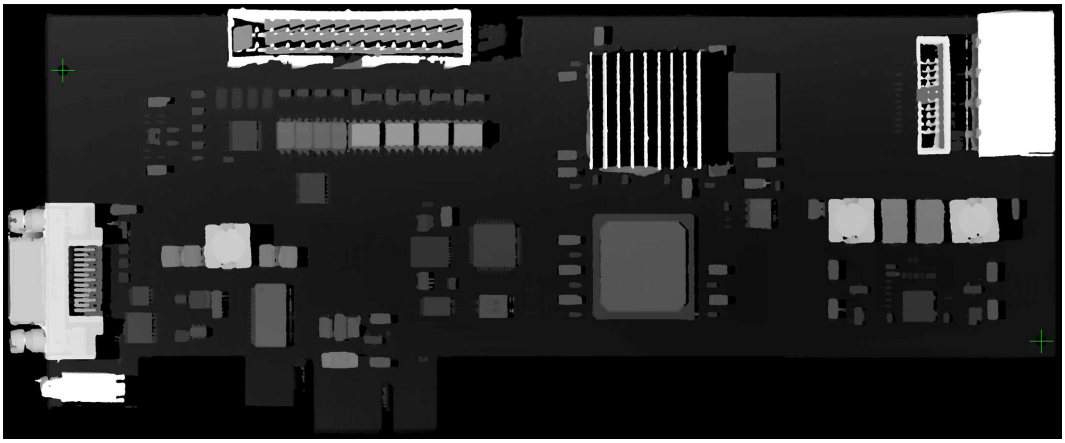
1. Perform a 3D acquisition or create the depth map with software laser line extraction (`ELaserLineExtractor` class). Retrieve the grayscale image corresponding to the depth map (`EDepthMapROI8.AsEImageBW8()` method).
2. Align the image using fiducial markers (`EMatcher` class).
3. Search for the PCB plane and subtract it from the aligned image, only the components and the connectors remain (`EasyImage::Oper(EArithmeticLogicOperation_Subtract…)` function).
4. Compare the processed image to a golden sample to detect missing or misplaced components (`EasyImage::Oper(EArithmeticLogicOperation_Compare…)` or `EChecker`).



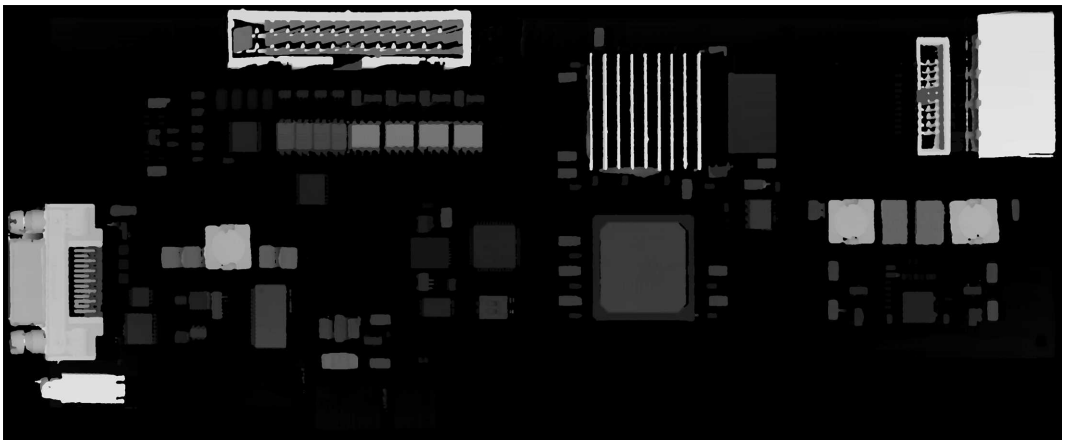
The source depth map of a PCB, outputs of CoaxLink Quad 3D-LLE



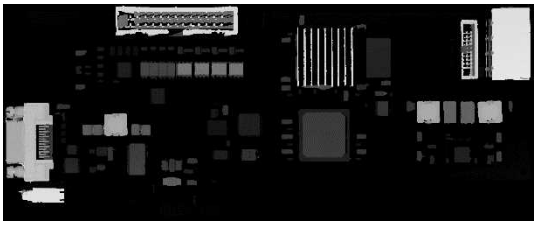
The same depth map displayed as a 3D point cloud with false colors

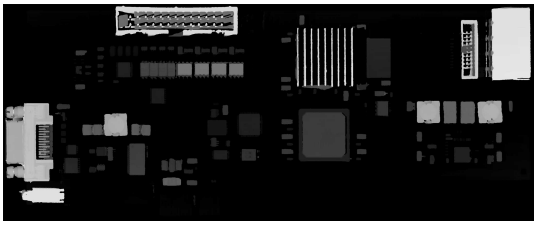


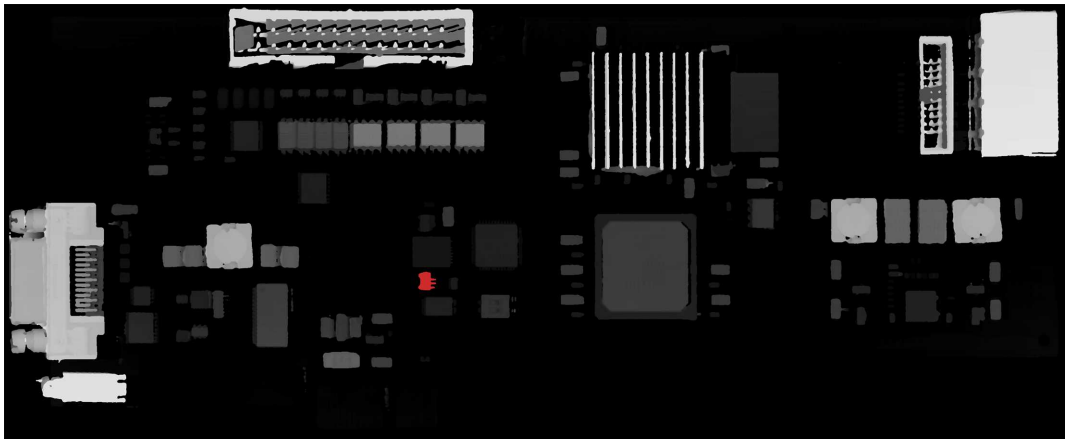
Align the image using fiducial markers (2 holes)



The image with reference plane subtracted, leaving only the components







The comparison of the image (left) with the golden sample (right, processed with the same workflow) shows the missing component (in red)

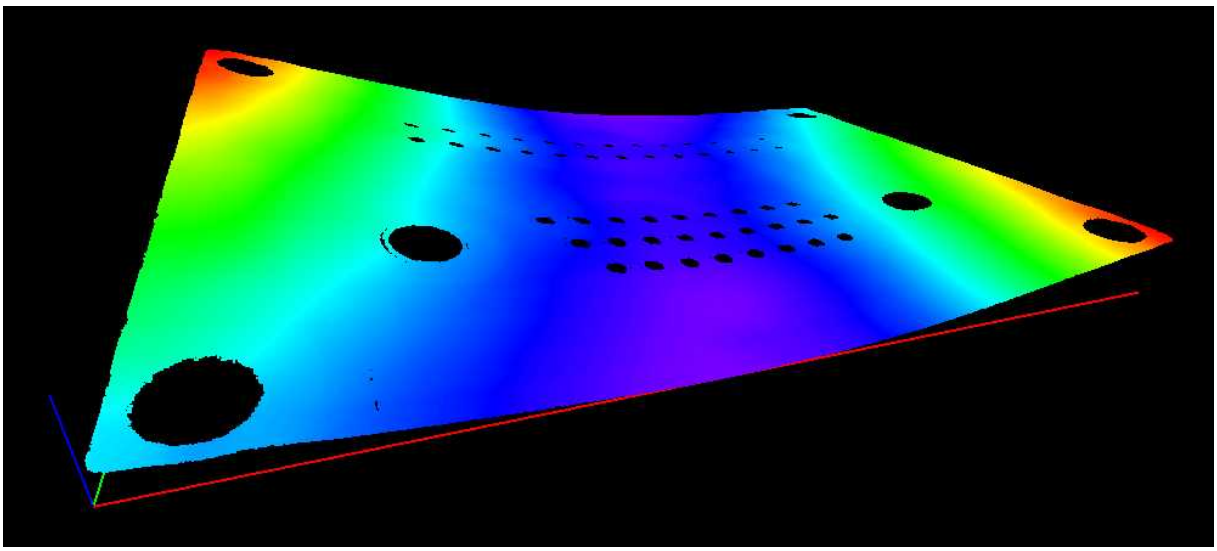
5.3. Measuring the Warpage of a PCB

Source code and images

This application example is provided as a C++ sample program, named `3DPCBWarpage`:

- The source code is located in `Sample Programs\MsVc samples\3DPCBWarpage`.
- The sample images are located in `Sample Images\Easy3D\PCB Warpage`.

NOTE
To run this program, you need the Easy3D and EasyGauge licenses.



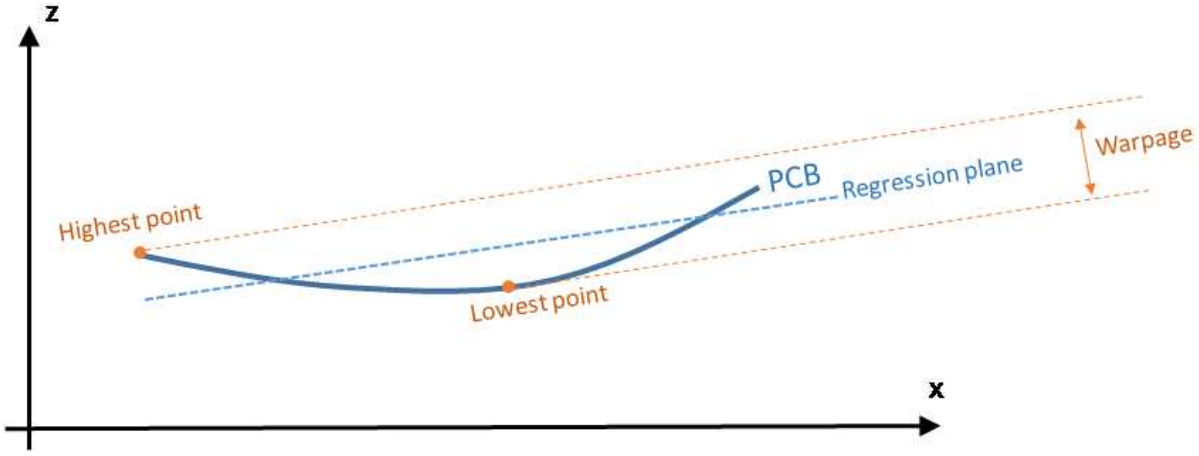
Display output of the 3D PCB Warpage application example

NOTE
The calibration process is not described in this document. We assume that a calibration has been done and that the metric unit used is the mm.

Application objective

This application demonstrates how to measure the warpage of a PCB.

TIP
In this application, we define the warpage as the difference between the highest and the lowest surface points when the PCB regression plane is oriented horizontally. In other words, we fit a plane through the PCB points and take the perpendicular distance between the highest point above and the lowest point below this regression plane.



The main steps of the process are:

1. Making an initial ZMap using a first estimation of an average PCB plane.
2. Filtering the data by:
   - Removing the points that show a large height deviation with respect to their neighbors.
   - Applying a smooth filter on the remaining points.

   For the generation of the final ZMap, the application will fit a regression plane through the remaining / filtered data.
3. On the ZMap, detecting the corners of the PCB for the alignment (optional).
4. Producing the final ZMap that the application will use to compute the warpage of the PCB.

TIP
The (optional) alignment on the PCB edges ensures that the resulting ZMap is always the same, independently of the orientation of the PCB during the measurement.

TIP
Moreover, on the final ZMap, the horizon is parallel with the PCB regression plane. This is necessary to have a well-defined warpage value.

Generating the initial ZMap

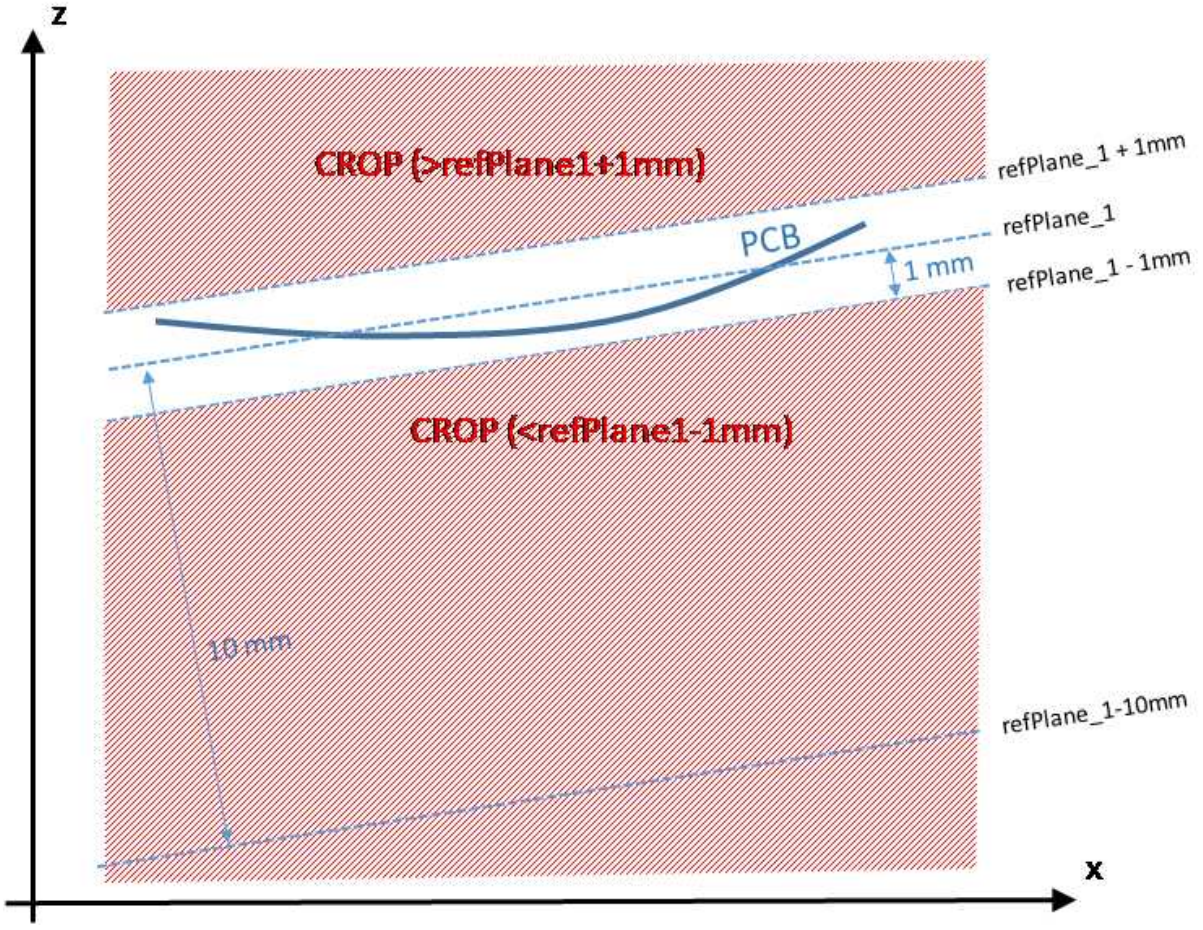
1. Using a calibration model (`model_` in the code) and a depth map (« `dm_` »), the application produces a point cloud (« `pc_` »).

> **TIP**
> Alternatively, you can load directly a point cloud from a file.

2. In this point cloud, the application localizes the PCB plane by searching for the largest plane, using a plane finder object of the type `E3DPlaneFinder`. As we want to handle a curved PCB, a large tolerance (+/- 1mm) is used by the plane finder object.

This step produces a reference plane called `refPlane_►`of the type `E3DPlane`.

3. The application crops any data point that is farther from the reference plane than 1 mm.
4. It uses `refPlane_►`» to generate the first ZMap (called `zmapBeforeAlignment`). Actually, the reference plane used for the ZMap generation is 10 mm below `refPlane_►`so that all pixel values of the ZMap are positive. This is illustrated on the figure below.

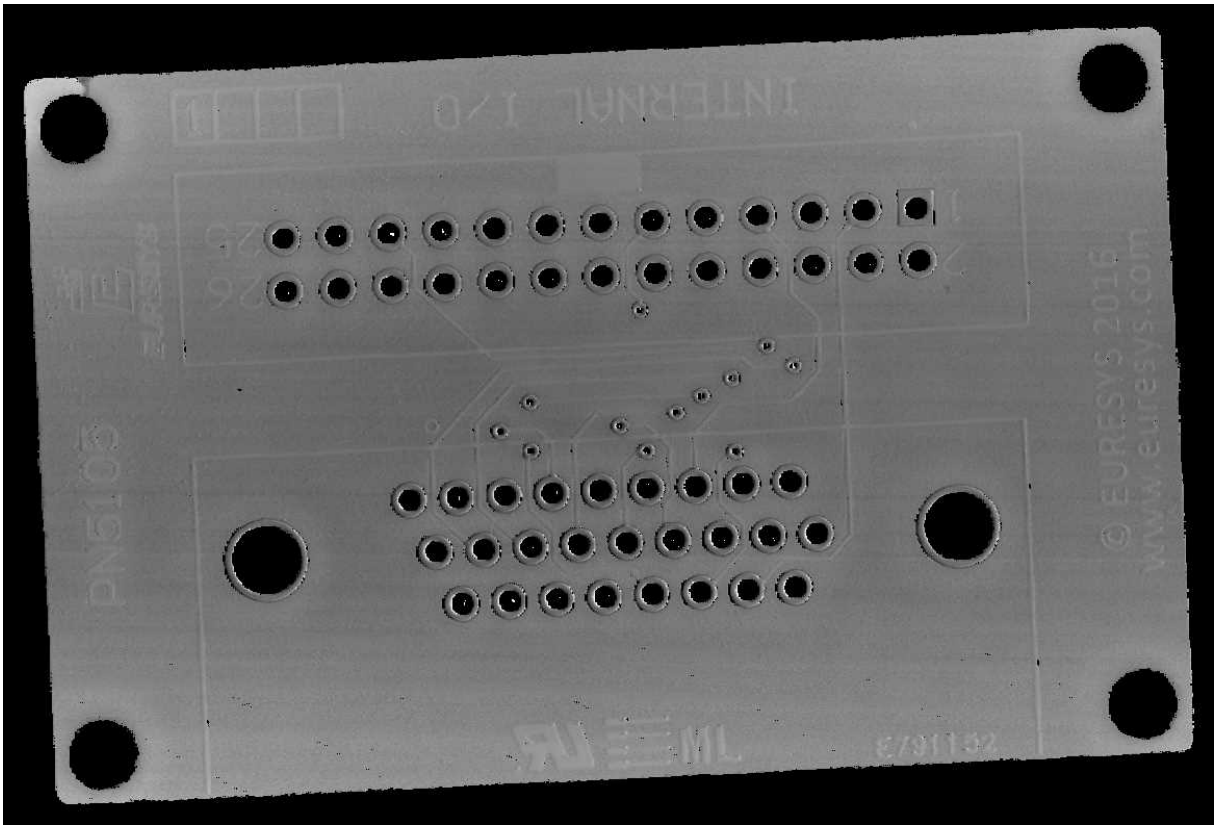


The code to produce the ZMap `zmapBeforeAlignment` is shown below.

```
// Apply calibration to the depth map, a metric 3D point cloud is generated
E3DDepthMapToPointCloudConverter converter;
```

```
converter.SetCalibrationModel(model_);
converter.Convert(dm_, pc_);

// Search for the PCB plane
float maximumDistanceToPlane = ►.0f; // ►.0 mm
E3DPlaneFinder finder(maximumDistanceToPlane); // tolerance for plane search = ►.0 mm
E3DPlane refPlane_► = finder.Find(pc_); // finds the largest plane in the point cloud

// Crop any point distant from PCB plane
E3DPlaneCropper cropperPCB(refPlane_►); // 'refPlane_►' = ref. plane for the cropper
EPointCloud pcPlaneOnly; // only keep points close to the ref. plane
cropperPCB.Crop(pc_, pcPlaneOnly, EPlaneCropperType_KeepClose, maximumDistanceToPlane);

// ZMap projection of PCB plane, using reference plane and fixed resolution
float zMapPixelSize = 0.050f; // ZMap horizontal resolution: ► pixel = 50µm = 0.050 mm
float zMapVerticalResolution = 0.00►f; // ZMap vertical resol.: ► gray value = ►µm (= 0.00► mm)
float zMapOffset = ►0.0f; // ►0 mm
E3DZMapGenerator zmapGenerator;
EZMap►6 zmapBeforeAlignment;
zmapGenerator.SetScale(zMapPixelSize); // horizontal resolution = 50µm/pixel
zmapGenerator.SetZScale(zMapVerticalResolution); // vertical resolution = ► µm/GV
zmapGenerator.SetReferencePlane(refPlane_► - zMapOffset); // ►0mm below refPlane_►
zmapGenerator.SetOrientationVectorMode(EZMapOrientationVectorMode_XAxis);
zmapGenerator.SetExtension(►.f);  // add a ►mm 3D extension, create a border around the ZMap
zmapGenerator.Convert(pcPlaneOnly, zmapBeforeAlignment);
int zmapWidth = zmapBeforeAlignment.GetWidth();
int zmapHeight = zmapBeforeAlignment.GetHeight();
```

The following image shows this first ZMap with a 16-bit per pixel resolution.



ZMap `zmapBeforeAlignement`

In this image:

- Background pixels have the value "0" (black). This value is reserved for “undefined pixels” (nothing detected). Pixels having a value different from zero are “valid pixels”.
- The horizontal resolution is set to 50 µm/pixel and the vertical resolution is set to 1 µm for one gray value.
  Because the reference plane of the ZMap is 10 mm below the PCB, the average gray value in the image is 10000 (10000 gray values = 10000 µm).
- The size of this ZMap is not specified; it is automatically computed from the size of the bounding box, enlarged by 1 mm so that there is a black border around the PCB. This enlargement is specified by the method `SetExtension` of the ZMap generator. The black border around the PCB helps for the detection of the edges.

Reducing and filtering the noise

On the ZMap, the application should ignore the following points during the computation of the warpage:

- Isolated noisy points on the background.
- Noisy points inside the holes or on the pads.

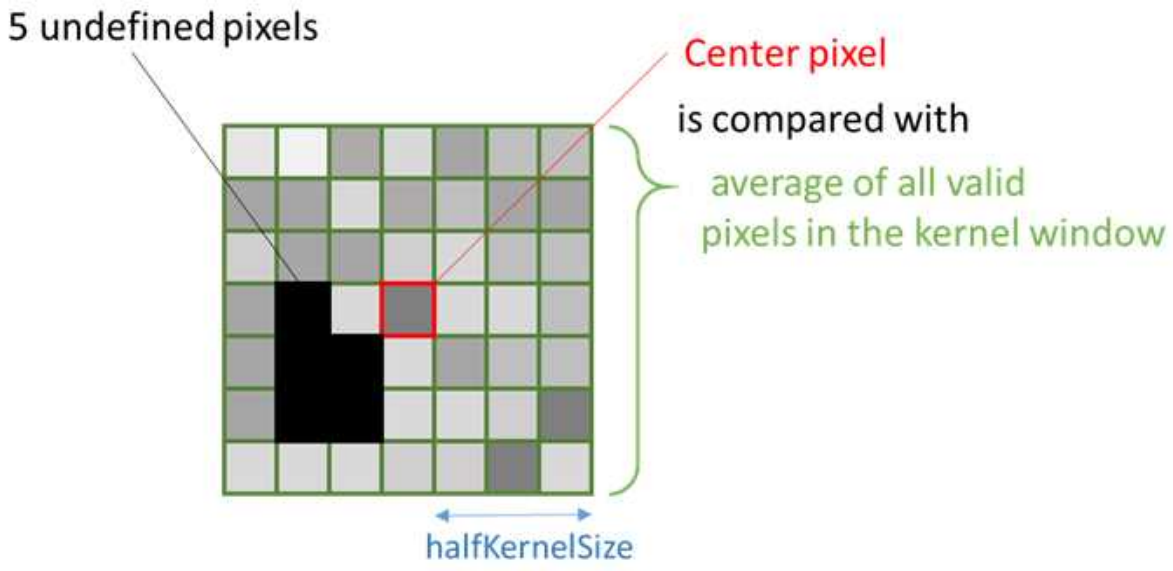
The application removes points and applies a low-pass filter on the remaining points to detect only the slow / global PCB deformations. This filtering is done in 2 steps.

Filter 1: removing the outliers

1. The filter `RemoveNoise` defines a kernel window that is moved over every pixel of the ZMap.
2. For each pixel of the ZMap image, the kernel window is centered on this pixel and the filter condition determines if the center pixel is either kept or removed.

   The filter condition used here is `E3DNoiseRemovalMethod_AbsoluteDifferenceFromMean`; it compares the value of the pixel in the center with the average of all valid pixels in the kernel window.

This is illustrated on the figure below.



The application evaluates the condition to keep or remove the center pixel as follow :

- If a window has less than 25% of defined pixels (see `ratioValidPixelsFilter` in the code) or if the center pixel is already undefined, this center pixel is marked as undefined.
- The application computes the height deviation of the center point with respect to all the valid points in the kernel window and, if the resulting height deviation exceeds 30 µm (see `thresholdFilter` in the code), the application removes the pixel in the center of the kernel window (it actually replaces it by 0, meaning « undefined pixel »).

Filter 2: applying an averaging filter

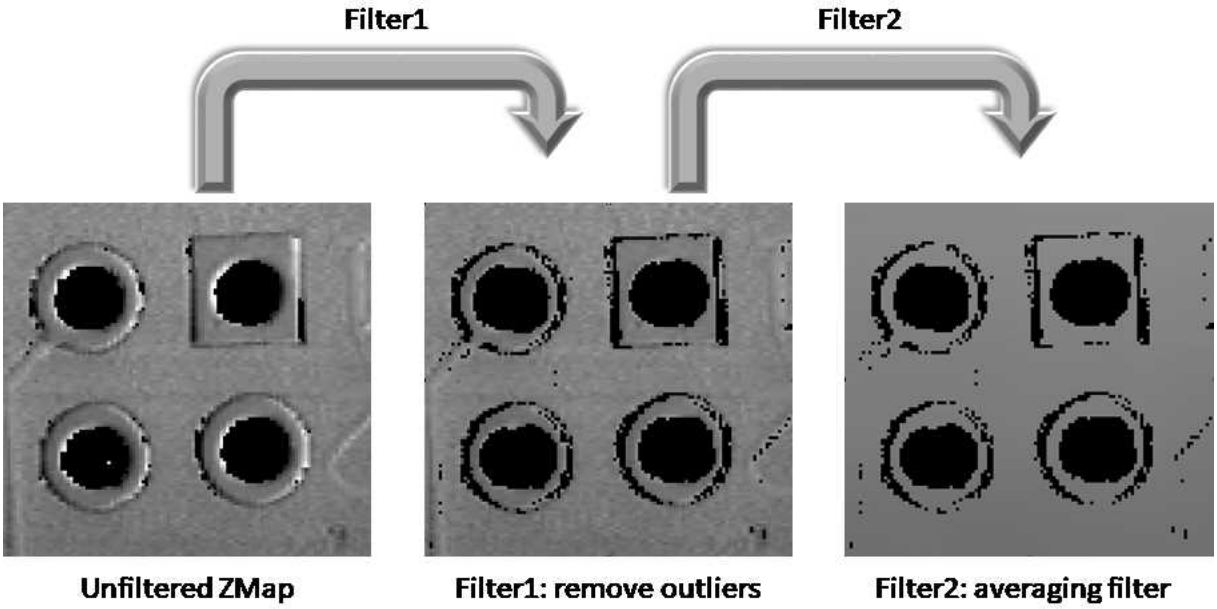
1. In a second step, the application applies an averaging filter (low-pass) in order to remove the random noise.
2. The filter `ComputeAverageMap` also defines a kernel window that is moved over every pixel.
3. If there are enough valid pixels within the window (at least 25% in this case) and if the center pixel is valid, this center pixel is replaced by the average of all pixels within the kernel window.

Filtering code

The code used for the filtering of the ZMap data is:

```
// Process the ZMap to remove noise and small scale structures
// Filters parameters
int halfKernelSizeFilter = 25; // kernel size = 2 x halfKernelSizeFilter + ►pixel = 5►
float thresholdFilter = 0.030f; // threshold = maximum deviation from mean
float ratioValidPixelsFilter = 0.25f; // requires at least 25% of valid points in the kernel

// Apply noise removal filter
EZMap►6 zmapBeforeAlignmentFilter►; // output of the filter
zmapBeforeAlignmentFilter►.SetSize(zmapBeforeAlignment);
Easy3D::RemoveNoise(zmapBeforeAlignment, zmapBeforeAlignmentFilter►,
                    E3DNoiseRemovalMethod_AbsoluteDifferenceFromMean,
                    halfKernelSizeFilter, thresholdFilter, ratioValidPixelsFilter, false);

// Apply low-pass filter
EZMap►6 zmapBeforeAlignmentFilter2; // output of the second filter
zmapBeforeAlignmentFilter2.SetSize(zmapBeforeAlignment);
Easy3D::ComputeAverageMap(zmapBeforeAlignmentFilter►, zmapBeforeAlignmentFilter2,
                          halfKernelSizeFilter, ratioValidPixelsFilter);
```

The different steps of the filtering are illustrated below:



The 2 steps of the ZMap filtering

Aligning the ZMap on the PCB edges (optional)

This optional step consists in finding the orientation of the PCB (detection of a rectangle).

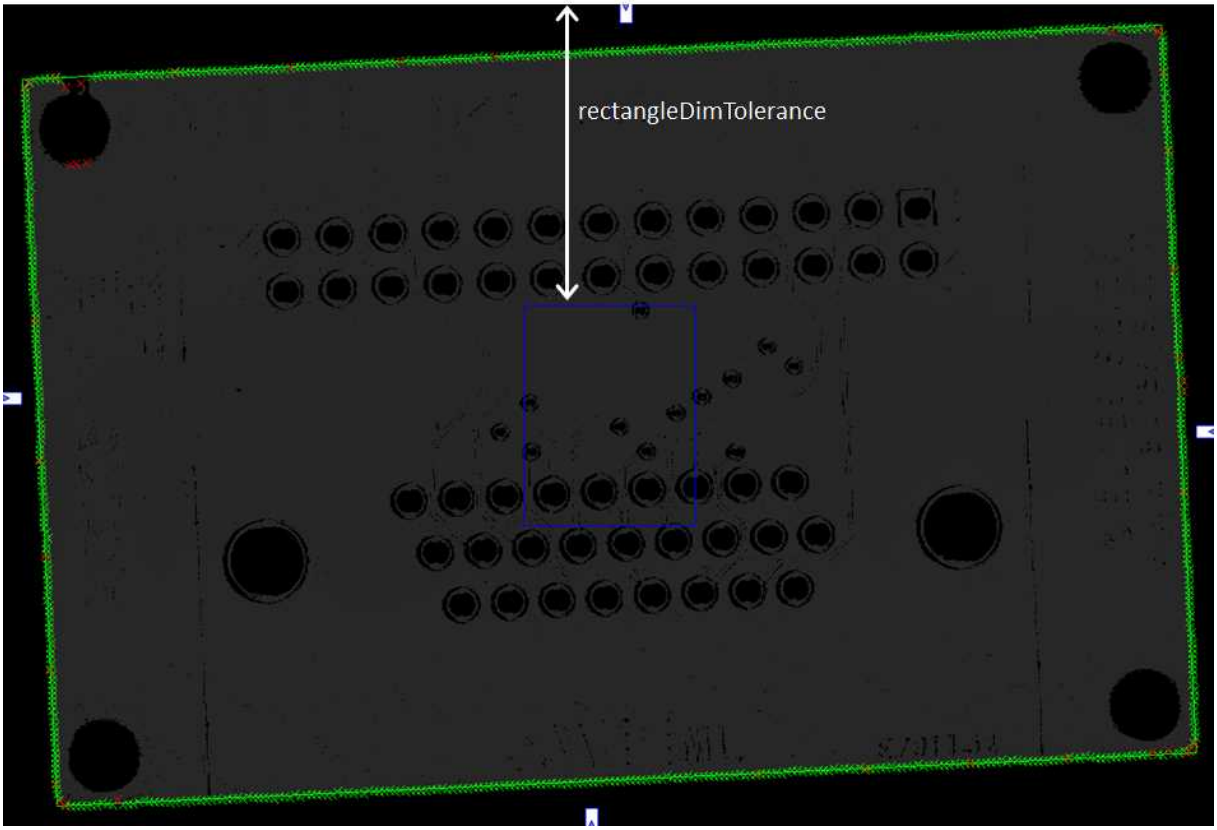
> **TIP**
> We could skip this step for the computation of the warpage but aligning on the edges makes the comparison of different ZMaps with each other easier.

To generate a ZMap aligned on the PCB edges:

1. The application converts the ZMap to an 8-bit image. This is necessary to use the 2D tool set of Open eVision.
2. Using EasyGauge, it detects the edges of the PCB by fitting a rectangle on the ZMap image.

The application uses the transitions between the undefined (0) and the valid (non-zero) pixels to detect the position of the edges of the rectangle.

The use of a rectangular gauge on the ZMap image is illustrated below:



The corresponding code is:

```
// From the ZMap create an 8-bit image for alignment
EImageBW8 imageBeforeAlignment8(zmapWidth, zmapHeight);
// conversion ↵6-bits to 8-bits
EasyImage::Convert(&zmapBeforeAlignmentFilter2.AsEImage(), &imageBeforeAlignment8);

// Search for the PCB "rectangle" in 8-bits image
float rectangleDimTolerance = 500.f; // 500 pixels tolerance on the rectangle's dimension
ERectangleGauge ERectangleGauge↵;
ERectangle measuredRectangle;
ERectangleGauge↵.SetTolerance(rectangleDimTolerance);
ERectangleGauge↵.SetSize((float)(zmapWidth), (float)(zmapHeight));
ERectangleGauge↵.SetThreshold(20);
ERectangleGauge↵.SetCenterXY((float)(zmapWidth / 2.0), (float)(zmapHeight / 2.0));
ERectangleGauge↵.SetTransitionChoice(ETransitionChoice_NthFromBegin);
ERectangleGauge↵.SetTransitionIndex(0); // take the first transition ...
ERectangleGauge↵.SetTransitionType(ETransitionType_Bw); // ... from black to white
ERectangleGauge↵.SetNumFilteringPasses(↵0);
ERectangleGauge↵.SetFilteringThreshold(5.0f); // threshold = 5 x the mean deviation
ERectangleGauge↵.Measure(&imageBeforeAlignment8);
measuredRectangle = ERectangleGauge↵.GetMeasuredRectangle();
float rectangleSizeX = ceil(measuredRectangle.GetSizeX()); // will be the width of the final ZMap
float rectangleSizeY = ceil(measuredRectangle.GetSizeY()); // will be the height of the final ZMap

// Store the 3D coordinates of the aligned rectangle corners
EPoint corner_2D[4];
E3DPoint corner_3D[4];
measuredRectangle.GetCorners(corner_2D[0], corner_2D[↵], corner_2D[2], corner_2D[3]);
for (int i = 0; i<4; i++)
{
  E3DPoint cornerPtZMap;
```

```
  cornerPtZMap = E3DPoint(corner_2D[i].GetX(), // X pixel position
                          corner_2D[i].GetY(), // Y pixel position
         zMapOffset / zMapVerticalResolution); // = ↵0000 (height of the ZMap reference plane)
  zmapBeforeAlignmentFilter2.PixelToWorld(cornerPtZMap, corner_3D[i]);
}
```

Creating the filtered point cloud

1. In order to create a new ZMap with a well-defined reference plane (parallel with the regression plane through the filtered points), the application generates a point cloud from the smoothed ZMap.

In the code below, the filtered point cloud is named `filteredPc`:

```
// From the filtered ZMap, generate a new 3D point cloud
// Use that point cloud to estimate a better reference plane
EPointCloud filteredPc;
zmapBeforeAlignmentFilter2.ToPointCloud(filteredPc);
E3DPlaneFitter planeFitter;
E3DPlane refPlane_2 = planeFitter.Fit(filteredPc);  // find the best fit plane
```

2. The application fits a plane (the final regression plane called `refPlane_2`) through the filtered data points.
3. This new reference plane, that is very close to `refPlane_↵`, is the new « horizontal » reference for the generation of the final ZMap on which the warpage is computed.

This plane is much less sensitive to the noise and outliers found in the original data.

Computing the warpage of the PCB

1. The application creates the final ZMap using the filtered point cloud.

The position of this new ZMap is based on:

- The plane `Ref_plane2` minus 10 mm as the reference plane.
- The 3D position of the corners to determine the reference (lower-left) corner and the new horizontal orientation (X axis). Using the corner positions, we specify the origin and the orientation vector for the generation of the new ZMap, assuming that the two planes are very close to each other.

The code that generates this aligned ZMap is:

```
// Generate the new ZMap with the filtered data
EZMap↵6 zmap_;
zmapGenerator.SetOrigin(corner_3D[2]);
zmapGenerator.SetReferencePlane(refPlane_2 - zMapOffset); // refPlane_2 – ↵0mm
E3DPoint horizDirection(corner_3D[↵].X - corner_3D[0].X,
                        corner_3D[↵].Y - corner_3D[0].Y,
                        corner_3D[↵].Z - corner_3D[0].Z);
zmapGenerator.SetOrientationVector(horizDirection);
zmapGenerator.SetResolution((int)rectangleSizeX, (int)rectangleSizeY);
zmapGenerator.SetExtension(0.f); // no border
zmapGenerator.Convert(filteredPc, zmap_);
```

2. To compute the warpage of the PCB, the application only needs the maximum and the minimum height from the aligned ZMap.

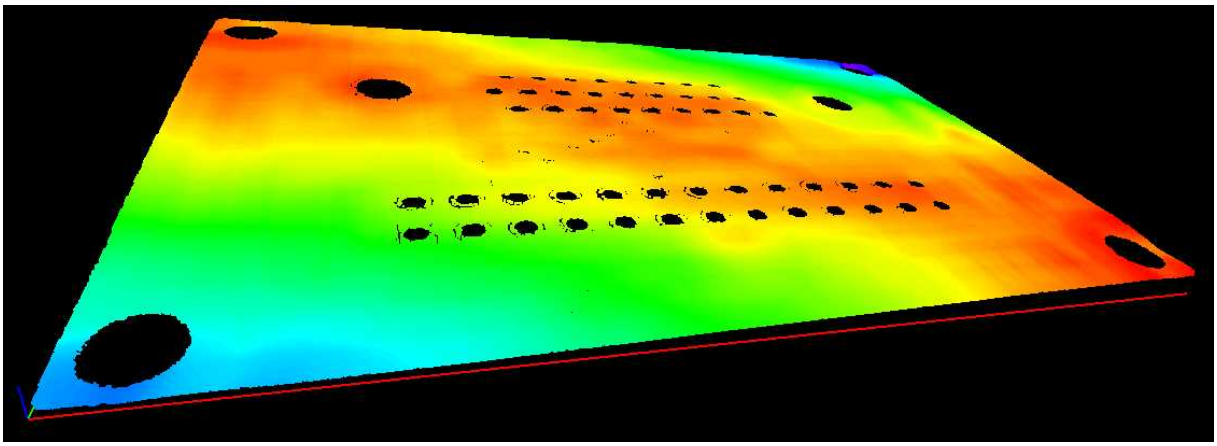
   It retrieves these values with the **static method** `ComputeStatistics` in the class `Easy3D`.

The corresponding code is:

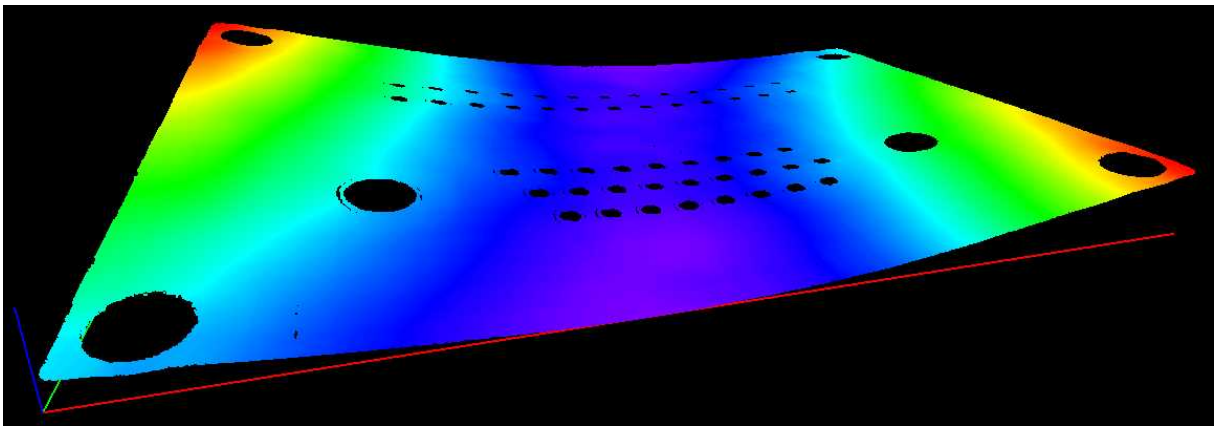
```
// Calculate warpage in metric unit
UINT32 validCount;
float minValue, maxValue, averageValue;
Easy3D::ComputeStatistics(zmap_, validCount, minValue, maxValue, averageValue);
float warpage = maxValue - minValue;
```

- The sample application displays the PCB in 3D and applies a color map.
- The 3D viewer applies a scale factor of 10 on Z axis to emphasize the warpage.

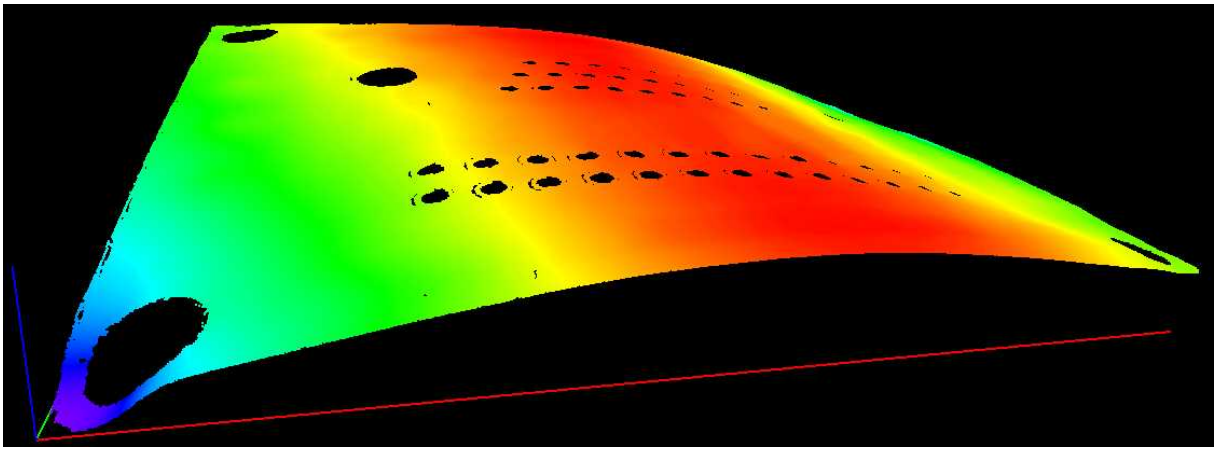
Sample 3D renderings of the resulting depth maps (showing the warpage) and their corresponding warpage measurement are illustrated below:



Warpage = 0.145 mm



Warpage = 0.407 mm



Warpage = 0.620 mm