3D Machine Vision course:

Overview and Laser Triangulation

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Course Outline

➢ What is 3D Machine Vision?

➢ Transformations of rigid bodies in space

➢ Laser Triangulation (or light stripe triangulation)
  ➢ Light stripe detection
  ➢ Occlusions or shadows
  ➢ Calibration for metric measurements
  ➢ Resolution and accuracy: how to tweak
  ➢ Linking to 2D tools (the Zmap)
  ➢ Match3D example

➢ New tools in SAL3D

➢ Questions, doubts, ...
What is 3D Machine Vision?
What is 3D Machine Vision?

3D ACQUISITION SYSTEM

Laser triangulation, stereo, shape-from-X, TOF, ...

RANGEMAP

3D RECONSTRUCTION

CLOUD OF POINTS

PROCESSING

- Measurement
- Alignment
- Comparison
- ...

CALIBRATION PARAMETERS

INTRODUCTION TO 3D ACQUISITION THEORY
Transformations of rigid bodies in space
Transformations of rigid bodies in space

- A Cloud Of Points is a mathematical representation of a rigid object in space.
- Such representation consists of a set of point coordinates X, Y, Z.
Transformations of rigid bodies in space

- A Cloud Of Points is a mathematical representation of a rigid object in space.

- Such representation consists of a set of point coordinates $X, Y, Z$.

- The ORIENTATION of a rigid body in space can be expressed with a coordinate system attached to it.
The position and orientation of a rigid body is always expressed as related to a reference coordinate system.

\[ \mathbf{T} \] is the Transformation that expresses the position and orientation of \{P\} with respect to \{W\}.
Transformations of rigid bodies in space

Properties

Orthogonal vectors

Ortho-normal Coordinate systems

Right-Handed Ortho-normal Coordinate systems
Transformations of rigid bodies in space

Rotations

ABOUT \( ^wZ \)

ABOUT \( ^wY \)

ABOUT \( ^wX \)
Transformations of rigid bodies in space

Translations

Translation vector

ΔX

ΔY

ΔZ

{P}

{W}
Transformations of rigid bodies in space

Expressing Rotations and Translations

**GRAPHICALLY**

- Rotation about $w_z$
- Orientation of $w_z$ does not change

**ALGEBRAICALLY**

Rotation about $z$

Orientation of $\vec{x}$

Orientation of $\vec{y}$

Orientation of $\vec{z}$

Rotation about $z$

$R_z = \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) & 0 \\ \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{pmatrix}$

$\vec{x} \times \vec{y} = \vec{z}$

$\vec{y} \times \vec{z} = \vec{x}$

$\vec{z} \times \vec{x} = \vec{y}$
Transformations of rigid bodies in space

Expressing Rotations and Translations

Rotation about X:

\[
R_x = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos(\alpha) & -\sin(\alpha) \\
0 & \sin(\alpha) & \cos(\alpha)
\end{pmatrix}
\]

Rotation about Y:

\[
R_y = \begin{pmatrix}
\cos(\alpha) & 0 & \sin(\alpha) \\
0 & 1 & 0 \\
-\sin(\alpha) & 0 & \cos(\alpha)
\end{pmatrix}
\]

Rotation about Z:

\[
R_z = \begin{pmatrix}
\cos(\alpha) & -\sin(\alpha) & 0 \\
\sin(\alpha) & \cos(\alpha) & 0 \\
0 & 0 & 1
\end{pmatrix}
\]
Transformations of rigid bodies in space

Expressing Rotations and Translations

Homogeneous transforms

Rotation

\[
R_Z = \begin{bmatrix}
\cos(\alpha) & -\sin(\alpha) & 0 & 0 \\
\sin(\alpha) & \cos(\alpha) & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Translation

Pure rotation (translation = \([0, 0, 0]^T\))

Pure translation (rotation = \(I\))

\[
T = \begin{bmatrix}
1 & 0 & 0 & T_x \\
0 & 1 & 0 & T_y \\
0 & 0 & 1 & T_z \\
0 & 0 & 0 & 1
\end{bmatrix}
\]
Transformations of rigid bodies in space

Expressing Rotations and Translations

Class
sal3d::Movement3D

\[
\mathbf{wT_p} = \begin{pmatrix}
0.8365 & -0.2241 & 0.5000 & 10.0000 \\
0.3387 & 0.9287 & -0.1503 & 1.0000 \\
-0.4307 & 0.2951 & 0.8528 & -1.0000 \\
0.0000 & 0.0000 & 0.0000 & 1.0000 \\
\end{pmatrix}
\]
Laser triangulation

Light stripe detection
Laser triangulation:

Light stripe detection

Grey level representation

Determination of the maximum value position up to $1/64^{th}$ of a pixel

A single point is obtained for each line across the laser stripe. This point is obtained at subpixel accuracy at a maximum of $1/64$ pixel. Lab tests revealed 5 microns in Z, with a FOV of 130mm.
Laser triangulation: *Light stripe detection*

Profiles can be gathered either row or column-wise in order to make up the depth map or "rangemap"
Laser triangulation:

**Light stripe detection**

Essentially, the depth information is obtained by sensing a deviation in X or Y on the light stripe image, due to a change on the height of the object.

A bigger $\Delta X$ corresponds to a bigger variation in height from the ground level.

The height representation in the computer memory corresponds to a line of grey levels for each laser profile.
Laser triangulation:  
\textit{Light stripe detection}

\begin{itemize}
\item \textbf{COG}
\item 8x to 10x better detection accuracy. (3\sigma orthogonal distance measurements of a plane reconstructed object)
\item Better detection allows smaller details to be visible.
\end{itemize}
Laser triangulation:

Light stripe detection

Coordinates: \((u, v, g)\)

- \(u\): Corresponds to the horizontal coordinate in **pixels**
- \(v\): Corresponds to the vertical coordinate in **pixels**
- \(g\): Corresponds to the height coordinate in **grey level**

Coordinates: \((x, y, z)\)

- \(x\): X coordinate in **mm**
- \(y\): Y coordinate in **mm**
- \(z\): Z coordinate in **mm**
Laser triangulation:

Light stripe detection

Coordinates: \((u, v, g)\)

- \(u\): Corresponds to the horizontal coordinate in pixels
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- \(g\): Corresponds to the height coordinate in grey level

Coordinates: \((x, y, z)\)

- \(x\): X coordinate in mm
- \(y\): Y coordinate in mm
- \(z\): Z coordinate in mm

2.5D

RANGEMAP

3D

POINT CLOUD

Introduction to 3D Acquisition theory
Laser triangulation: Occlusions or shadows

The areas where the camera does not record any stripe position are left blank, that is, in absence of data, which are represented as black areas in the rangemap.

Because the laser stripe may be projected onto spots that are “hidden” to the camera, the camera will simply NOT record the laser position at those spots.
Laser triangulation: Occlusions or shadows

Rangemap as acquired with camera A

Rangemap as acquired with camera B

Rangemap with less occlusions after smoothly merging A and B rangemaps
Laser triangulation
Calibration for metric measurements
Laser triangulation:
*Calibration for metric measurements*

The Pinhole camera model

- Captures all light rays through a single tiny hole or point
- This point is called Center of Projection
- The image is formed on the image plane
- The focal length ($f$) is the distance between the center of projection and the image plane
Laser triangulation: Calibration for metric measurements

Perspective Distortion

Because of the perspective projection, the 3rd dimension is lost, angles are not preserved and lengths are not preserved.
Laser triangulation: Calibration for metric measurements

Focussing the lenses

Object  Lens  Image Plane

Circle Of Confusion

Depends on the focal length but also on the lens quality
Laser triangulation:

Calibration for metric measurements

Focussing the lenses

\[ \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \]

Points satisfying this equation are in-focus
Laser triangulation:
*Calibration for metric measurements*
Laser triangulation:

*Calibration for metric measurements*

Depth of Field

http://www.cambridgeincolour.com/tutorials/depth-of-field.htm
Laser triangulation:

*Calibration for metric measurements*

- Depth of Field becomes larger as the aperture size is decreased.
- Image intensity is decreased as the aperture size is decreased!!

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**Diagram:**

- Depth of Field
- Aperture
- Object
- Image
Laser triangulation: Calibration for metric measurements

Large aperture = small DOF
Small aperture = large DOF
Laser triangulation:

Calibration for metric measurements

Lens distortion

No distortion  Pincushion  Barrel

Rule of thumb:
Larger f induces less lens distortion, but...

USE LOW DISTORTION LENSES!!
Laser triangulation: 
*Calibration for metric measurements*

**Rangemap** → **Point Cloud**

**Metric Calibration Tool** → **Calibration Parameters** → **SAL3D Core** → **Point Cloud**
Laser triangulation: Calibration for metric measurements

1. Scan the calibration object
2. Input the rangemap into the Metric Tool and obtain the calibration parameters

Linear calibration

Specially designed calibration object
Laser triangulation: 
*Calibration for metric measurements*

Static calibration

1. Grab one profile

2. Input the profile into the Metric Tool and obtain the calibration parameters

Specially designed calibration object
Laser triangulation: Calibration for metric measurements

Single pattern

More complex associations of calibration units to deal with 360° field of view
Laser triangulation: Calibration for metric measurements

With or Without calibration

Uncalibrated view

Calibrated view
Laser triangulation:
Resolution and accuracy: how to tweak

1) Better height resolution
- Height sampling with COG
- Height sampling with Peak Detector

2) More compact design at the same performance
- Using COG
- Using Peak
Laser triangulation: 
*Linking to 2D Tools (The ZMap)*

Orthogonal projection onto the Z plane
Laser triangulation: 

*Linking to 2D Tools (The ZMap)*

Rangemaps contain perspective distortion. COPs can be manipulated according to the user's needs, finally generating the ZMap in the desired orientation.

The ZMap is a "flat representation" of a 3D Cloud of Points, which can be processed with 2D tools (MIL, Halcon, CVB, OpenCV, etc...) to get metric measurements.
Laser triangulation: 

*Linking to 2D Tools (The ZMap)*

- A Zmap is actually a 2D image of float values, that can be represented as gray levels.
- The height of a Zmap is proportional to the total Y dimension of the COP.
- The width of a Zmap is proportional to the total X dimension of the COP.
- The gray level of a Zmap is proportional to the height or Z coordinates of the COP.
# Laser triangulation: 
**Linking to 2D Tools (The ZMap)**

<table>
<thead>
<tr>
<th>Rangemap vs. ZMap</th>
<th>Rangemap</th>
<th>ZMap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preserves metric properties</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Independent of acquisition source</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Can be used by 2D tools</td>
<td>SOMETIMES</td>
<td>ALWAYS</td>
</tr>
<tr>
<td>Can be used to locate 3D features using 2D tools, in 3D space</td>
<td>INDIRECTLY</td>
<td>YES</td>
</tr>
<tr>
<td>Removes perspective distortion</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>
Laser triangulation:  
**Match3D example**

**Speed:** The Match3D tool features a patent-pending technology allowing an ultra-fast alignment of point clouds at unparalleled speed

- Single Core PC (Benchmark)
- 1 million points for both model and scanned point clouds
- $\pm 10^\circ$ initial misalignment on any of the X, Y and Z axis
- 4% initial translation along any of the X, Y and Z axis
Laser triangulation:

*Match3D example*

Differences between the model and the scanned surface
The differences are directly obtained through the subtraction of both point clouds, and they express the distance in mm

**DISPARITY MAP**

It's a floating point value image which directly conveys 3D metric localized information on the difference between model and part.

**Defect in 3D**

**Defect in 3D (side view)**
Laser triangulation: *Match3D example*

Display of row # 515 and column # 888 of the disparity map.

Heights are in mm.

Disparity map is close to zero when the model and scan are “equal”.

Introduction to 3D Acquisition theory
Laser triangulation:  
*Match3D example*
New Tools in SAL3D
New Tools in SAL3D

CAD Import Tool

The **CAD Import Tool** of SAL3D allows the obtention of COPs (SAL3D's representation of Cloud of Points) to be used in conjunction with the Match3D Tool.
New Tools in SAL3D

CAD designs in **IGES** or **STL** format can be imported into SAL3D COPs
New Tools in SAL3D

View selection and resolution set-up
New Tools in SAL3D

Importing into SAL3D COP
New Tools in SAL3D

Imported COP visualization
New Tools in SAL3D
New Tools in SAL3D

Integration Tool

Complete Model

Multiple aligned views
Questions, Doubts, ...

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