> Machine Vision Revision (Summarized from lessons)
> Prof. Hu Liang
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> 200320721 Tang Longbin
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> 欢迎补充！

Lec 1 Introduction

What can Machine Vision do?

- Increase profits
- Reduce defects
- Increase yield
- Track, Trace and Control

How?

- Measurement (Gauging)
- Counting
- Location
- Decoding
- Inspection (Defect detection)

Key parts of a Machine Vision System

- Lighting
- Lens
- Sensor (CCD/CMOS)
- Vision Processing (Algorithm & Software)
- Communication

Lec 2 How to design a MV system

Machine Vision System Design

Specialization of the task

- Task and Benefit
- Part (Shape and features)
  - Part Presentation
  - Part motion (Indexed positioning / Continuous movement)
- Performance Requirements
  - Accuracy
  - Time performance
- Information Interface

- Installation Space
- Environment
- Checklist

Design of the system

- Camera Type
- **Field of View (FOV)**
- Resolution
  - camera sensor resolution (R*C)
  - Spatial Resolution (Depends on the camera sensor and FOV)
  - Measurement Accuracy (Depends on spatial resolution, feature contrast and software algorithms)
  - Calculation of Resolution
- Choice of Camera, Frame Grabber and Hardware Platform
- Lens Design
  - Focal length
  - Lens Flange Focal Distance (法兰距)
  - Lens Diameter and Sensor Size
- Choice of Illumination
- Mechanical Design
- Electrical Design
- Software
  - **ROI (Region Of Interest)**

Calculation of costs

Development and installation of the system

Field of View (FOV)

FOV = maximum part size + tolerance in positioning + margin + adaption to the aspect of the camera sensor

Calculation of Resolution

$$R_s = \frac{FOV}{R_c} = \frac{S_f}{N_f}$$

$$R_c = \frac{FOV}{R_s} = FOV * \frac{N_f}{S_f}$$

Name	Variable	Unit
Camera resolution	R_c	pixel
Spatial resolution	R_s	mm/pixel
Field of View	FOV	mm
Size of the smallest feature	S_f	mm
Number of pixels to map the smallest feature	N_f	pixel

Pixel Rate

$$PR = Rc_{hor} * Rc_{ver} * fr + overhead(10\% - 20\%)$$

Name	Variable	Unit
Pixel Rate	PR	pixel/s
Camera resolution horizontal	Rc_{hor}	pixel
Camera resolution vertical	Rc_{ver}	pixel
Frame Rate (帧率)	fr	Hz
Camera resolution	R_c	pixel
Line Frequency	fs	Hz

Focal length

$$\frac{1}{f'} = \frac{1}{a'} - \frac{1}{a}$$

f' : focal length

a : standoff distance (work distance)

a' : distance between the lens and the image sensor

The magification β

$$\beta = \frac{y'}{y} = \frac{a'}{a}$$

y : size of real-world object

y' : size of the image object

$$\beta = -\frac{sensor\ size}{FOV}$$

so

$$f' = a * \frac{\beta}{1 - \beta}$$

$$a = f' * \frac{1 - \beta}{\beta}$$

Example

shown in the pdf (end of the lec2)

Lec 3 Camera Sensor

Light and CCD/CMOS sensor

- Quantum Efficiency (QE, 量子效率) : the ratio of light that the sensor converts into charge.
- **The Full Well Capacity (满井容量)** : the maximum number of electron that register a signal in a pixel.
  - 4,000 electrons --- small pixels
  - 10,000 electrons --- medium pixels
  - 50,000 electrons --- large pixels
- CCD and CMOS (The difference is how they transfer the charge out of the pixel and into the camera's electronic "read out".)
  - CCD : high image quality, low speed.
  - CMOS : low image quality, high speed.

Digital Cameras: Basics

- Camera Controls (What can affect the quality of images?)
  - Gain
  - Exposure
  - Trigger
  - Image Format
  - Resolution
- Shutter
  - Global shutter (全局快门)
  - Rolling shutter (卷帘快门)
- Trigger
  - Hardware trigger (external)
    - Strobe (频闪)
  - Software trigger (internal)

Camera Type

Area Camera

- Fixed aspect ratio
- Easy image processing
- Longer intergration time possible
- Skipping and Binning (将相邻像元感应的电荷加在一起，以单个像素的模式读出)

Color Area Camera

- 3-CCD (using a separate CCD for each color)
  - great image quality
  - expensive
- 1-CCD (Bayer Pattern)
  - Green 50%, Blue 25%, Red 25%
  - Lower color spatial resolution
  - Lower manufacturing cost

Line Scan Camera

- 2nd dimension comes by movement
- Very good price/pixel performance
- High pixel fill-factor (typically 100%)
- Very short intergration time
- Difficult design in image processing
- $\frac{L_o}{H_c} = \frac{V_o}{V_c}$ (**图像不拉伸或者压缩的条件**)

Camera Interfaces

- **GigE Vision Standard**
- IEEE 1394 (Vision Standard : DCAM)
- Camera Link
- USB
- Interface Comparison and the GenICam Standard

GigE Vision

- Main advantages
  - Cable length and cost effective components
  - Accessories are reliable

IEEE 1394

- Invented by Apple and TI in the late 1980s
  - Apple's original name : **"FireWire"**
- Standardized by IEEE in 1995

Camera Link (CL)

- Require a "camera file"
- High Speed

USB

- Maximum cable length is 5m

vInterface Comparison and the GenICam Standard (相机通用接口)

Smart Camera

Lec 4 Lens

- Pinhole camera model (小孔成像)

Gaussian Optics

- Light Refraction ($n_1 \sin \alpha_1 = n_2 \sin \alpha_2$)
- Paraxial Approximation (近轴近似) when α is small ($\sin i \approx i$)

Glossary of Terms for Lens

- Field of View (FOV)
- Depth of Field (DOF)
- Work Distance (WD)
- Resolution
- Sensor Size
- Primary Magnification (Pmag)

Resolution

Contrast

$$Contrast = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

- Resolution is defined at a specific contrast

Modulation Transfer Function (MTF)

$$F_{MTF} = \frac{g_1 - g_2}{255}$$

Depth of Field (DoF)

- F# and Aperture (光圈)

$$F\# = \frac{f}{D}$$

- 大光圈，小景深；小光圈，大景深

Distortion (畸变)

$$Distortion = \frac{AD - PD}{PD} * 100\%$$

AD : Actual distance
PD : Predicted distance

- Distortion < 0： 负畸变（桶形畸变）
- Distortion > 0： 正畸变（枕形畸变）

Lec 5 Lighting

Vision Lighting Sources

- **LED-Light Emitting Diode**
- Quartz Halogen-W/Fiber Optics
- Fluorescent
- Xenon

- Metal Halide
- High Pressure Sodium

Solid Angle

$$d\Omega = \frac{dA\cos\theta}{r^2}$$

Measuring LED light power

- 光通量 Flux（Φ）
  - 单位： 流明 (lm)
- 光强 (I)
  - $I = \frac{d\Phi}{d\Omega}$
  - 单位：坎德拉 (cd)
- 照度（E）
  - $E = \frac{d\Phi}{dS}$
  - 单位： 勒克斯 (lx)
- 亮度（L）
  - $L = \frac{d\Phi}{dSd\Omega\cos\theta}$
  - 单位： 尼特 (nit)

How to change contrast

- Light Pattern (Structure)
- Direction (Geometry)
- Spectrum (Color/WaveLength)
- Light Character (Filtering)

Basic Lighting Techniques

- Bright Field (亮场照明) : greater than 45°
- Dark Field Lighting (暗场照明）: less than 45°
  - 表面凹凸表现力强
- Vertical Lighting
- Back Lighting
- Multi-angle Lighting
- Diffuse Dome
- On-axis Diffuse
- Flat Diffuse
- Point Source1
- Strobe

Pass Filters and Polarization Filters

Shown in the end of the pdf (lec 5)

Lec 6 Introduction of MV Software

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Lec 7 Algorithm

Binary Image

- Component Labeling
  - Row-by-Row (most common)
  - 行程编码 DFS
- Size Filter
- Euler Number (Genus)
  - $E = C - H$
  - C : the number of components
  - H : the number of holes
- Boundary
- Distance
  - Euclidean
  - city block
  - chessboard

Image Enhancement

- Gray Value Transformations (GVT)
  - can use LUT (Lookup Table) to increase the speed
- Radiometric Calibration
- Image Smoothing
  - Temporal averaging (时域平均)
  - Mean Filter (均值滤波)
  - Gaussian Filter
  - Median and Rank Filter
- Fourier Transform
  - DFT
  - FFT

Lec 8 Algorithm Fundamentals

Geometric Transformations

Affine Transformations (仿射变换)

- rotation and translation (平移)
- apparent change in size

$$\begin{bmatrix} \hat{r} \\ \hat{c} \\ 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} r \\ c \\ 1 \end{bmatrix}$$

Translation

$$\begin{bmatrix} 1 & 0 & t_r \\ 0 & 1 & t_c \end{bmatrix}$$

Scaling

$$\begin{bmatrix} s_r & 0 & 0 \\ 0 & s_c & 0 \end{bmatrix}$$

Rotation by α

$$\begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \end{bmatrix}$$

Skew (倾斜) of the vertical axis by θ

$$\begin{bmatrix} \cos\theta & 0 & 0 \\ \sin\theta & 1 & 0 \end{bmatrix}$$

Projective Transformations (投影变换)

- H : homography (单应), DoF = 8

$$\begin{bmatrix} \hat{r} \\ \hat{c} \\ 1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} * \begin{bmatrix} r \\ c \\ w \end{bmatrix}$$

Nearest-Neighbor Interpolation

- the closest of the four adjacent pixel centers

Bilinear Interpolation

- use four corresponding gray values and weights them appropriately

Bicubic Interpolation

Smoothing to avoid aliasing

Polar Transformations

Image Segmentation

Subpixel-Precise Thresholding

- 插值得到二维曲面，然后二值化

Feature Extraction

Region Features

- Area
- Moments (矩)
  - $m_{p,q} = \Sigma g_{r,c} r^p c^q$
  - 通过二阶中心矩的长轴短轴比可以判断圆与椭圆
- Ellipse Parameters
- Enclosing Rectangles and Circles
- Contour Length
  - Compactness of a region : $c = \frac{l^2}{4\pi a}$
- Rectangularity
  - $R = \frac{A_0}{A_{MER}}$
- Roundness
  - $C = \frac{P^2}{4\pi A}$
  - P is the perimeter
  - A is the area
- Circularity
  - $C = \min(1, C')$
  - $C' = \frac{A}{\pi d_{max}^2}$
- Statistical Features
  - minimum and maximum gray value in a region
  - mean gray value within the region
  - the varianve of the gray values
  - standard deviation

Morphology

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Blob analysis

- Blob 是指对一个提取的 Region 进行特征分析的过程

Lec 9 NCC Template Matching

- To descrip the object to be found by a template
- By computing the similarity between the template and the image

Gray-Value-Based Template Matching

Similarity Measures Based on Gray Value Differences

- $SAD(r,c) = \frac{1}{n}\Sigma_{(u,v)}|t(u,v) - f(r+u, c+v)|$
- $SSD(r,c) = \frac{1}{n}\Sigma_{(u,v)}(t(u,v) - f(r+u, c+v))^2$
  We can find instances with a certain upper threshold.
  Disadvantage : Affected by the lighting.

Normalized Cross-Correlation (NCC)

$$NCC(r,c) = \frac{1}{n}\Sigma_{(u,v)}\frac{t(u,v)-m_t}{\sqrt{s_t^2}} * \frac{f(r+u,c+v)-m_f(r,c)}{\sqrt{s_f^2(r,c)}}$$

$$m_t = \frac{1}{n}\Sigma_{(u,v)}t(u,v)$$

$$s_t^2 = \frac{1}{n}\Sigma_{(u,v)}(t(u,v)-m_t)^2$$

$$m_f = \frac{1}{n}\Sigma_{(u,v)}f(r+u,c+v)$$

$$s_f^2 = \frac{1}{n}\Sigma_{(u,v)}(f(r+u,c+v)-m_f(r,c)^2$$

Matching Using Image Pyramids

- Image Pyramids --- Sub-sampling

Robust Template Matching

- Mean squared edge distance
- Hausdorff distance

Lec 10 Robust Template Matching

Generalized Hough Transform (广义霍夫变换)

- Compute centroid (x_c, y_c)
- For each egde point (x, y), compute its distance to centroid $r(x-x_c, y-y_c)^T$
- Find edge orientation (gradient angle ϕ)
- Construct a table (R-table) of angle and r values

Detection precedures

- For each edge point
  - create an accumulator array of 2D (x, y)
  - For each edge point (x_i, y_i, ϕ_i), to use its gradient orient to index stored table
  - For each entry r_k^i in table, compute:
    - $x_c = x_i + r_k^i \cos\theta_k^i$
    - $y_c = y_i + r_k^i \sin\theta_k^i$
  - Incremental accumulator : $A(x_c, y_c) = A(x_c, y_c) + 1$
  - Find local maxima in $A(x_c, y_c)$

Handle Scale and Rotation

- Use accumulator array : $A(x_c, y_c, S, \alpha)$
- S is the scale factor
- α is the rotation factor
- Use
  - $x_c = x_i + r_k^i S\cos(\theta_k^i + \alpha)$
  - $y_c = y_i + r_k^i S\sin(\theta_k^i + \alpha)$
- $A(x_c, y_c, S, \alpha) = A(x_c, y_c, S, \alpha) + 1$

Shape-Based Matching

- Similar with Gray-Value-Based Template Matching but using gradient
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Deformable Matching

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Lec 11 Edge Detection and 1D 2D measurement

Definition of Edges

- Definition of Edges of 1D
  - $f''(x) = 0$
  - $f'(x) > 0$: positive edge
  - $f'(x) < 0$: negative edge
- Definition of Edges of 2D
  - gradient $\max(|\nabla f(r,c)|)$
  - zero-crossings of the Laplacian $\Delta f(r,c) = 0$

1D Edge Extraction

- The first derivative is given by : $f_i' = \frac{1}{2}(f_{i+1} - f_{i-1})$
- The second derivative is given by : $f_i'' = \frac{1}{2}(f_{i+1} - 2f_i + f_{i-1})$
- Using two convolution masks $\frac{1}{2}(1\ 0\ -1)$ and $\frac{1}{2}(1\ -2\ 1)$

2D Edge Extraction

- Discrete derivatives are given in 2D
  - $f'_{r;i,j} = \frac{1}{2}(f_{i+1,j} - f_{i-1,j})$
  - $f'_{c;i,j} = \frac{1}{2}(f_{i,j+1} - f_{i,j-1})$
  - $f_r = \begin{bmatrix} -1 & -a & -1 \\ 0 & 0 & 0 \\ 1 & a & 1 \end{bmatrix}$ $f_c = \begin{bmatrix} -1 & 0 & 1 \\ -a & 0 & a \\ -1 & 0 & 1 \end{bmatrix}$
  - a = 1 : Prewitt Filter
  - a = $\sqrt{2}$: Frei Filter
  - a = 2 : Sobel Filter

- Non-Maximum Supression

Accuracy and Precision of Edges

- Precision : how repeatable we can extract the value; the official name for precision is **repeatability**. Given by the variance $V[x] = \sigma_x^2$.
- Accuracy : how close on average the extracted value is to its true value. Discripted by the difference of the expected value $E(x)$ of the value to the true value T : $[E(x) - T]$.

补充内容 Segmentation and Fitting of Geometric Primitives

Fitting Lines

- Line equation : $y = mx + b$
- Hessian normal form of the line : $\alpha r + \beta c + \gamma = 0$ with $\alpha^2 + \beta^2 = 1$
- Least-Squares Line Fitting
    - $\min \epsilon^2 = \Sigma(\alpha r_i + \beta c_i + \gamma)^2 - \lambda(\alpha^2 + \beta^2 - 1)n$
- Robust Line Fitting
    - weight w_i for each point depending on the distance $\delta_i = |\alpha r_i + \beta c_i + \gamma|$.
    - 首先令 $w_i = 1$, 计算出当前 α 和 β，然后得出新 w_i 进行迭代。

Fitting Circles

- Least-Squares Circle Fitting
    - $\min \epsilon^2 = \Sigma(\sqrt{(r_i - \alpha)^2 + (c_i - \beta)^2} - \rho)^2$
- Robust Circle Fitting
    - same as line fitting

Fitting Ellipses

- similar with circles fitting

Segmentation of contours

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Camera Calibration

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