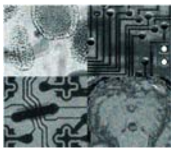


3-D Optical Measurement Technology

Prof. Liang-Chia Chen
Department of Mechanical Engineering
National Taiwan University

3D 機器視覺技術

- 三角法
- 飛行時間法
- 疊紋法
- 干涉法
- 光度法
- FFT 相位法
- 其他

Source from Prof. Chang

光學非接觸式三維輪廓量測技術

- 光學非接觸式量測
  - 主動式
    - 光雷達法
      - 時間差測定
      - 相位差測定
    - 主動立體法
      - 點光
      - 單線光、多線光
      - 階段光
      - 編碼化圖案光
      - 濃度、彩色梯度圖案光
    - 照度差立體法
    - 疊紋法
    - 干涉法
  - 被動式
    - 透鏡焦點法
    - 立體視覺法
      - 雙鏡頭
      - 參鏡頭、多鏡頭
      - 攝影機移動型
    - 動畫(物體移動)

Source from Prof. M. Chang

Visual Cues

Shading

Texture

Focus

Motion

Others:

- Highlights
- Shadows
- Silhouettes
- Inter-reflections
- Symmetry
- Light Polarization
- ...

Shape From X

- X = shading, texture, focus, motion, ...

Materials taken from Prof. S. Seitz, Carnegie Mellon University,2001

Visual Cues

Shading

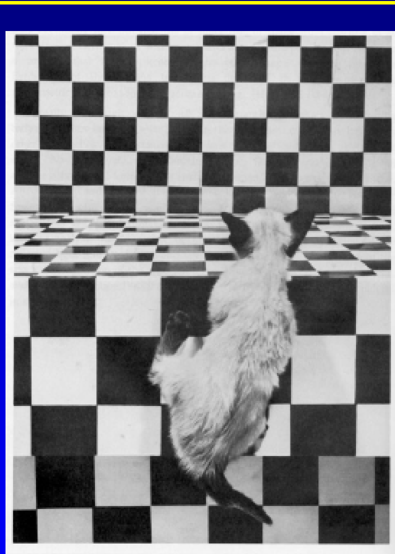
Merle Norman Cosmetics, Los Angeles

Materials taken from Prof. S. Seitz, Carnegie Mellon University,2001

Visual Cues

Shading

Texture



The Visual Cliff, by William Vandivert, 1960

Visual Cues

Shading

Texture

Focus

From *The Art of Photography*, Canon

Materials taken from Prof. S. Seitz, Carnegie Mellon University,2001

Visual Cues

Shading

Texture

Focus

Motion

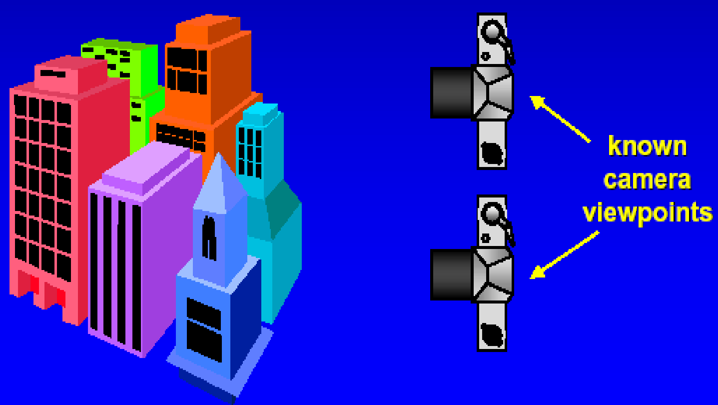
Stereo Detection

AOI
Lab

Stereo Reconstruction

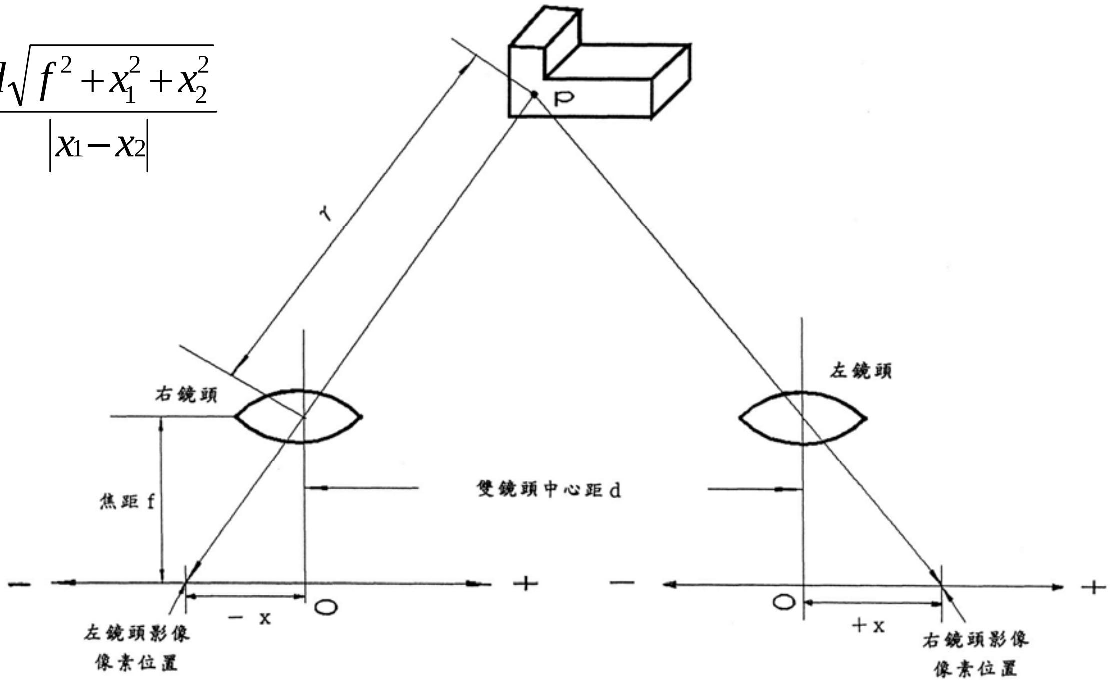
The Stereo Problem

- Shape from two (or more) images
- Biological motivation



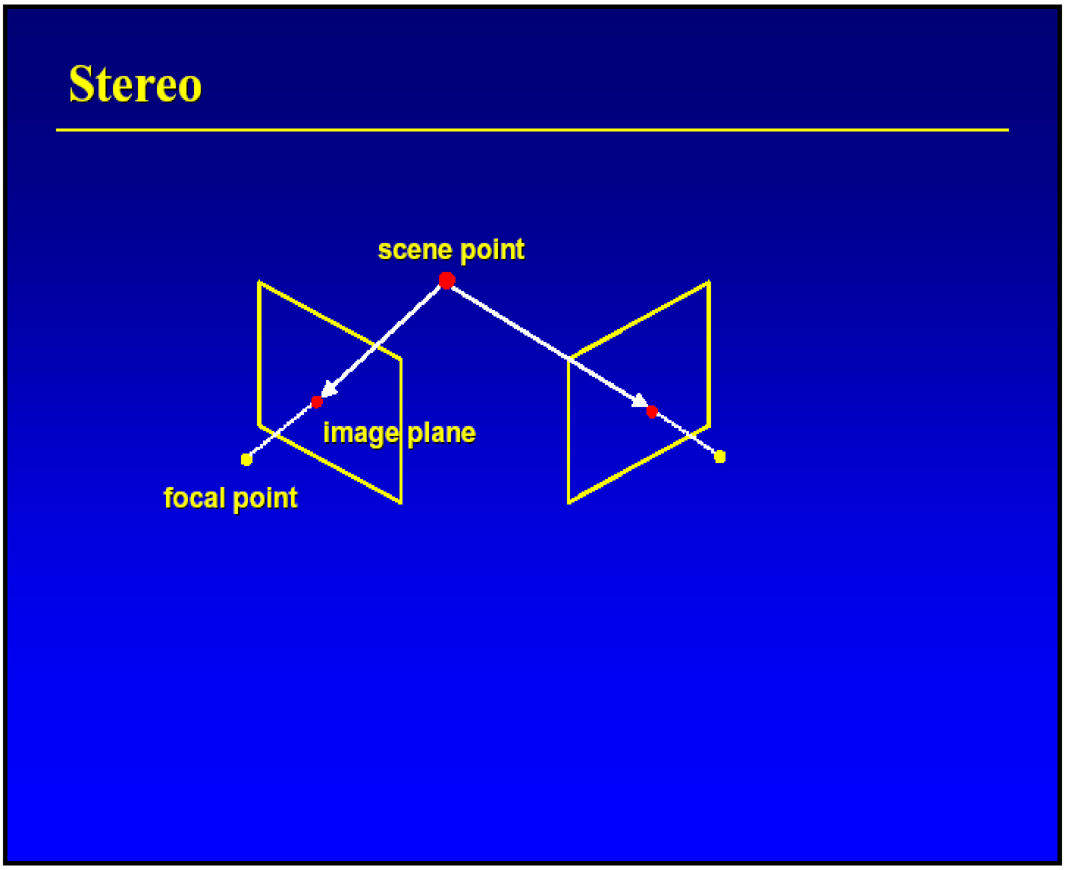
雙鏡頭法

$$r \approx \frac{d\sqrt{f^2 + x_1^2 + x_2^2}}{|x_1 - x_2|}$$



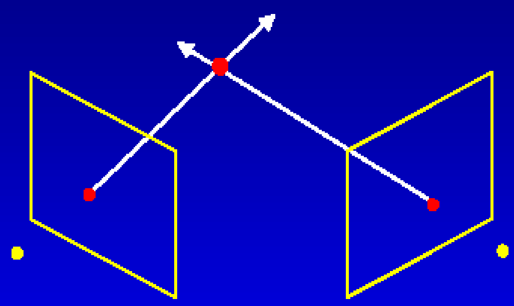
Source from Prof. Chang

AOI
Lab



Materials taken from Prof. S. Seitz, Carnegie Mellon University,2001

Stereo



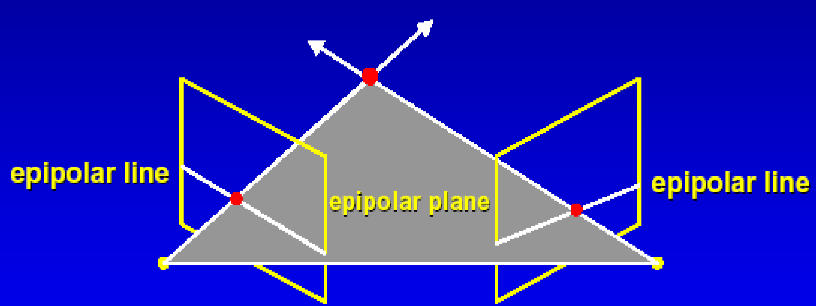
Basic Principle: Triangulation

- Gives reconstruction as intersection of two rays
- Requires *point correspondence*

Stereo Correspondence

Determine Pixel Correspondence

- Pairs of points that correspond to same scene point



Epipolar Constraint

- Reduces correspondence problem to 1D search along *conjugate epipolar lines*

Stereo Matching Algorithms

Match Pixels in Conjugate Epipolar Lines

- **Assume color of point does not change**
- **Pitfalls**
  - > specularities
  - > low-contrast regions
  - > occlusions
  - > image error
  - > camera calibration error
- **Numerous approaches**
  - > dynamic programming [Baker 81,Ohta 85]
  - > smoothness functionals
  - > more images (trinocular, N-ocular) [Okutomi 93]
  - > graph cuts [Boykov 00]

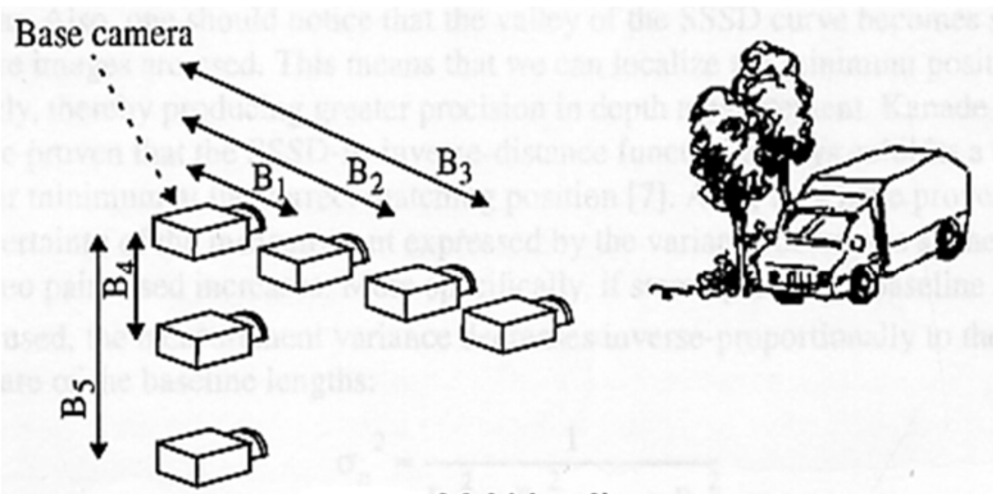
Materials taken from Prof. S. Seitz, Carnegie Mellon University,2001

Multiple image-based SSSD Method

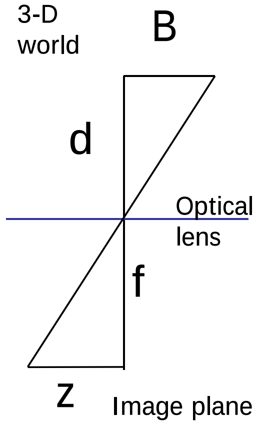
SSSD algorithm

(Sum of Sums of Squared Difference)

Multi-baseline stereo



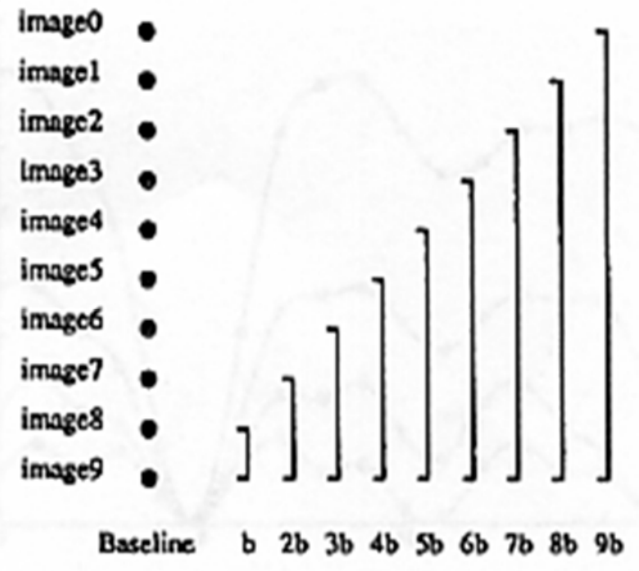
Multi-baseline stereo setup



$$\frac{d}{f} = \frac{B}{z}$$

Inverse distance $\quad \zeta = \dfrac{d}{BF} = \dfrac{1}{z}$

Inverse distance: different base distance



"Town" data set image sequence.

圖樣比對(Template Matching)

比對則法做介紹，可以分為五大類：

- **相關係數法(Correlation Measures)**
- **亮度差異量測(Intensity Difference Measures)**
- **循序相似偵測演算(Sequential Similarity Detection Algorithms)**
- **正負號改變準則(Sign Change Criteria)**
- **矩量法(Moments)**

相關係數法

在一幅W×H的影像$I(u,v)$中尋找和圖樣$T(i,j)$相匹配的子影像乃利用影像相關的觀念。

$I(u,v)$和$T(i,j)$影像之間的相關定義如下：

$$c(u,v)=\sum_{i=0}^{M}\sum_{j=0}^{N} I(u+i,v+j)T(i,j)$$

其中　i=0，1，2，...，M-1；j=0，1，2，...，N-1，而且運算的範圍總是在I和T相重疊的影像區域上進行的。

Normalization

$$r(u,v)=\frac{N\sum_{i=0}^{M}\sum_{j=0}^{N}I(i+u,j+v)T(i,j)-\left(\sum_{i=0}^{M}\sum_{j=0}^{N}I(i+u,j+v)\right)\left(N\overline{T}\right)}{\sqrt{N\sum_{i=0}^{M}\sum_{j=0}^{N}I^{2}(i+u,j+v)-\left(N\overline{I}\right)\sum_{i=0}^{M}\sum_{j=0}^{N}I(i+u,j+v)}\sqrt{N\sum_{i=0}^{M}\sum_{j=0}^{N}T^{2}(i,j)-\left(N\overline{T}\right)\sum_{i=0}^{M}\sum_{j=0}^{N}T(i,j)}}$$

$$r(u,v)=\frac{N\sum_{i=0}^{M}\sum_{j=0}^{N}I(i+u,j+v)T(i,j)-\left(\sum_{i=0}^{M}\sum_{j=0}^{N}I(i+u,j+v)\right)\left(\sum_{i=0}^{M}\sum_{j=0}^{N}T(i,j)\right)}{\sqrt{\left[\left(N\sum_{i=0}^{M}\sum_{j=0}^{N}I^{2}(i+u,j+v)\right)-\left(\sum_{i=0}^{M}\sum_{j=0}^{N}I(i+u,j+v)\right)^{2}\right]\left[\left(N\sum_{i=0}^{M}\sum_{j=0}^{N}T^{2}(i,j)\right)-\left(\sum_{i=0}^{M}\sum_{j=0}^{N}T(i,j)\right)^{2}\right]}}$$

亮度差平方(Sum of Squared Differences or Squared Error)(SSD)：

這個相似性的量測方法等效於均方根距離，而且計算量少，速度較快。其定義如下：

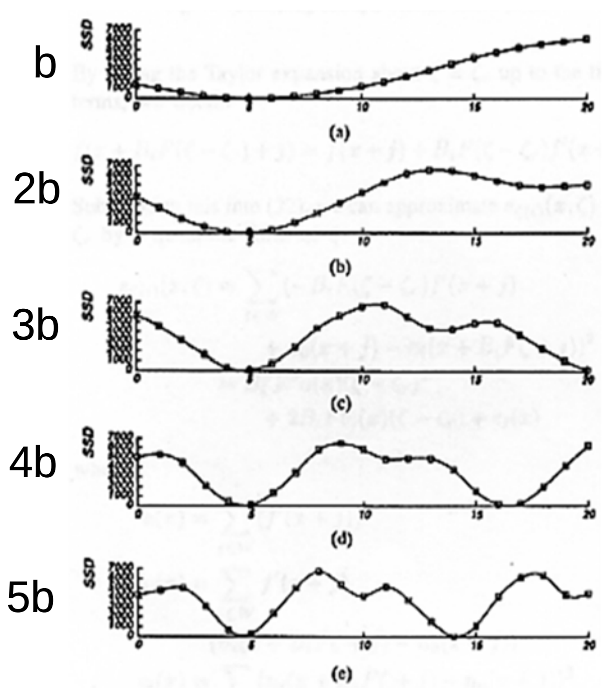
$$d_{ssd}(f,g)=\sum_{x=1}^{M}\sum_{y=1}^{N}\left(f(x,y)-g(x,y)\right)^{2}$$

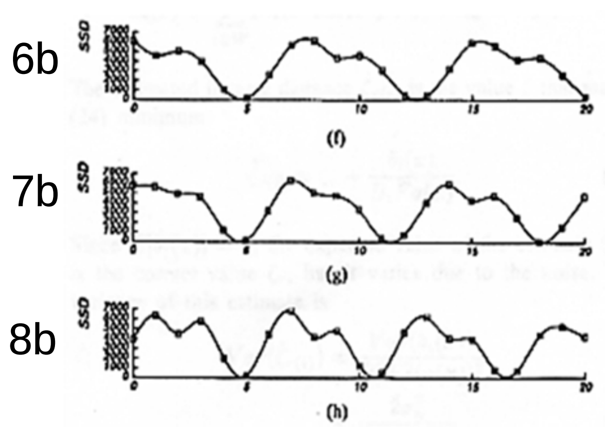
差異絕對值總和(Sum of the Absolute Valued Differences)(SAVD)：

為最簡單且常用的方法，其定義如下：

$$d_{savd}\left(f,g\right)=\sum_{x=1}^{M}\sum_{y=1}^{N}\left|f\left(x,y\right)-g\left(x,y\right)\right|$$

Inverse distance: Different base distance

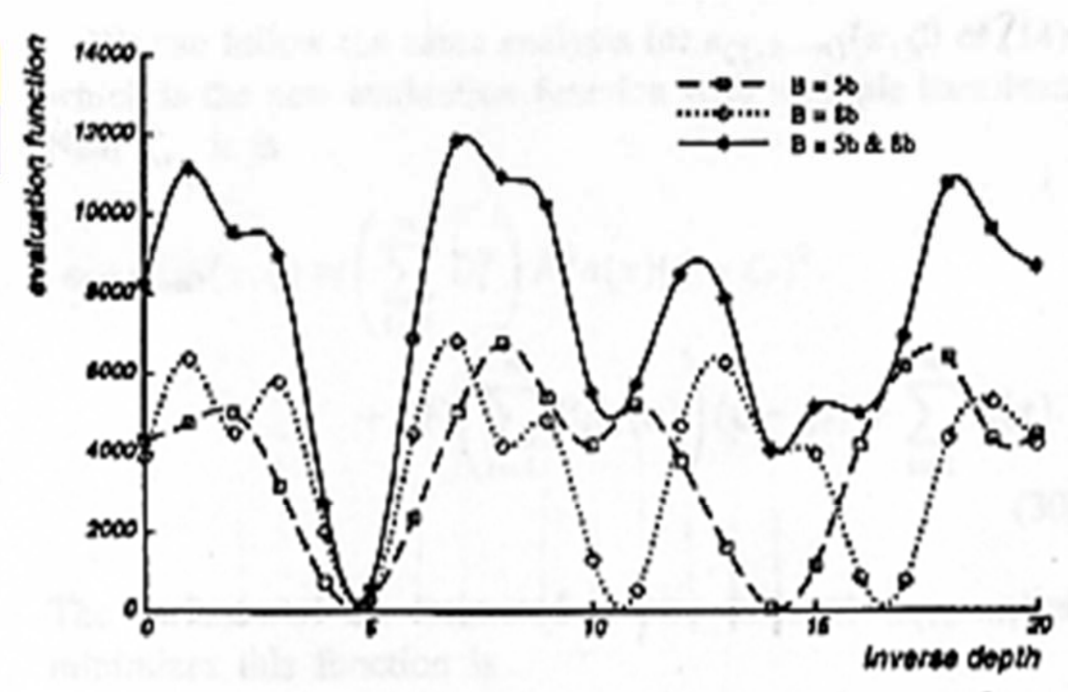




$$SSD(x,\zeta)\equiv\sum_{j\in W}(I_0(x+j)-I_i(x+B_iF\zeta+j))^2$$

note: $d=BF\zeta$

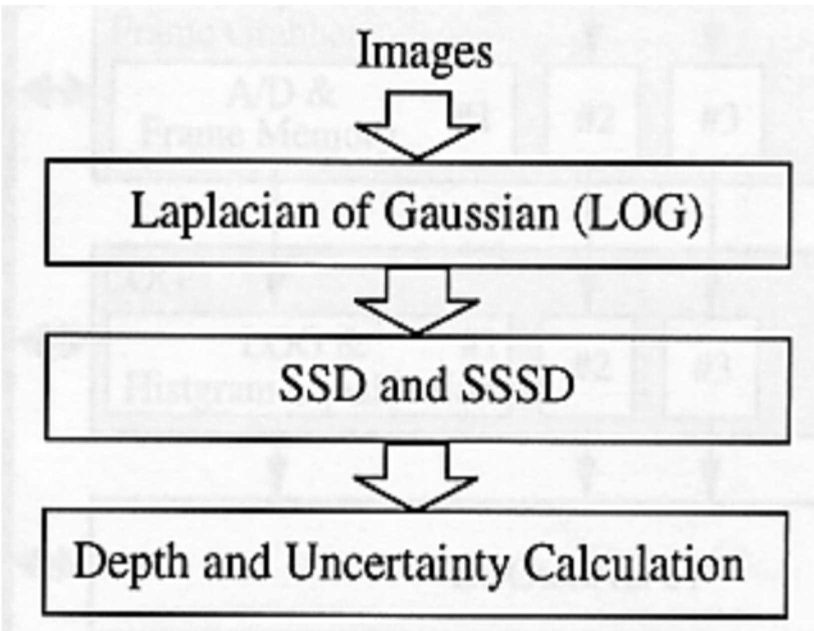
Materials taken from Prof. T. Kanade, Carnegie Mellon University, 1995



Combining two stereo pairs with different baselines.

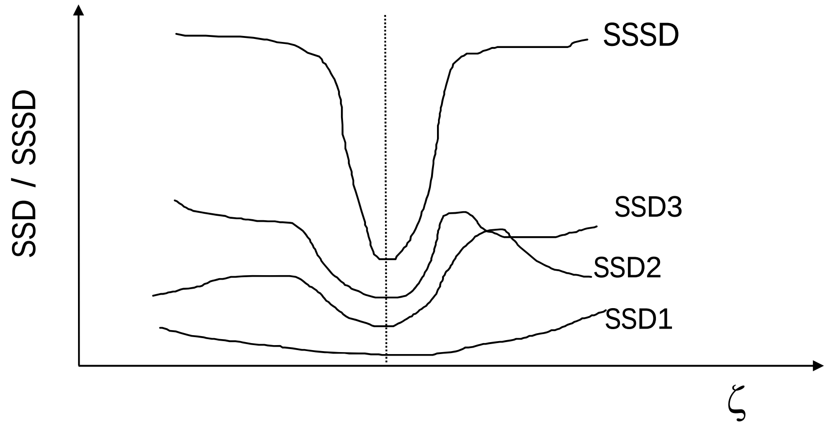
Materials taken from Prof. T. Kanade, Carnegie Mellon University, 1995

Outline of Multi baseline stereo detection



Materials taken from Prof. T. Kanade, Carnegie Mellon University, 1995

$$SSD(x,\zeta) \equiv \sum_{j \in W} (I_0(x+j) - I_i(x + B_i F \zeta + j))^2$$



(the inverse distance)

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Measurement Variance

$$\sigma_n^2 \approx \frac{1}{B_1^2 + B_2^2 + \ldots + B_n^2}$$

the measurement variance decreases inverse-proportionally to the sum of the square of the baseline lengths:

Materials taken from Prof. T. Kanade, Carnegie Mellon University, 1995

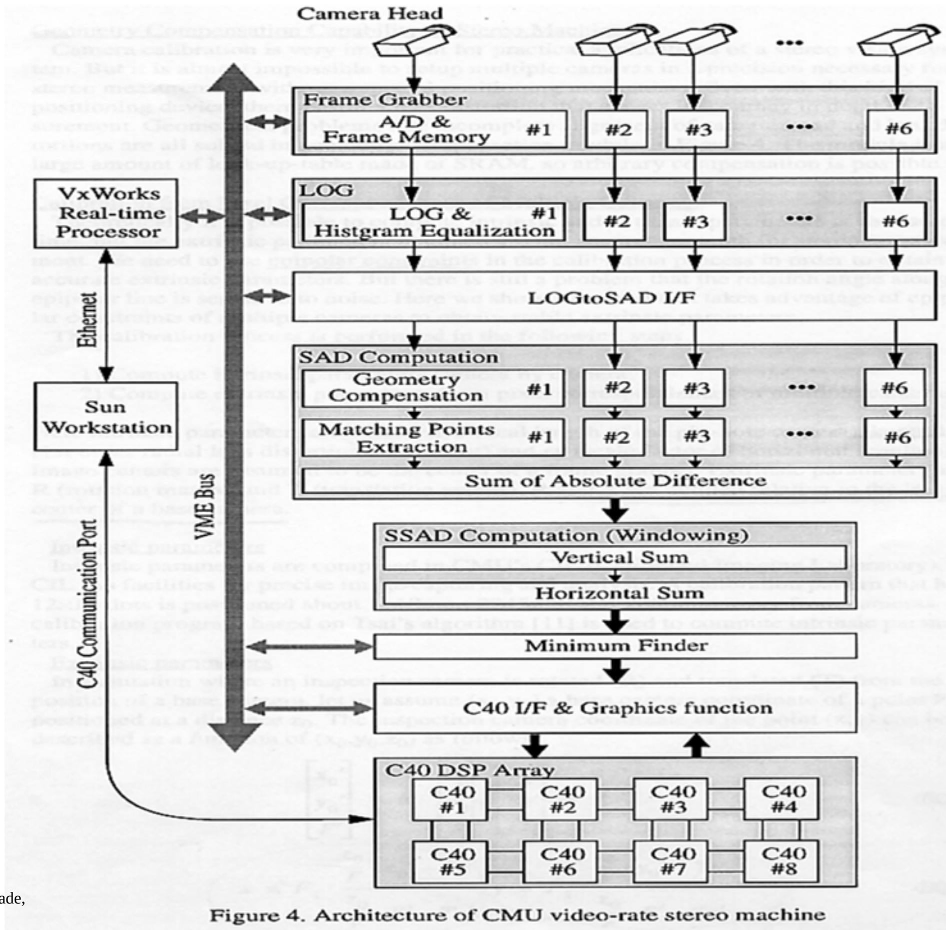
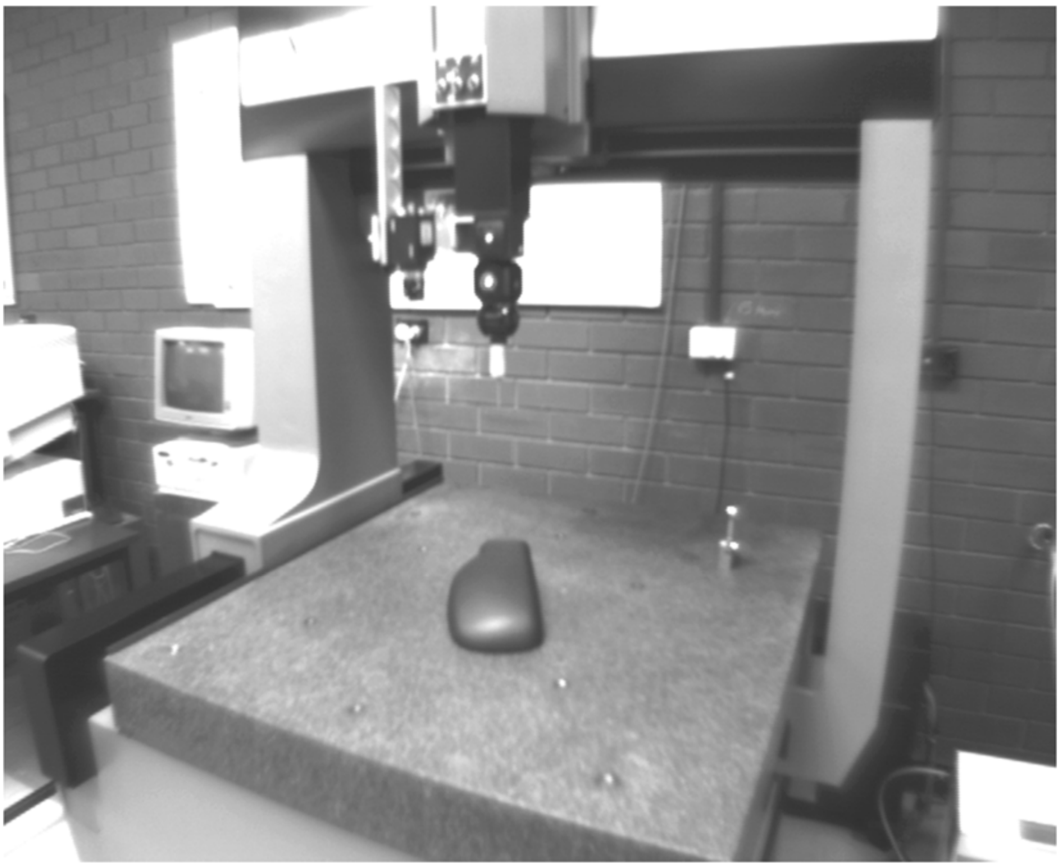


Figure 4. Architecture of CMU video-rate stereo machine

Materials taken from Prof. T. Kanade, Carnegie Mellon University, 1995

AOI Lab



Flow chart of the stereo detection method

Transform the extracted characteristic point from distorted image frame to undistorted image

↓

Subpixel interpolation to obtain one-tenth subpixel precision

↓

Calculate SSD and SSSD

↓

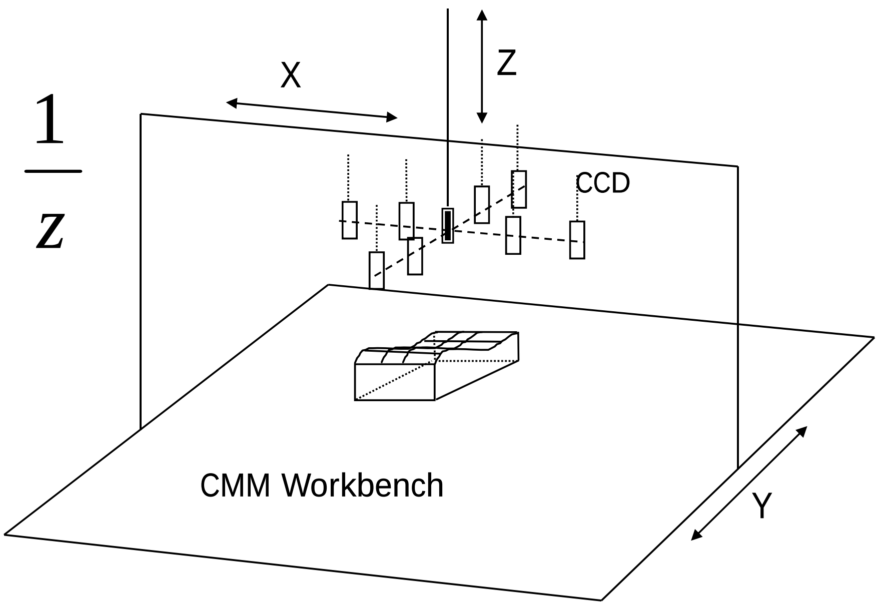
Search for the minimal SSSD in order to decide the inverse distance

↓

Calculate the depth

Calculation of Inverse distance

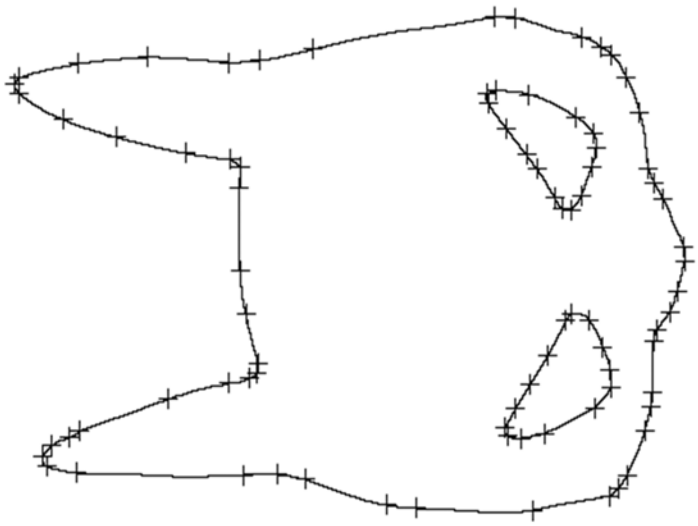
$$\zeta = \frac{d}{BF} = \frac{1}{z}$$

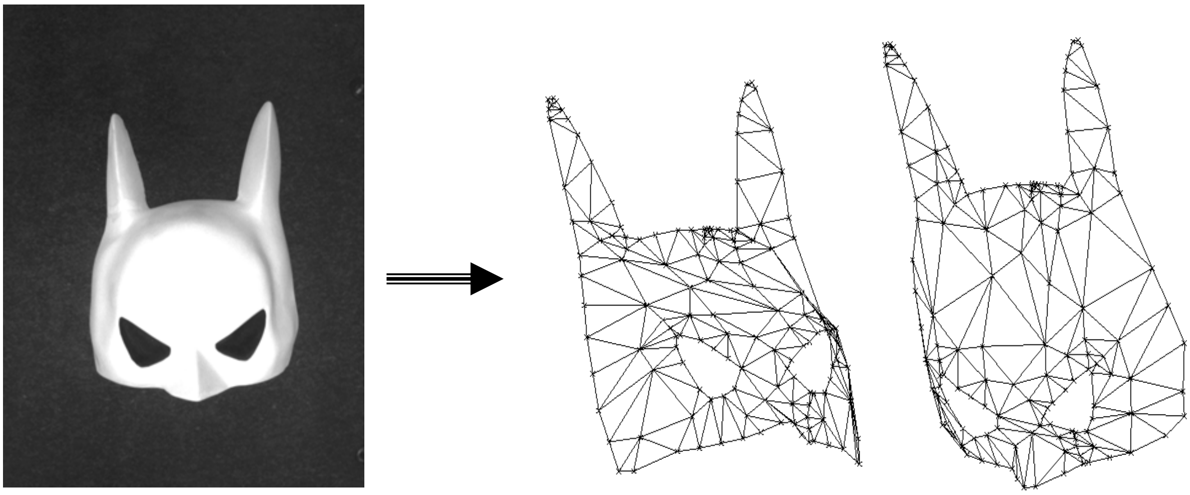


Experimental result from the stereo image detection method

Sample No.	Real Depth (mm)	Measured Depth (mm)	Error (%)
1	370.0	379.0	2.4
2	370.0	367.0	-0.8
3	370.0	355.0	-4.0
4	420.0	412.3	1.7
5	420.0	427.5	1.8
6	420.0	422.4	0.5
7	320.0	318.8	-0.4
8	320.0	329.5	2.9
9	320.0	315.5	-1.4

Extraction of the boundary characteristic points

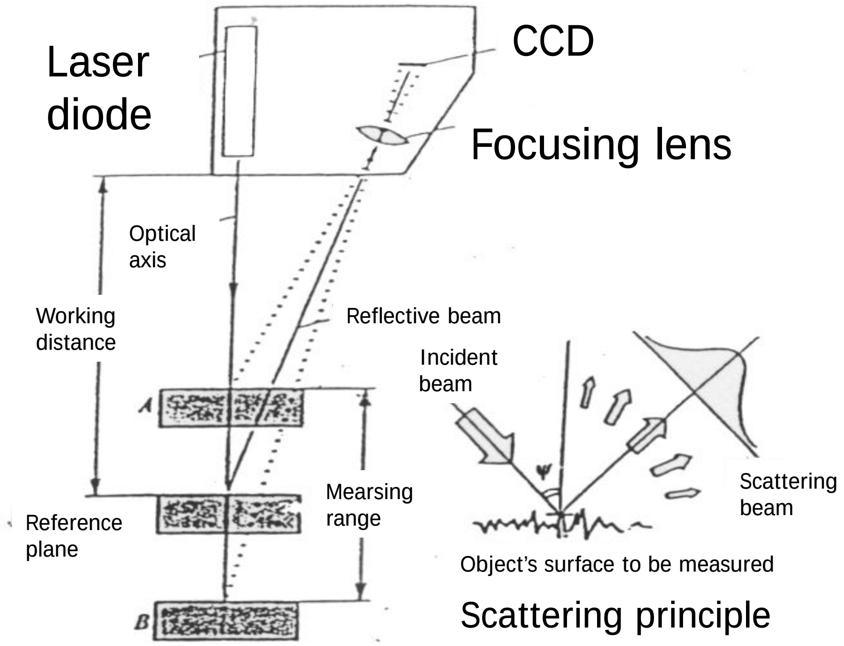




Active 3-D Vision Methods

1. Laser triangulation principle
2. Mapping method
3. Binary encoding method

Laser triangulation principle



Laser Probe using scattering principle

Light reflection model

The reflected color of the measured surface can be roughly described by considering the coefficients of ambient and diffuse reflection as having red, green and blue components:

$$I_R = \int_{\lambda_{R1}}^{\lambda_{R2}} I_{a\lambda} k_a(\lambda) d\lambda + \int_{\lambda_{R1}}^{\lambda_{R2}} \frac{I_{i\lambda}(k_d(\lambda)(\hat{L}\cdot\hat{N}) + k_s(\lambda)(\hat{R}\cdot\hat{V})^n)}{(r+k)} d\lambda$$

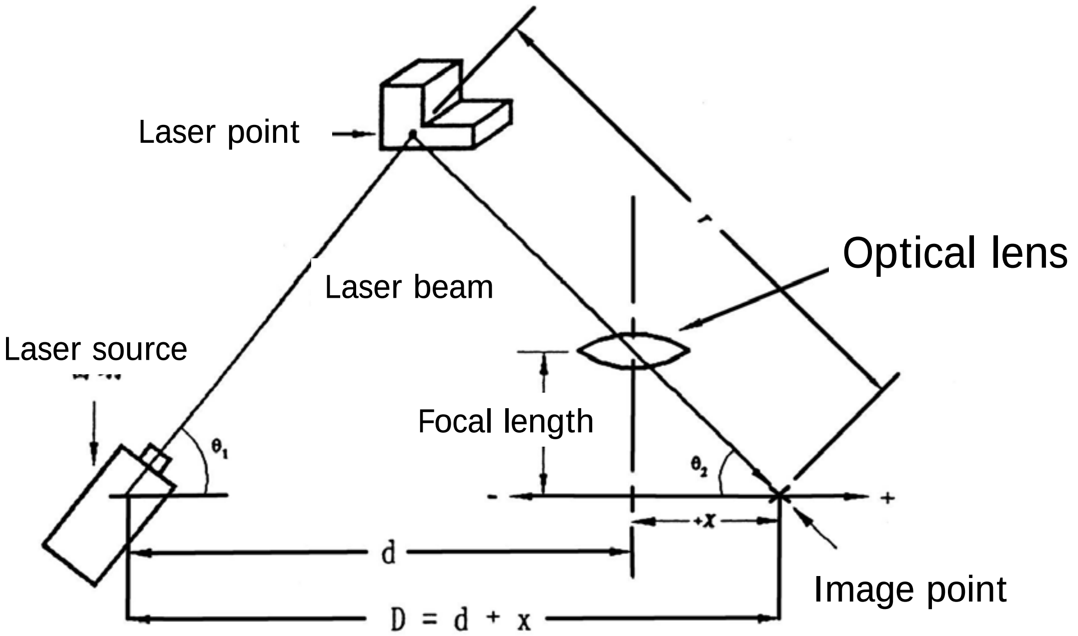
$$I_G = \int_{\lambda_{G1}}^{\lambda_{G2}} I_{a\lambda} k_a(\lambda) d\lambda + \int_{\lambda_{G1}}^{\lambda_{G2}} \frac{I_{i\lambda}(k_d(\lambda)(\hat{L}\cdot\hat{N}) + k_s(\lambda)(\hat{R}\cdot\hat{V})^n)}{(r+k)} d\lambda$$

$$I_B = \int_{\lambda_{B1}}^{\lambda_{B2}} I_{a\lambda} k_a(\lambda) d\lambda + \int_{\lambda_{B1}}^{\lambda_{B2}} \frac{I_{i\lambda}(k_d(\lambda)(\hat{L}\cdot\hat{N}) + k_s(\lambda)(\hat{R}\cdot\hat{V})^n)}{(r+k)} d\lambda$$

Key factors:

1. view direction of CCD.
2. incident direction of light.
3. coefficient of specular reflection.
4. coefficient of diffuse reflection.
5. surface properties

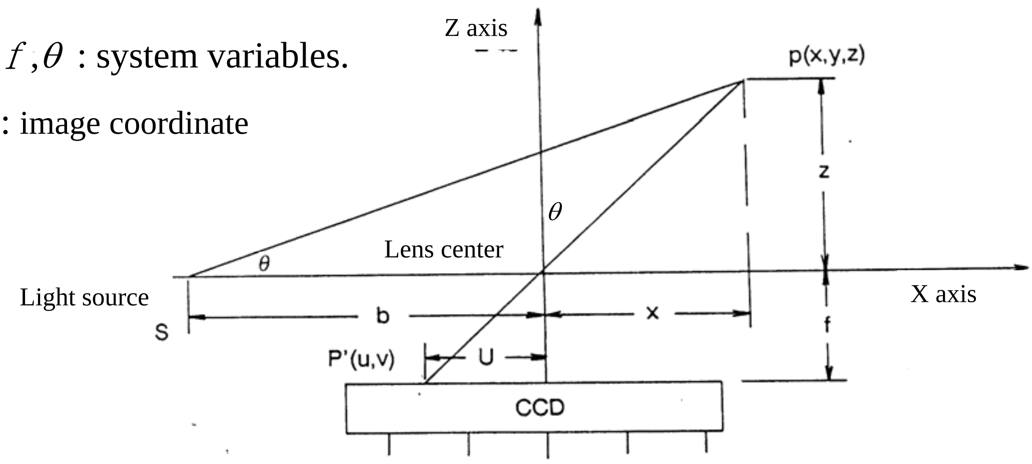
Laser triangulation principle



Linear model of laser triangulation

b, f, θ : system variables.

u,v : image coordinate

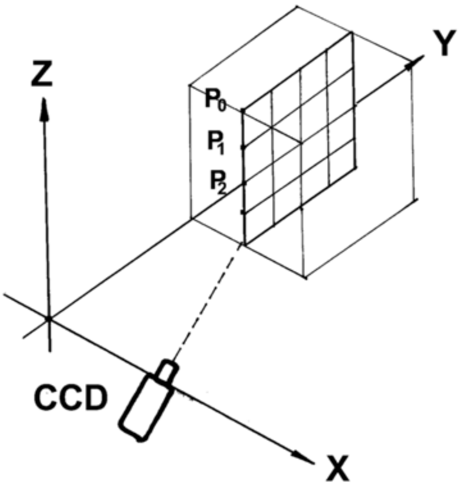


(x,z) Plane: $\frac{f}{u} = \frac{z}{x} \rightarrow \frac{b+x}{z} = \cot\theta \rightarrow x = \frac{bu}{f\cot\theta - u}$

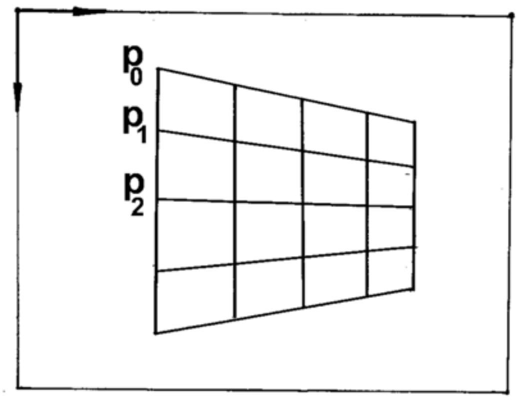
(y,z) Plane: $\frac{f}{v} = \frac{z}{y} \rightarrow \frac{x}{y} = \frac{u}{v} \rightarrow y = \frac{bv}{f\cot\theta - u}$ $\quad z = \frac{bf}{f\cot\theta - u}$

Mapping methods used in 3D Vision

Perspective projection from 3D to 2D



Structured pattern in 3D space



CCD Image

Source from Prof. Chang

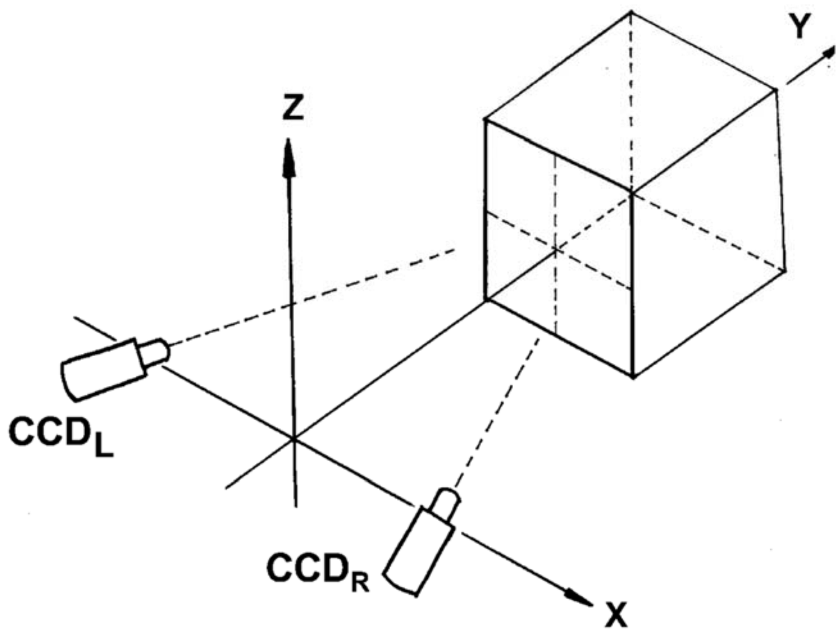
Mapping function for (Y,Z) in 3D to 2D

- Mapping function using multi-element polynomial function
  - 3D space: (X,Y,Z)
  - CCD coordinate: (u,v)

$$Y = g\ (u_k, v_k) = \sum_{j=0}^{n} \sum_{i=0}^{n-j} b_{ij} u^i v^j$$

$$Z = h\ (u_k, v_k) = \sum_{j=0}^{n} \sum_{i=0}^{n-j} c_{ij} u^i v^j$$

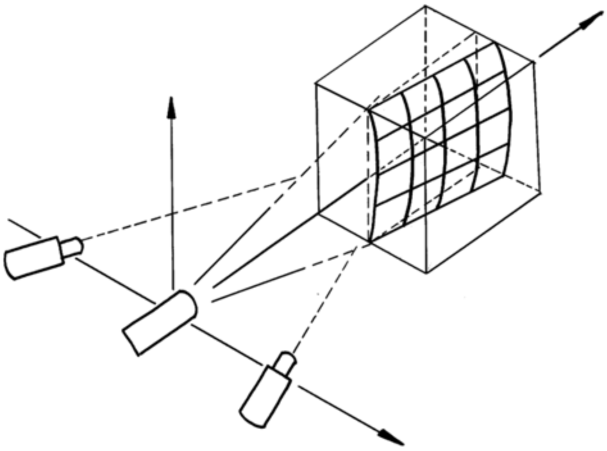
Two-CCD optical configuration



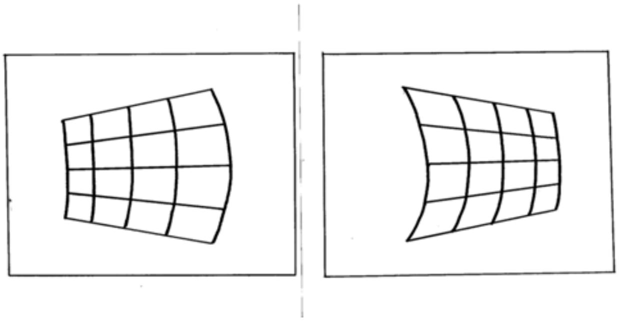
Source from Prof. Chang

Single laser-line projection with 2 CCDs

- Laser Line Projection



- CCD images in left and right camera



3D mapping from two images

- 3-D mapping from two image coordinates:
  - 3D coordinate:(X,Y,X)
  - Left CCD image:(u_L,v_L)
  - Right CCD image:(u_R,v_R)

$$X_L = f_L(u_L,v_L,u_R) = \sum_{l=0}^{n}\sum_{k=0}^{n-k}\sum_{j=0}^{n-k-j} a_{ijk} u_L{}^i v_L{}^j u_R{}^k$$

$$Y_L = g_L(u_L,v_L,u_R) = \sum_{l=0}^{n}\sum_{k=0}^{n-k}\sum_{j=0}^{n-k-j} b_{ijk} u_L{}^i v_L{}^j u_R{}^k$$

$$Z_L = h_L(u_L,v_L,u_R) = \sum_{l=0}^{n}\sum_{k=0}^{n-k}\sum_{j=0}^{n-k-j} c_{ijk} u_L{}^i v_L{}^j u_R{}^k$$

Resolving the unknown coefficients using least-squares approximation

$$x_i = a_1 u_i^2 + b_1 v_i^2 + c_1 u_i v_i + d_1 u_i + e_1 v_i + f_1$$

$$E_i^x = a_1 u_i^2 + b_1 v_i^2 + c_1 u_i v_i + d_1 u_i + e_1 v_i + f_1 - x_i$$

$$E^x = \sum_i (E_i^x)^2$$

$$\frac{\partial E^x}{\partial a_1} = 0 \quad \frac{\partial E^x}{\partial b_1} = 0 \quad \frac{\partial E^x}{\partial c_1} = 0 \quad \frac{\partial E^x}{\partial d_1} = 0 \quad \frac{\partial E^x}{\partial e_1} = 0 \quad \frac{\partial E^x}{\partial f_1} = 0$$

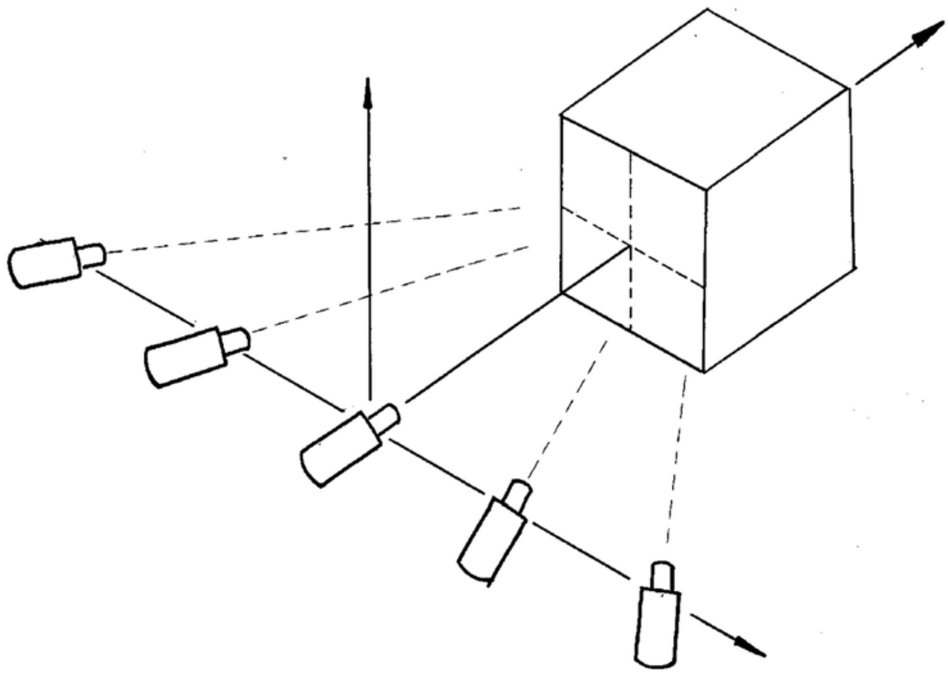
$$z_i = a_2 u_i^2 + b_2 v_i^2 + c_2 u_i v_i + d_2 u_i + e_2 v_i + f_2$$

$$E_i^z = a_2 u_i^2 + b_2 v_i^2 + c_2 u_i v_i + d_2 u_i + e_2 v_i + f_2 - z_i$$

$$E^z = \sum_i (E_i^z)^2$$

$$\frac{\partial E^z}{\partial a_2} = 0 \quad \frac{\partial E^z}{\partial b_2} = 0 \quad \frac{\partial E^z}{\partial c_2} = 0 \quad \frac{\partial E^z}{\partial d_2} = 0 \quad \frac{\partial E^z}{\partial e_2} = 0 \quad \frac{\partial E^z}{\partial f_2} = 0$$

Multiple CCDs for 3-D detection



Mapping model for multiple CCDs

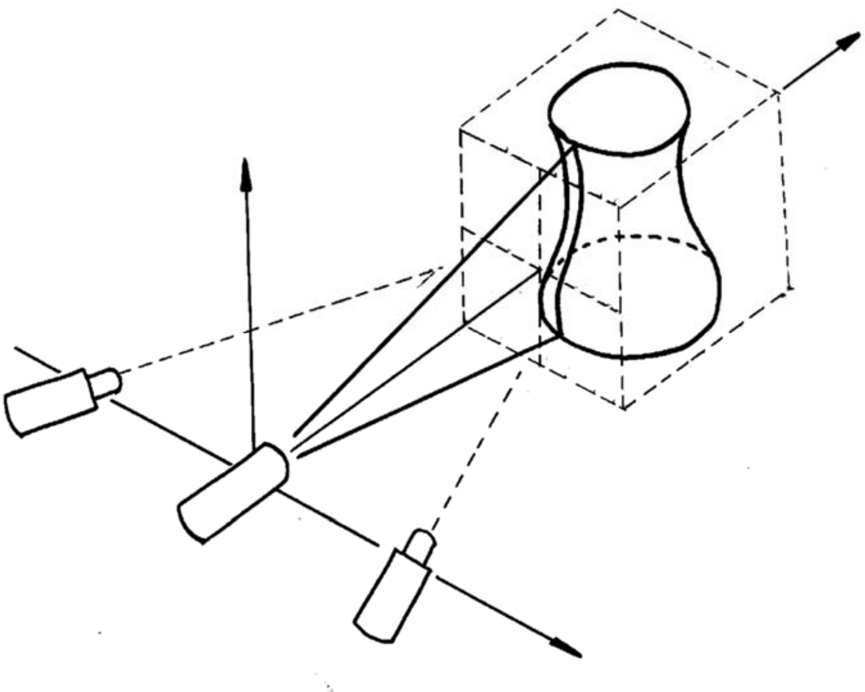
- 3-D mapping from two image coordinates:
  - 3D coordinate:(X,Y,X)
  - CCD M: (u_M, v_M)
  - CCD N: (u_N, v_N)

$$X_{MN} = f_M(u_M, v_M, u_N) = \sum_{l=0}^{n}\sum_{k=0}^{n-k}\sum_{j=0}^{n-k-j} a_{ijk} u_M{}^{i} v_M{}^{j} u_N{}^{k}$$

$$Y_{MN} = g_M(u_M, v_M, u_N) = \sum_{l=0}^{n}\sum_{k=0}^{n-k}\sum_{j=0}^{n-k-j} b_{ijk} u_M{}^{i} v_M{}^{j} u_N{}^{k}$$

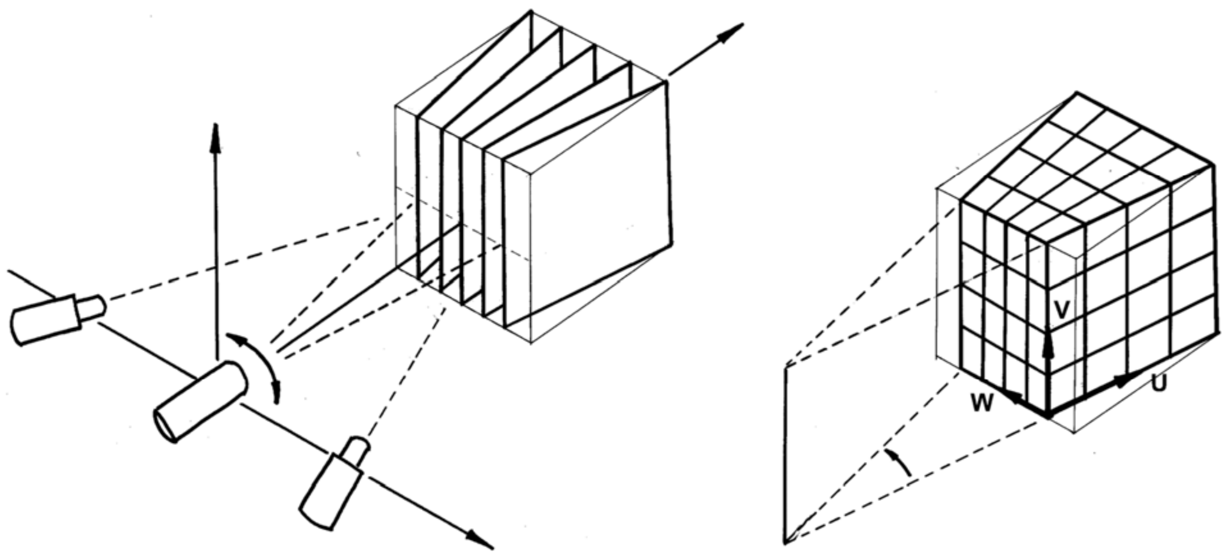
$$Z_{MN} = h_M(u_M, v_M, u_N) = \sum_{l=0}^{n}\sum_{k=0}^{n-k}\sum_{j=0}^{n-k-j} c_{ijk} u_M{}^{i} v_M{}^{j} u_N{}^{k}$$

Laser line scanning for 3D profiles



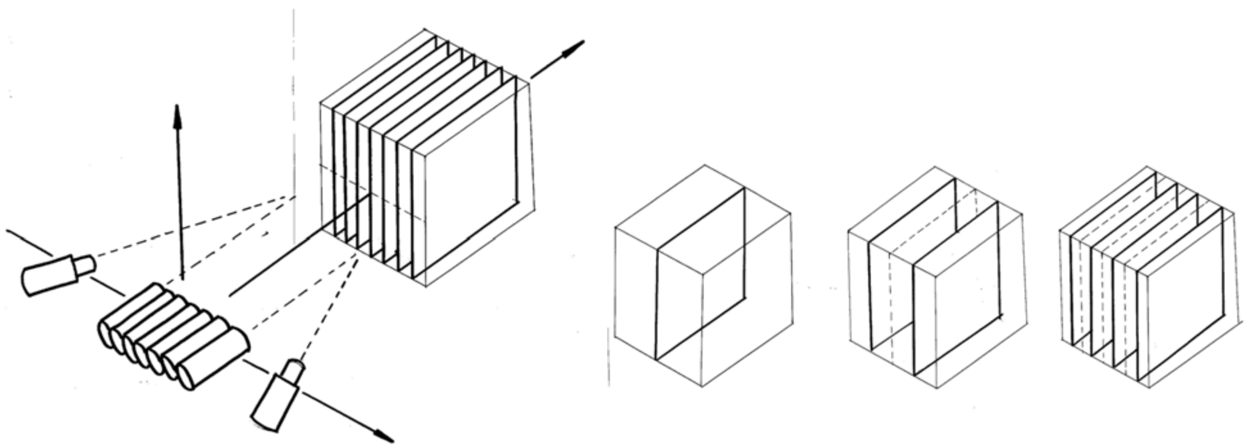
Source from Prof. Chang

Line laser scanning method

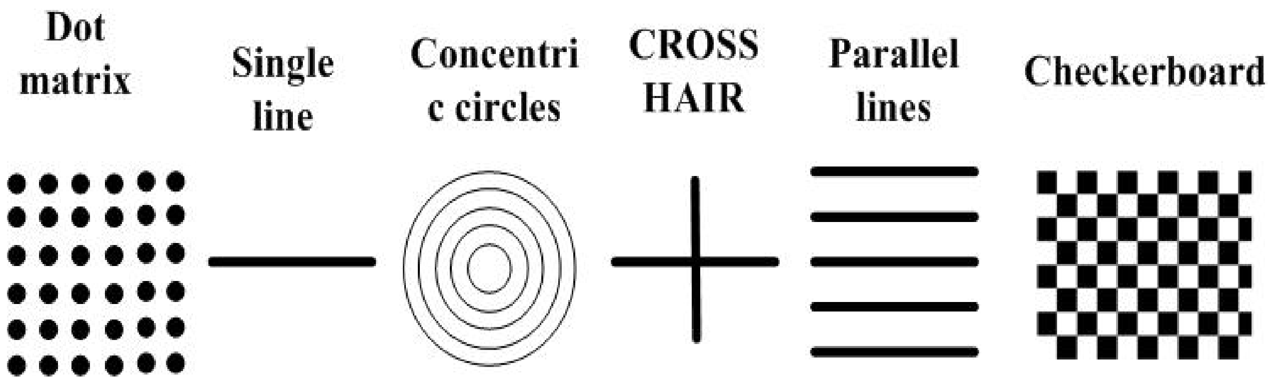


Source from Prof. Ming Chang

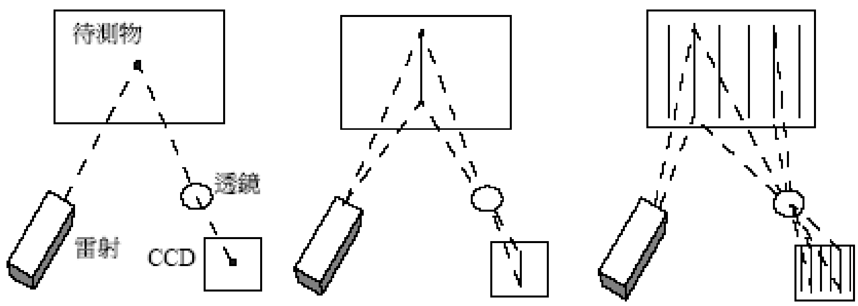
Multiple laser with 2-CCD configuration



Various design patterns of structured light

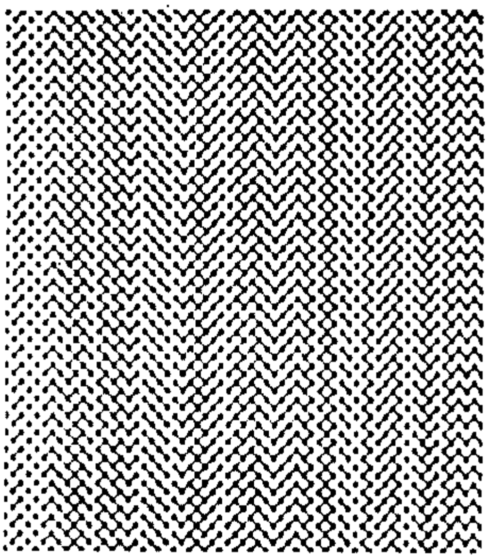


Optical layout of 3D vision system



Source from Dr. 戴文智

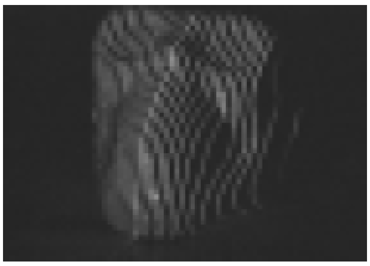
Example of structured light projection on measured objects

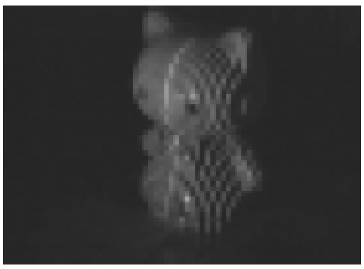


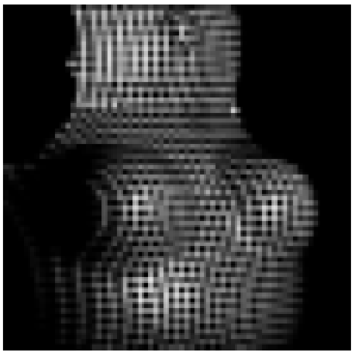
(a)

(b)

Example of structured light projection on measured objects

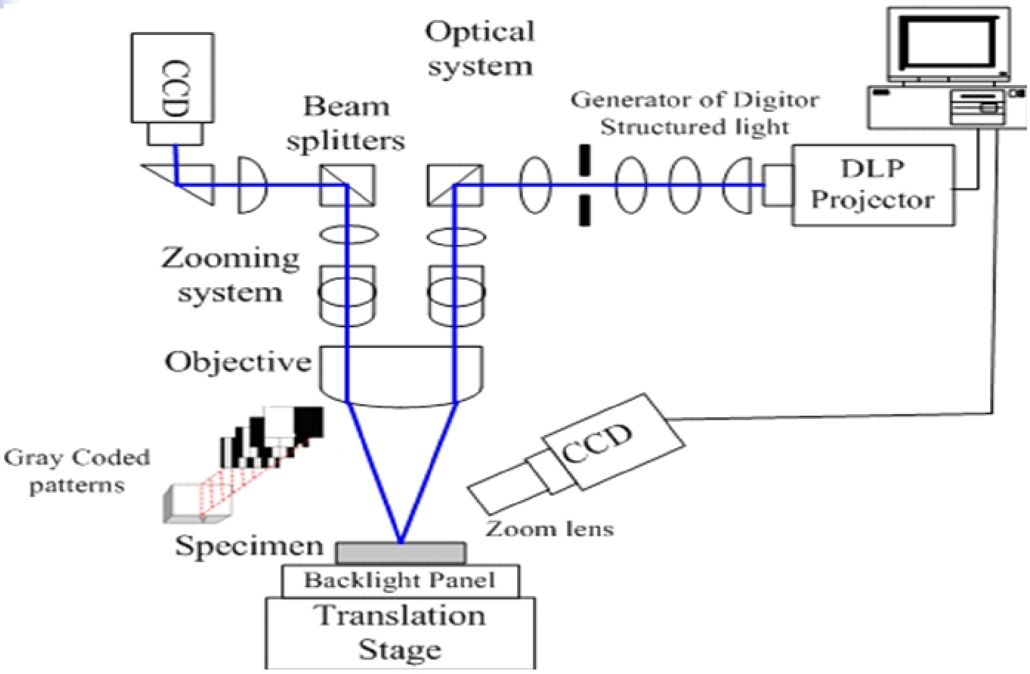




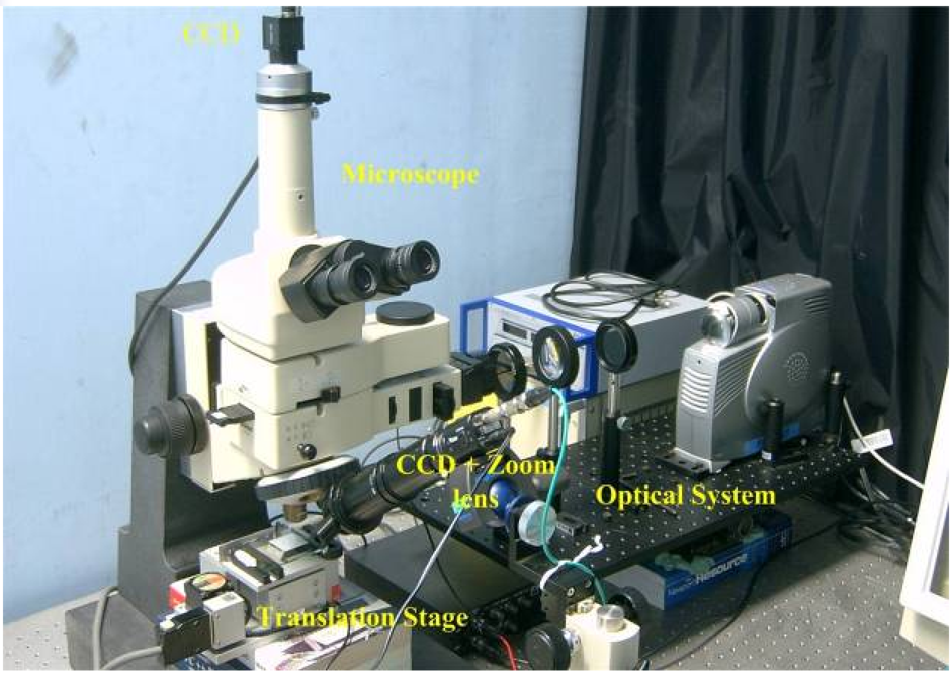


Source from Dr. 戴文智

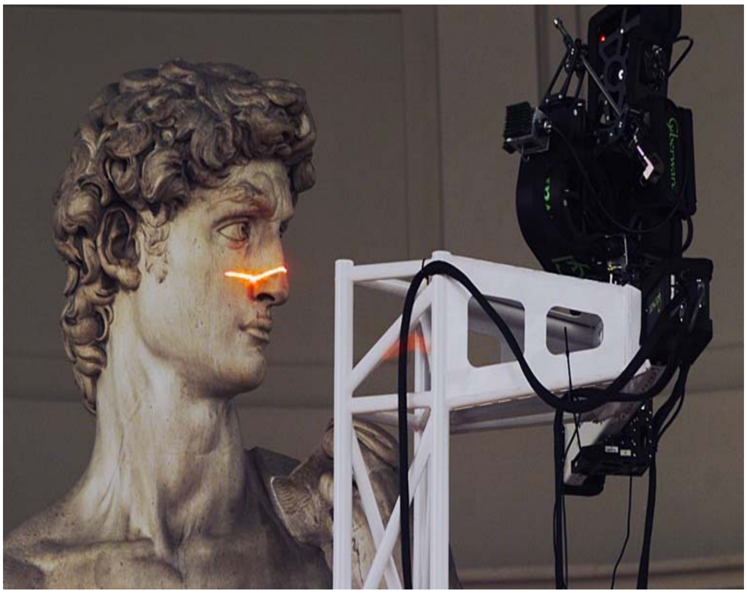
Micro 3-D vision system based on structured light

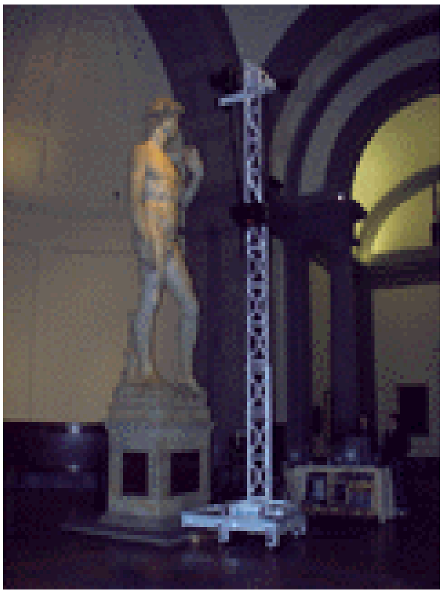


Hardware setup of a micro-scale 3-D vision system



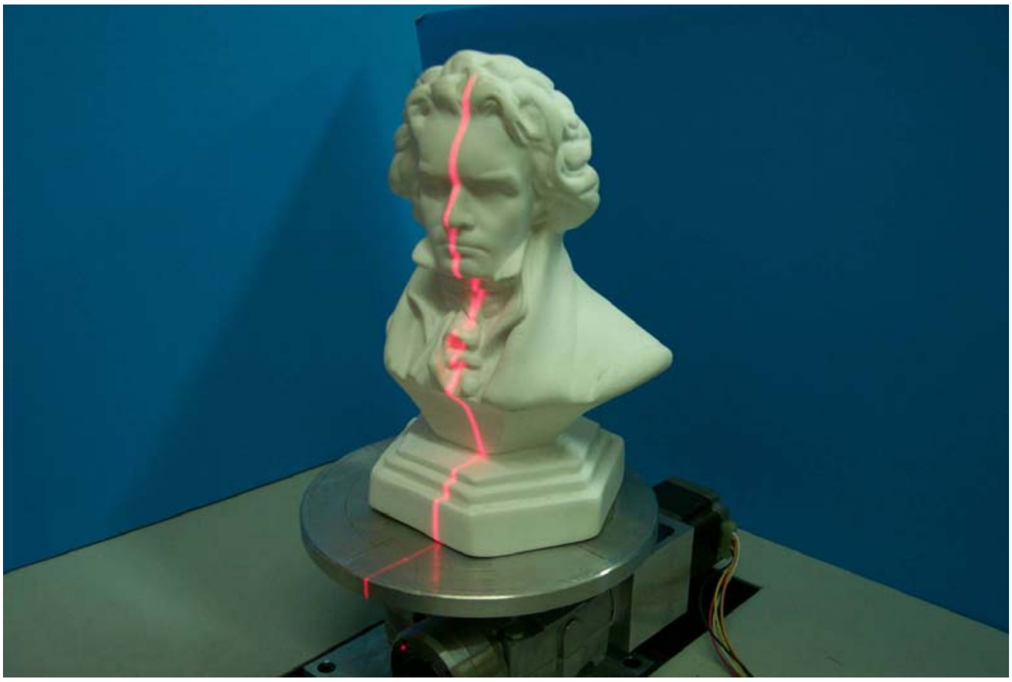
Laser line scanning for 3-D profiles





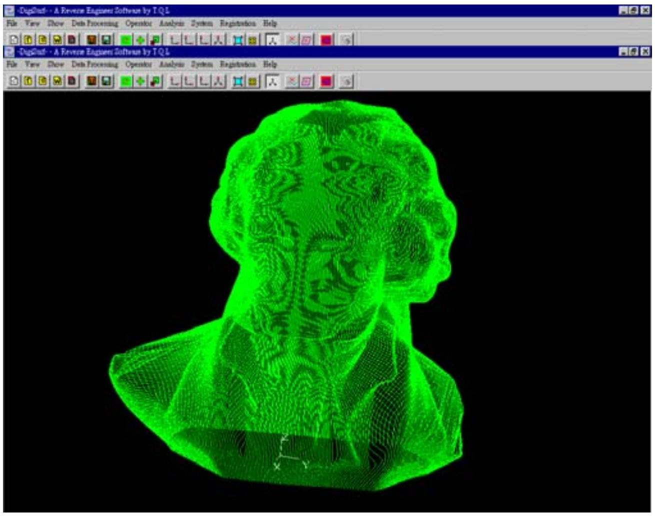
Source from Prof. Chang

Laser line scanning for 3D profiles

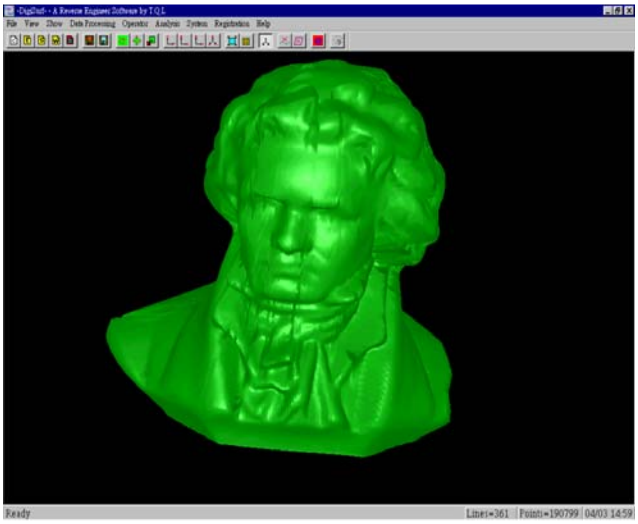


Source from Prof. Chang

Laser line scanning for 3D profiles



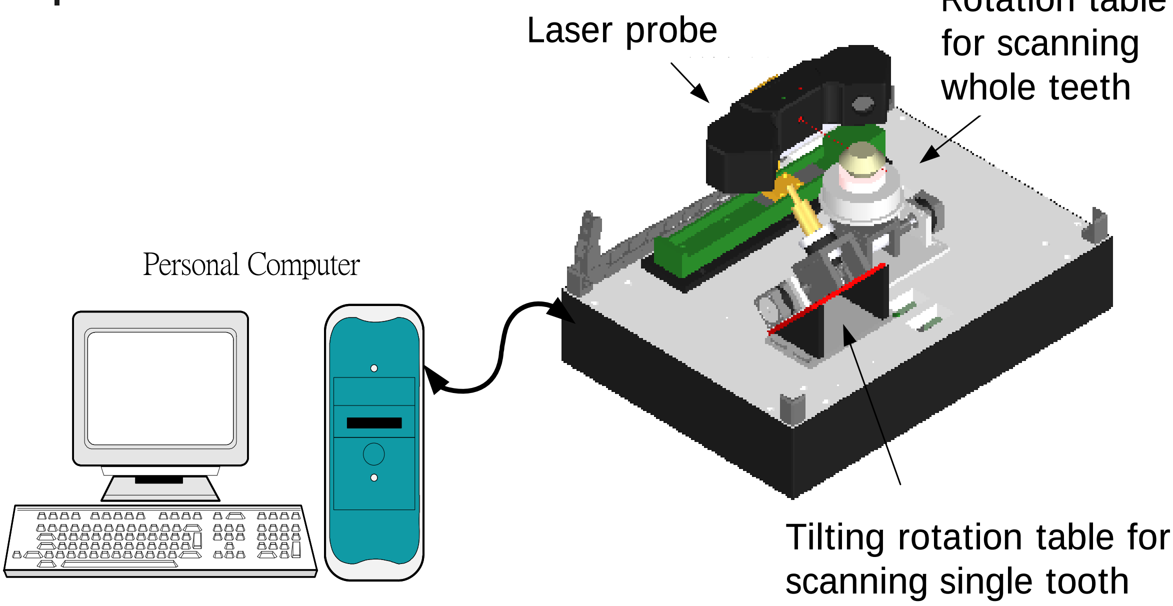
3D point clouds



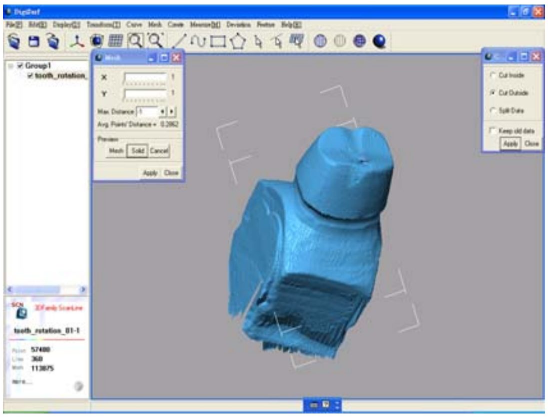
3D model using color shadowing

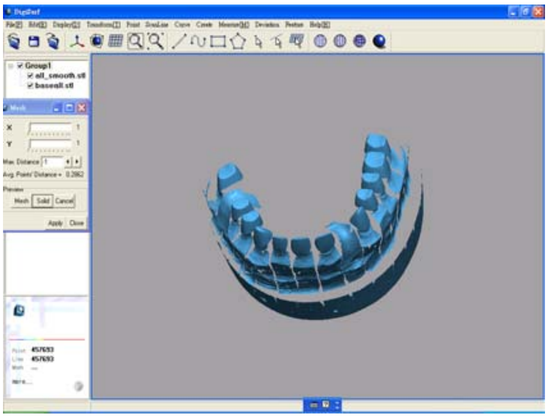
Source from Prof. Chang

3-D dental scanning system

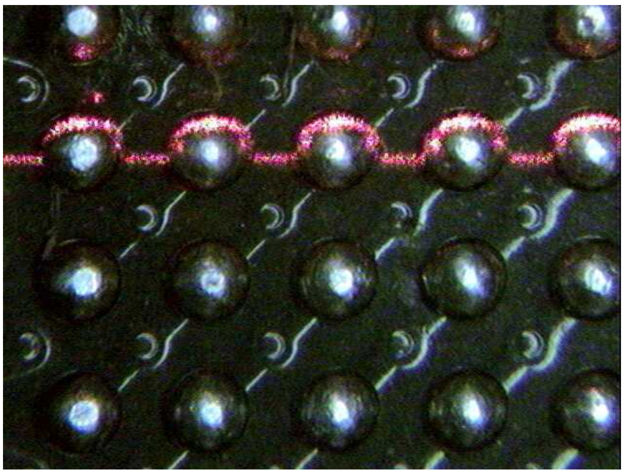


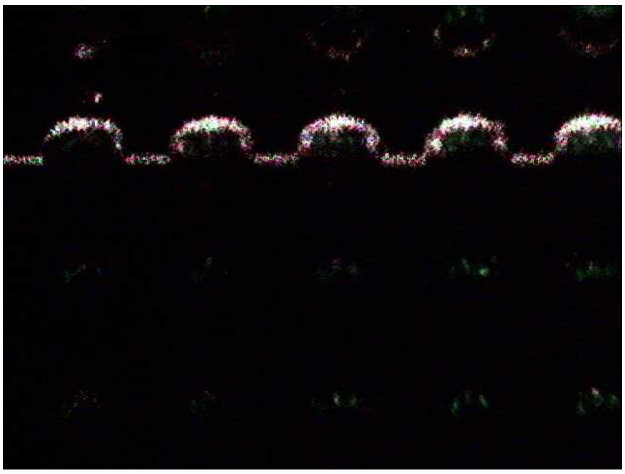
3-D teeth models





BGA (Ball gray array) Coplanarity inspection





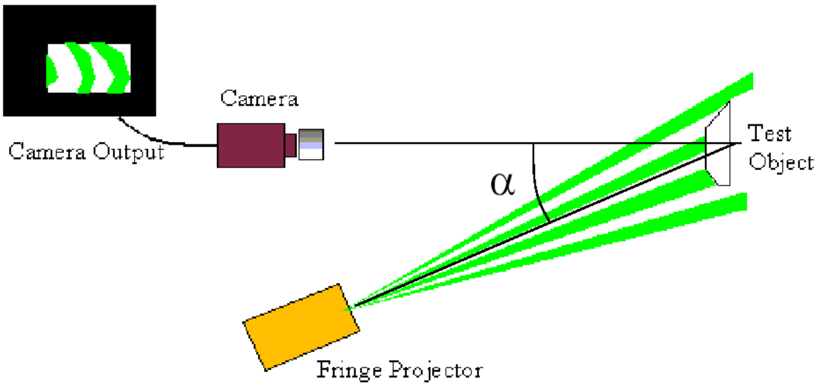
Source from Prof. Chang

Question 1

- Perform the calibration operation required for single laser line projection with single CCD.
- Perform the calibration operation required for single laser line projection with double CCDs.

White light
Binary encoding method

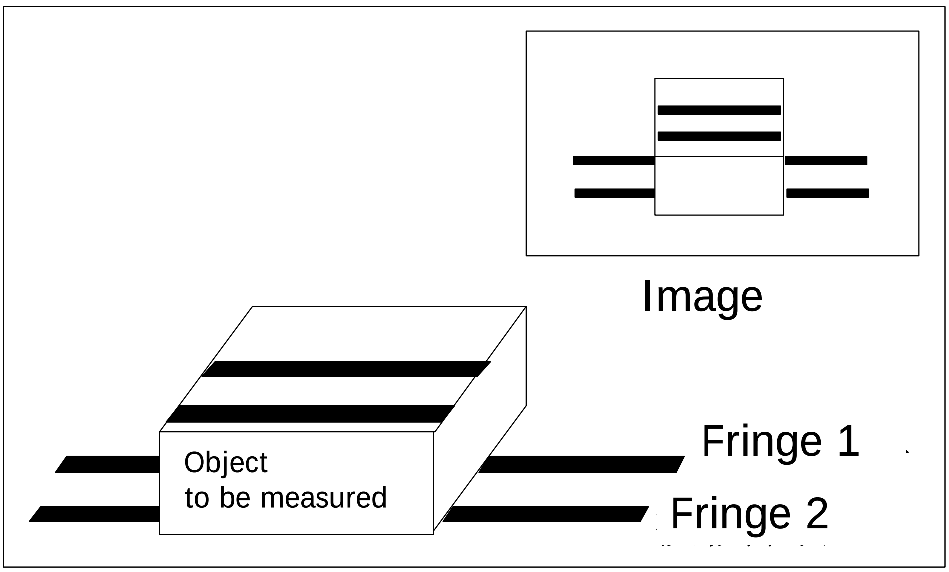
Fringe Projection.



- Consider as a set of (near) parallel lines.
- With appropriate analysis obtain a co-ordinate for every camera pixel.
- Potential data rates of 1,000,000 in 10 seconds.

Optical 3D – Measurement in Volkswagen, ATOS (GOM).

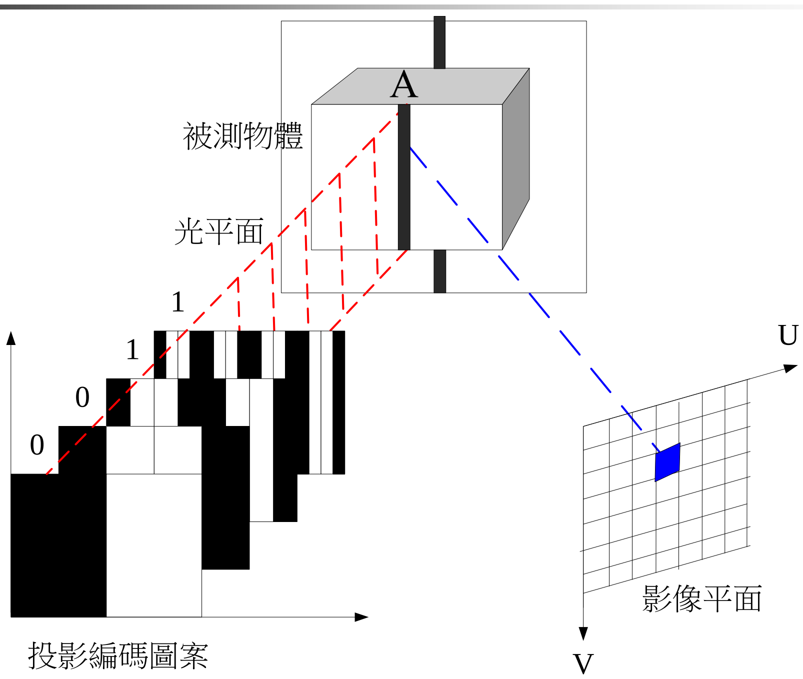
Fringe recognition problem



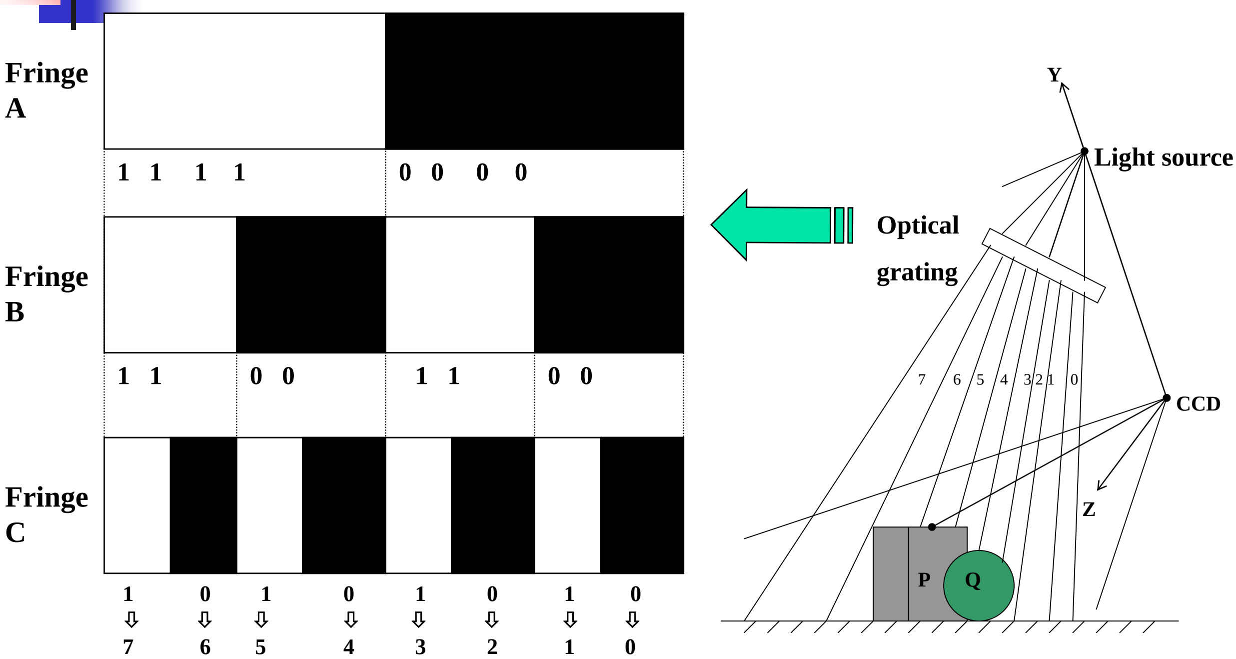
Dealing With Range (or Phase Shift) Ambiguities

- The sequential projection of encoded patterns is another elegant way.
- The most popular methods for pattern projection use binary coded or phases shift fringes patterns. Gray codes binary images use multiple frames with increased resolution (bits) to encode a pixel on the CCD with its corresponding range.
- Sub-pixel resolution is obtained by detecting the edge transitions in the highest resolution image.

Spatial recoding method



Binary encoding method

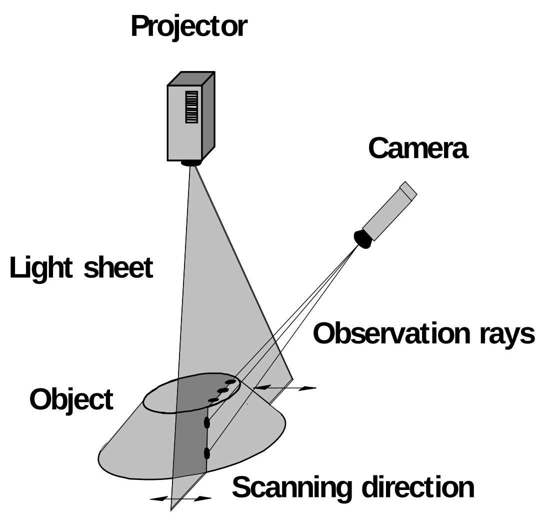


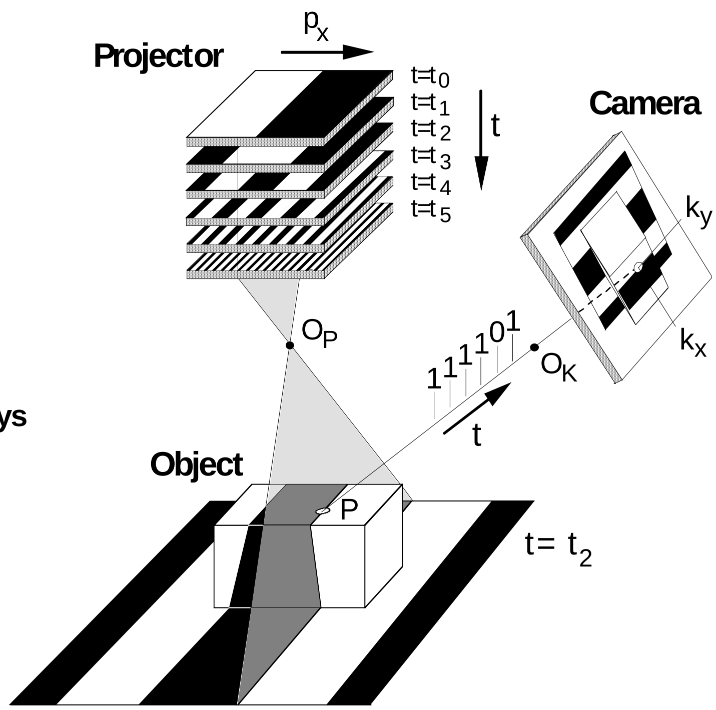
Source from Prof. Chang

White-light Binary encoding methods

- Binary encoding methods are today popular because of the availability of low cost projectors and a full 3D volume can be acquired quickly in just a few video frames.
- The use of incoherent light reduces speckle noise associated with laser and consequently provides better surface smoothness.
- The depth of view is smaller when compared to laser strip scanners and absolute accuracy for an equivalent 3-D volume (not only on the surface) will be relatively smaller than their laser counterparts.

Binary encoding method





Fringe Projection Method

Coded Light Approach

Optical 3D – Measurement in Volkswagen, ATOS (GOM).

Optical 3D – Measurement in Volkswagen, ATOS (GOM).

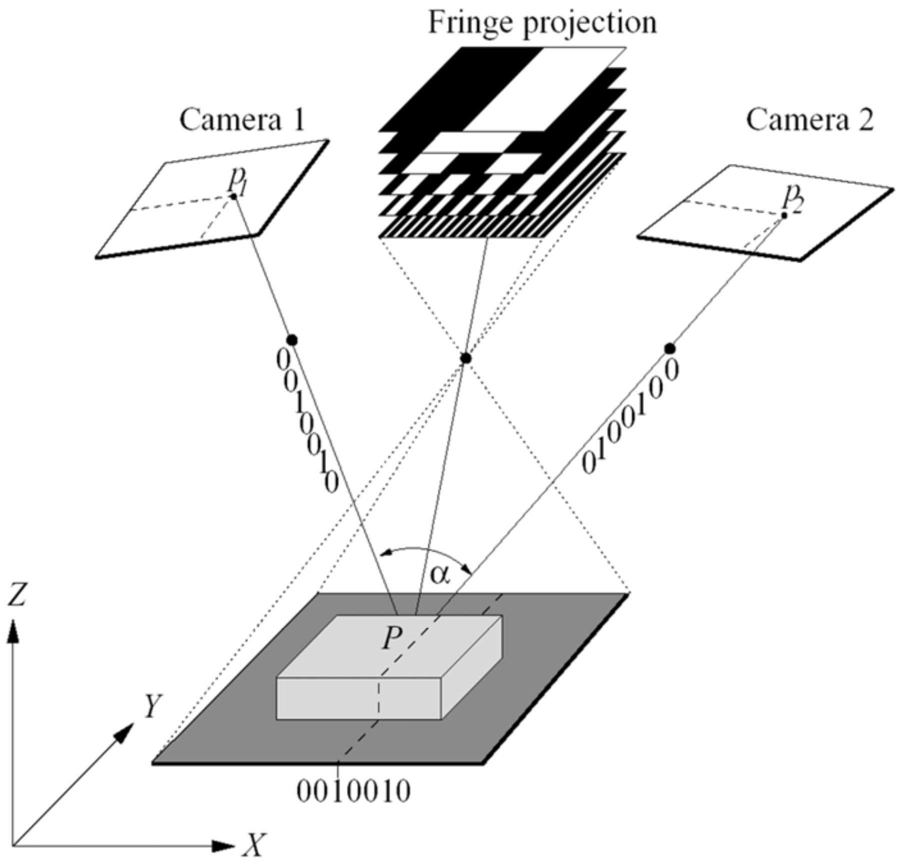


Figure 3: Principle setup of the fringe projection sensor

Combination Photogrammetry - Fringe Projection Method

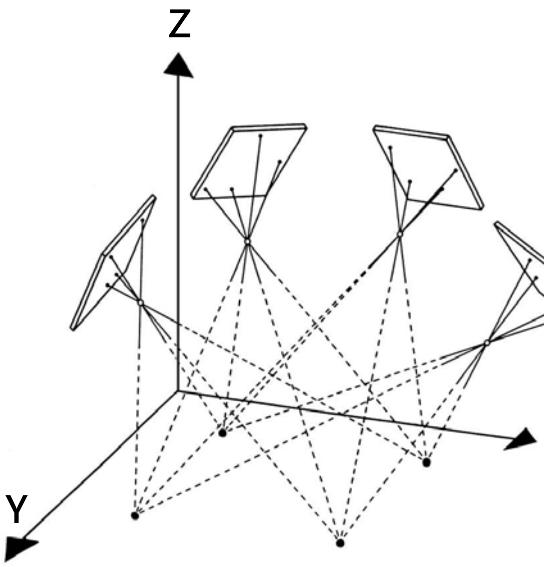
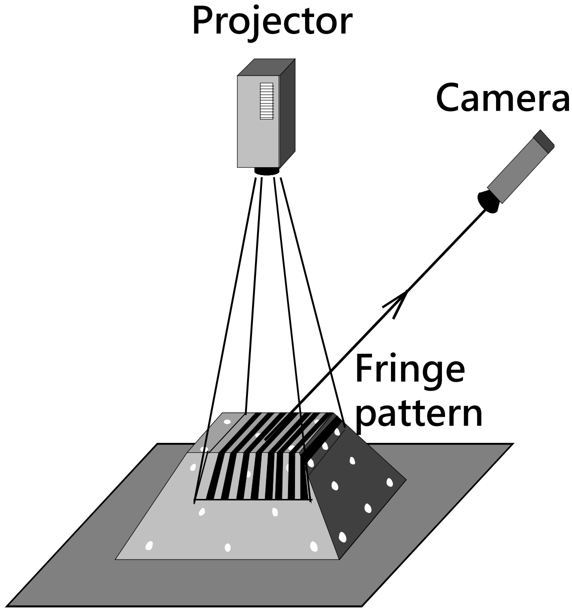


Image bundle



Object with reference points

Optical 3D – Measurement in Volkswagen, ATOS (GOM).

Fringe Projection System

Atos-Sensor (GOM)

Optical 3D – Measurement in Volkswagen, ATOS (GOM).

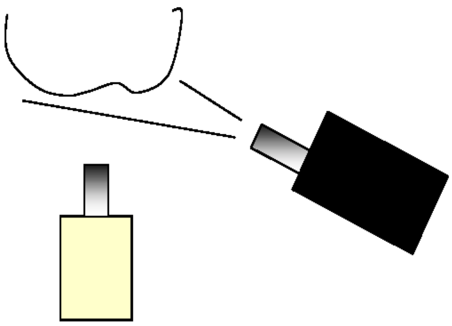
System Calibration

Ballplate for coordinate

Measuring machines (PTB)

White Light Fringe Projection.

- ATOS system by GOM achieves dynamic range of 3000.
- White light systems in general have.
  - Calibrate using known objects scanned through measurement volume.
  - Fixed optical setup.
  - Depth of field limit through:
    - project grating onto object,
    - image the fringes onto the CCD.



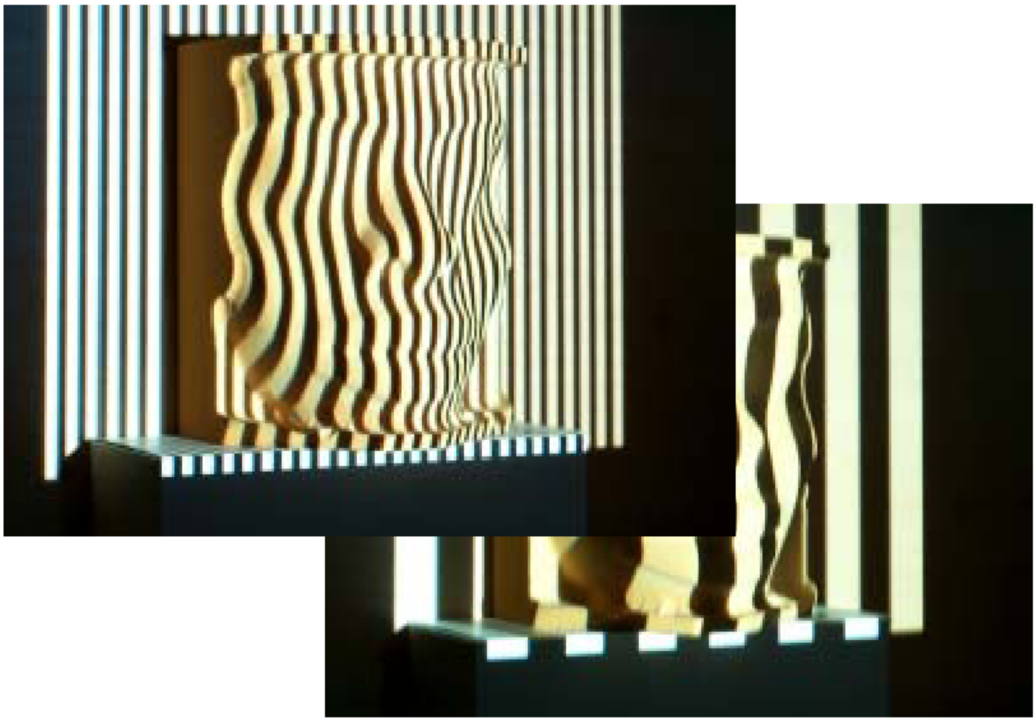


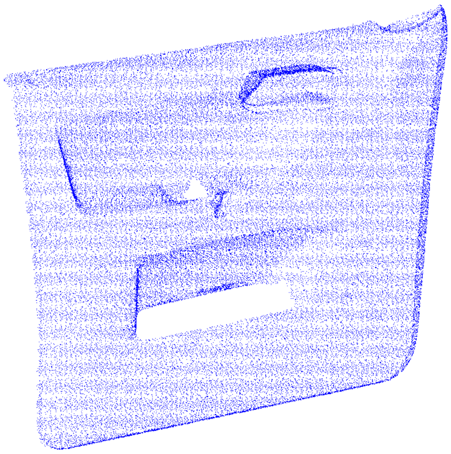
Figure 6: Binary coded pattern projection; a 3D image can be acquired in a few frames.

Optical 3D – Measurement in Volkswagen, ATOS (GOM).

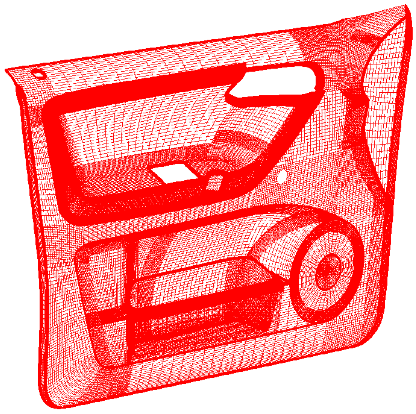
Measuring Interior Door

Optical 3D – Measurement in Volkswagen, ATOS (GOM).

Measuring Interior Door

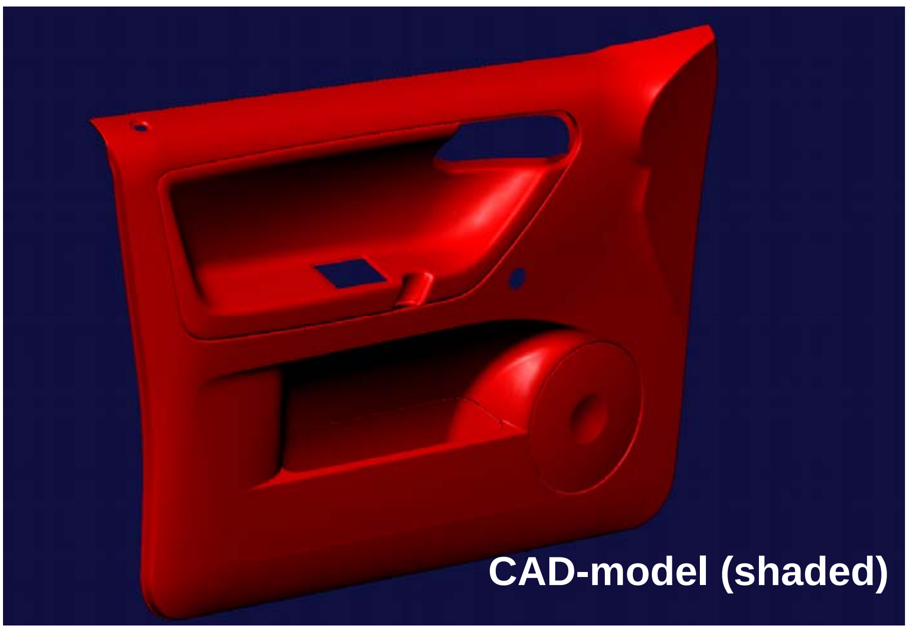


Point cloud

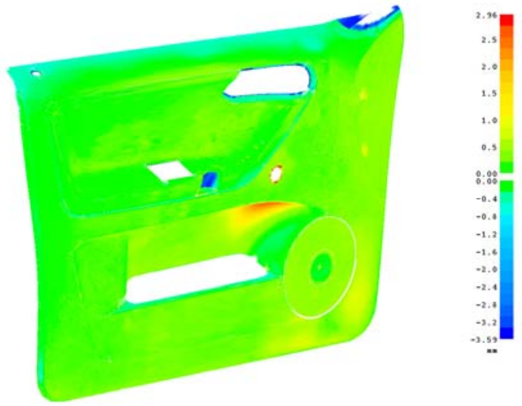


CAD-model

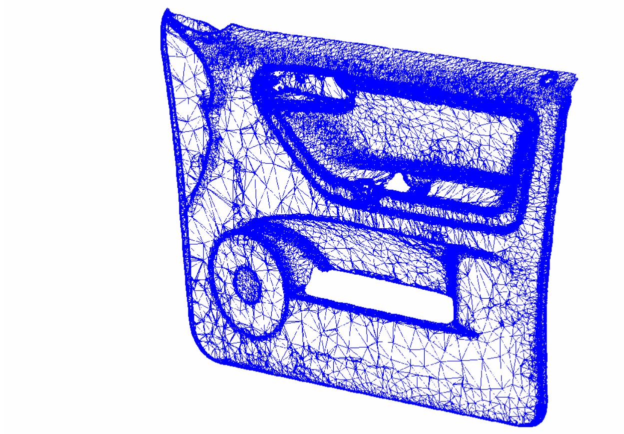
Measuring Interior Door



Measuring Interior Door



Nominal/actual comparison



Polygonized point cloud

Optical 3D – Measurement in Volkswagen, ATOS (GOM).

Question 2

- How to perform the calibration procedure for the binary encoding method? You should identify the system transformation matrix and its projection plane equation.

Reference Sources

1. Prof. 章明, AOI三維量測技術與實務,北科大專題演講資料.
2. 北科大, AOI Lab. 研究專題資料
3. Dr. 戴文智, AOI三維量測技術,北科大專題演講資料.
4. Optical 3D – Measurement in Volkswagen, ATOS (GOM).