Dimensional Metrology

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Lecture Notes: Photomechanics for Engineers

IMAC, EPFL

29 Sept. 2009

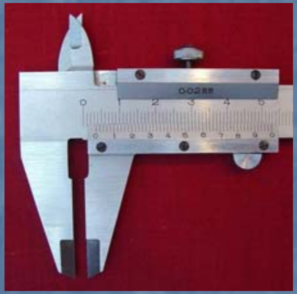
Outline

- One-dimensional (1D) and two-dimensional (2D) measurements
- Three-dimensional (3D) measurements
  - Fringe Projection Technique
    - Applications
    - Overview
    - Detailed Perspective

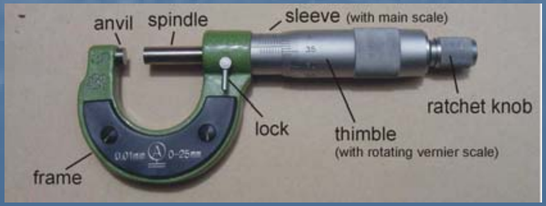
1D and 2D Measurement Tools

- Hand Tools:
  - Yardstick

  - Vernier Caliperse



  - Screw Gauge



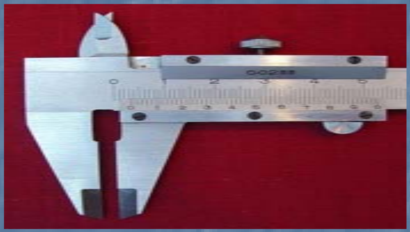
1D and 2D Measurements Cont… (Wish List)

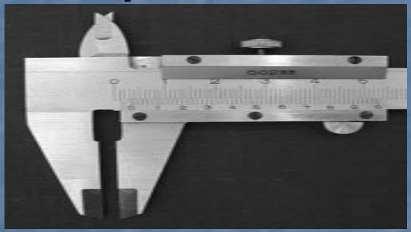
- Can we make measurements without touching the object?
- Can we have variable measurement range?
- Can we have variable measurement resolution?
- Can we automate the measurement process?
- Do we have a device which is having all of the above features???

Yes: It is a digital camera!!!

1D and 2D Measurements Cont…

- Digital Image (Grayscale Image): 2D Matrix
  - Elements of the matrix are referred to as pixels
  - Values of the elements represent intensity (0 to 255)





- Zoom-in, zoom-out and changing the distance from the object: enalbe to have varialbe resolution and variable range of measurement !
- Analysis of the acquired images to automate the measurement process !!
- We dont have to touch the object !!!

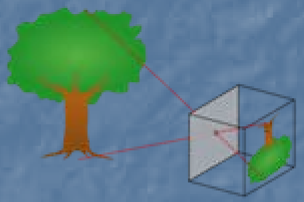
1D and 2D Measurements Cont…

- Height of the Eiffel tower?

- There are many factors that govern the conversion between the number of pixels to real world dimensions.
- Some of them: Zoom (i.e. Focal length of the lens), position of the camera w.r.t the object, type of camera used etc.
- How do we know them in practice?

1D and 2D Measurements Cont…

- Is there a mathematical relation that governs this conversion?
- Pinhole camera model



- Projective mapping of world coordinates to pixel coordinates is described by:

$$z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = A \begin{bmatrix} R & T \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix}$$

$\begin{bmatrix} u & v & 1 \end{bmatrix}^T$ 2D positions in pixel coordinates

$\begin{bmatrix} x_w & y_w & z_w & 1 \end{bmatrix}^T$ 3D positions in real world coordinates

Intrinsic parameters $A = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix}$

$(u_0 \quad v_0)$ coordinates of the principle point

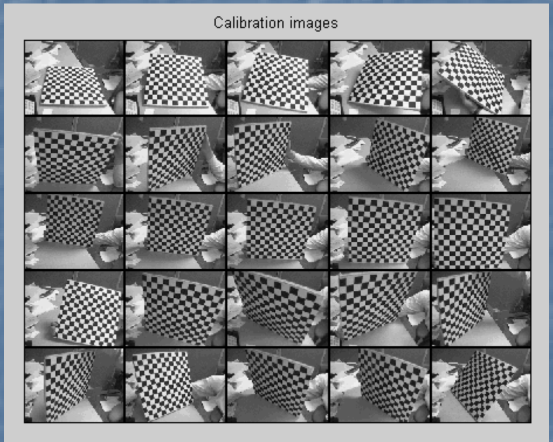
$(\alpha \quad \beta)$ scale factors in image coordinates

γ parameter describing the skewness of the two image axes.

R and *T* are the extrinsic parameters which denote the coordinates system transformations from 3D world coordinates to 3D camera coordinates. They define the position of the camera center and the camera heading in the world coordinates.

1D and 2D Measurements Cont…

- Practical Solution?
- Camera Calibration Toolbox for MATLAB

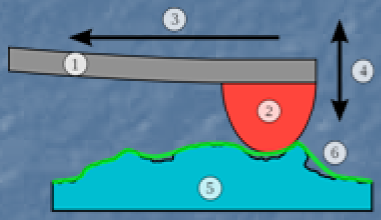


http://www.vision.caltech.edu/bouguetj/calib_doc/

- 'Comparative review of camera calibrating methods with accuracy evaluation' by Salvi et al., Pattern Recognition 2002; 35(7):1617-1635.

3D Shape Measurement

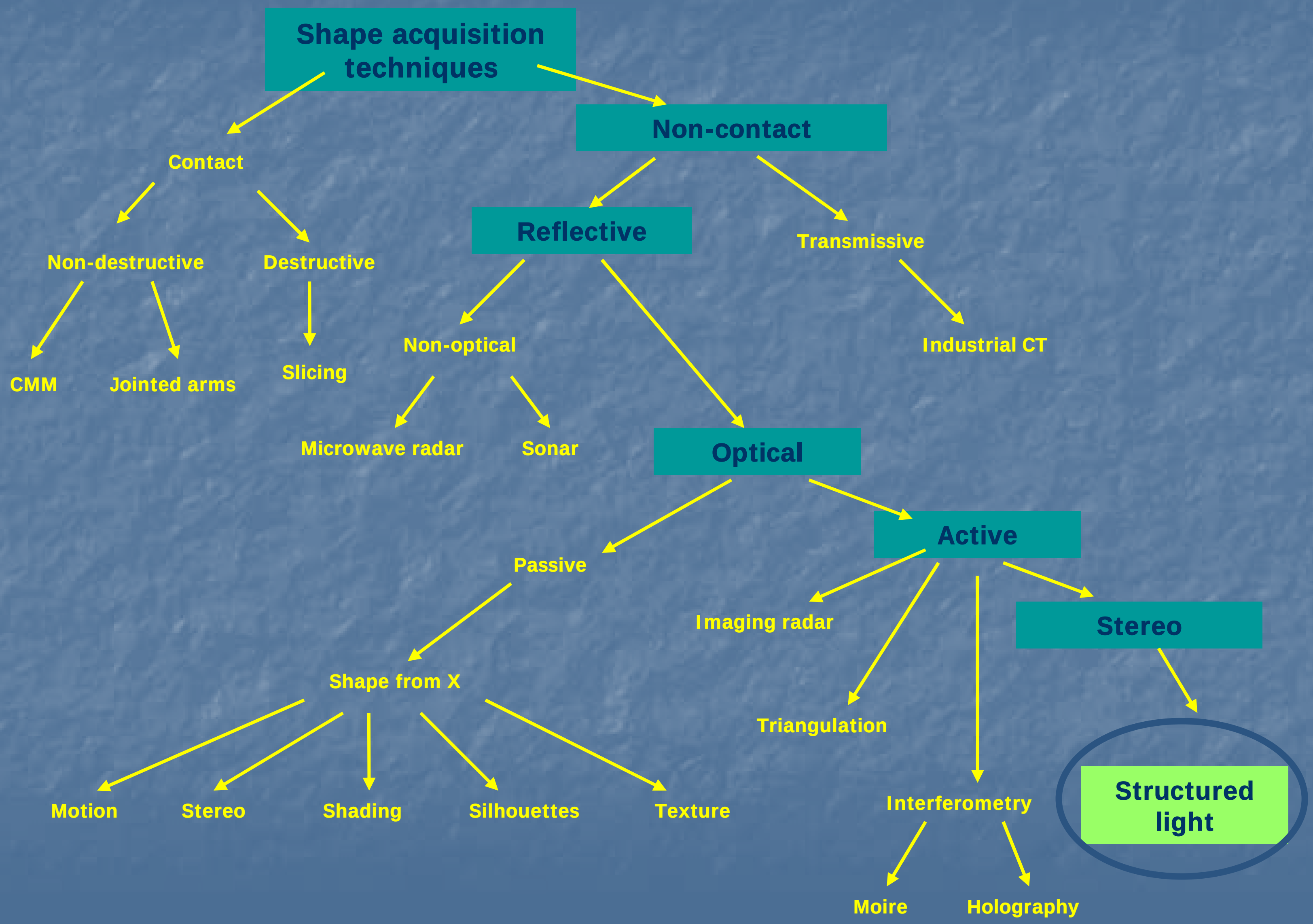
- Coordinate Measurement Machine (CMM)



  - Measurements are defined by a probe attached to the third moving axis of this machine

- Can we inherit the benefits that we have in making 1D and 2D measurements with digital camera, while measuring 3D shapes?

3D Shape Measurement Techniques



Optical Triangulation

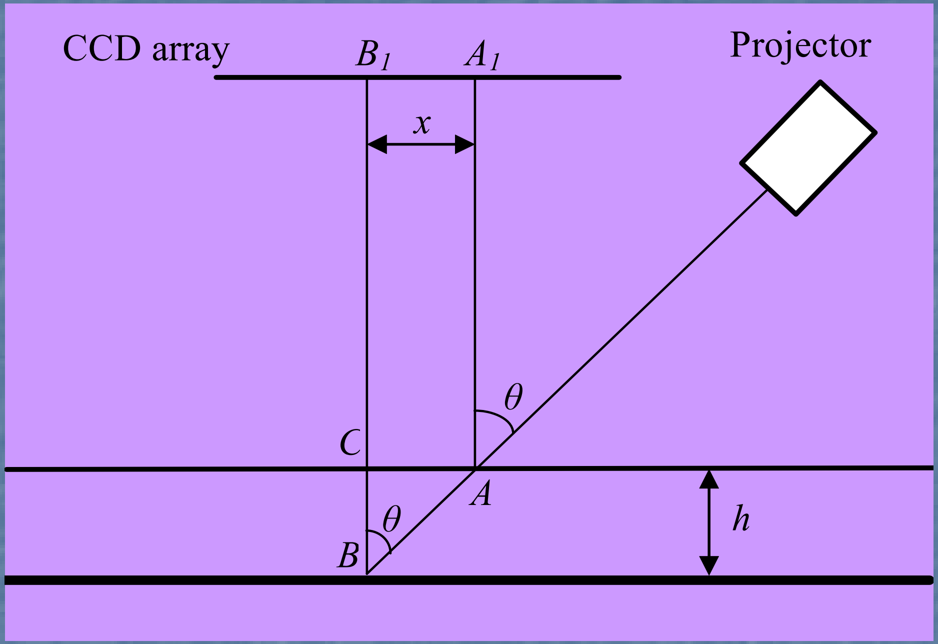
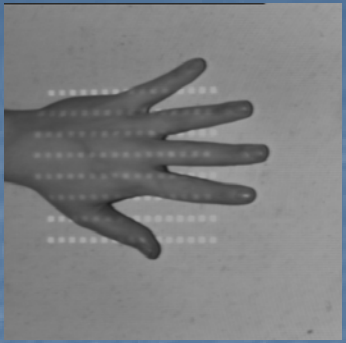


Figure: Optical triangulation geometry

$$h = \frac{x}{\tan(\theta)}$$

3D Shape Measurement cont..



- Point rastar – grid of dots
- Line rastar

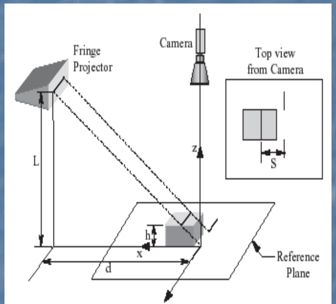
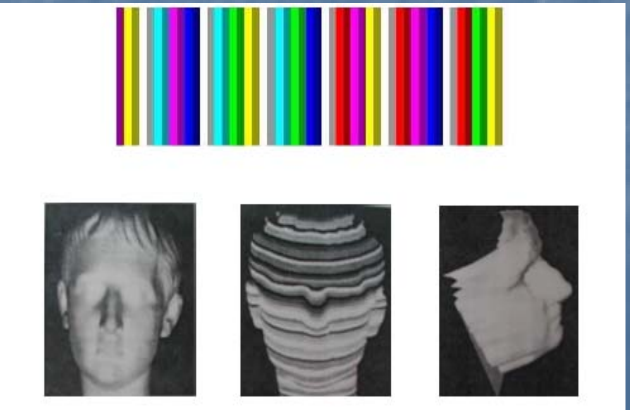


Fig. 1. Schematic layout of the projection and imaging system.

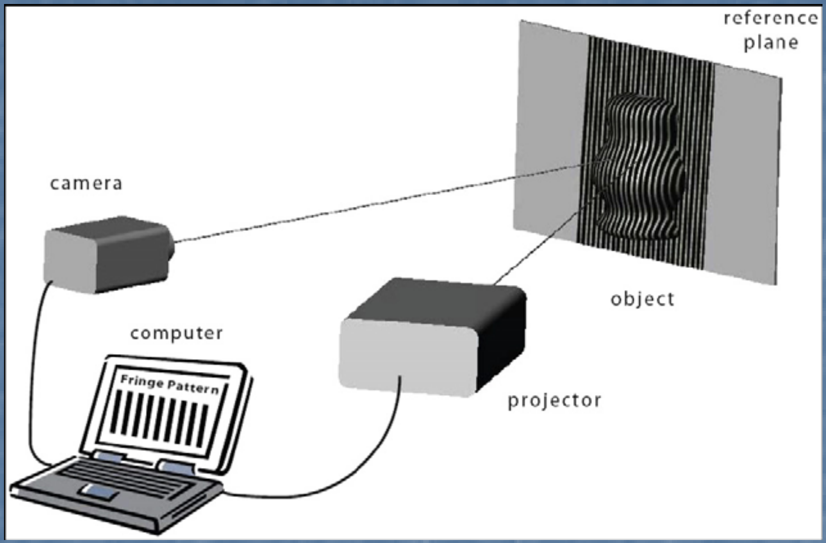
- Color-coded projection

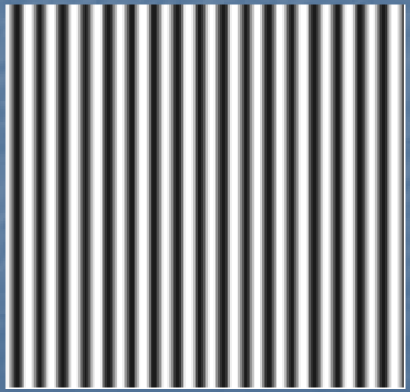
Lie W et al., Applied optics 39 (20), 3504, 2000
Li Zhang et al., 3DPVT'02, 2000



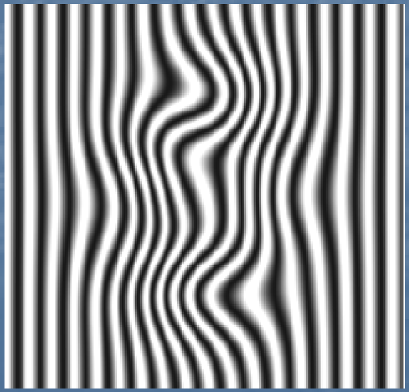
Color-coded pattern designed by Weiyi Liu et al., and measurements they performed with it on a mask

Fringe Projection Technique





$$h(x, y) = \frac{l_0 * \Delta\varphi(x, y)}{\Delta\varphi(x, y) - 2\pi f_0 d}$$

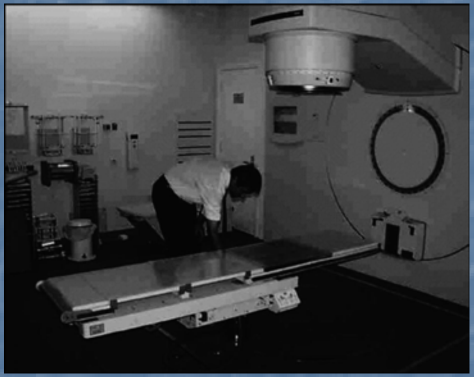


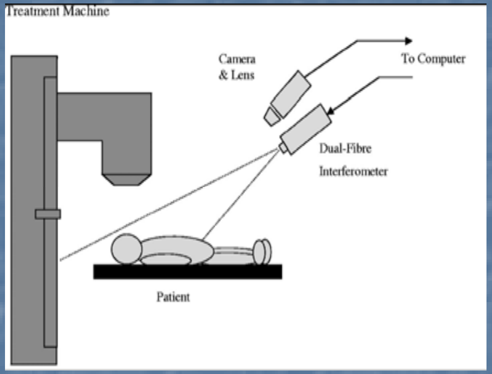
$g_0(x, y) = a(x, y)+b(x, y) \cos(2\pi f_0 x+\phi_0(x, y))$

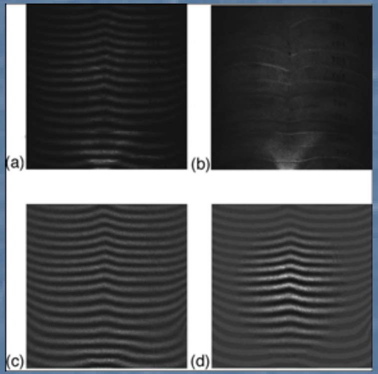
$g(x, y) = a(x, y) + b(x, y) \cos(2\pi f_0 x+\phi(x, y))$

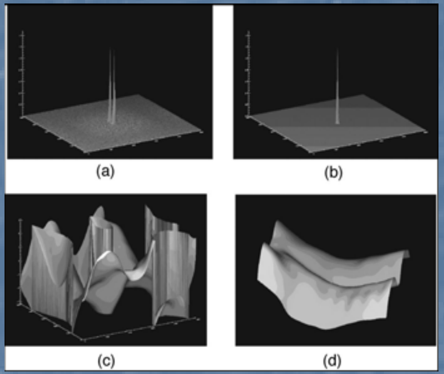
Applications of Fringe Projection Technique

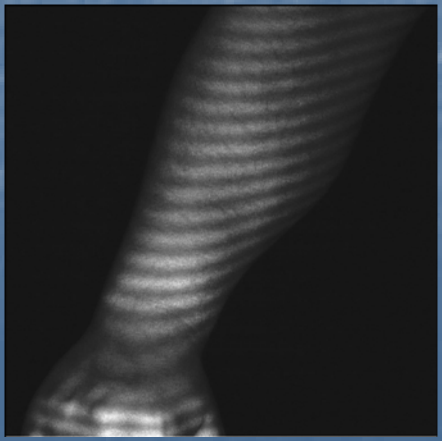
- Biomedical Applications
  - Shape guided radiotherapy treatment

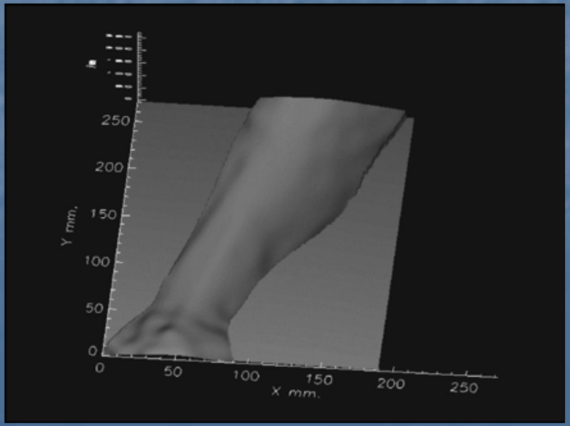








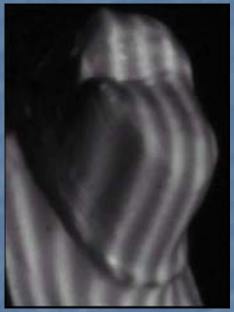


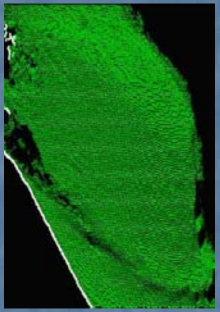


Lilley F et al., optical Engineering 39(1), 187, 2000

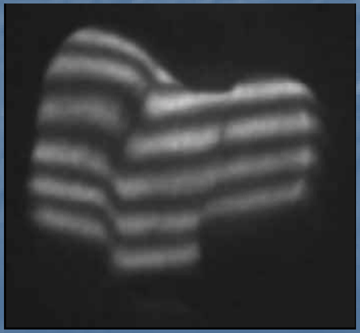
Applications of Fringe Projection Technique cont..

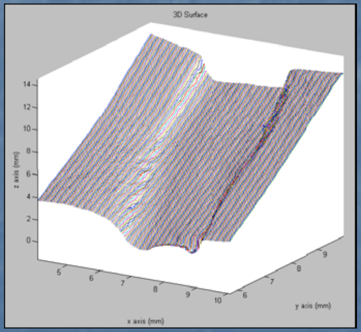
- Biomedical Applications
  - 3D intra-oral dental measurements





Chen L et al., Measurement Science and Technology 16(5), 1061, 2005



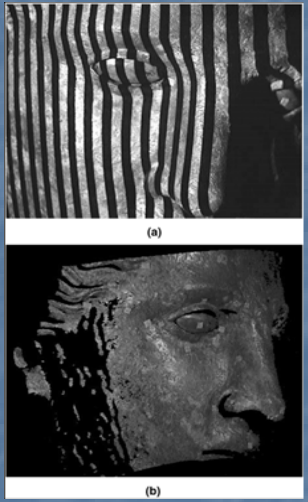


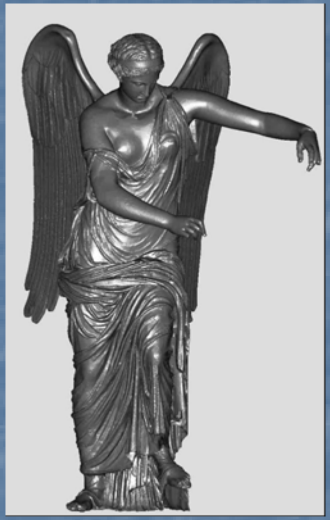
Applications of Fringe Projection Technique cont..

- Biomedical Applications cont..
  - Non-invasive 3D monitoring of vascular wall deformations
  - Lower back deformation measurement
  - Detection and monitoring of scoliosis
  - Inspection of wounds
  - Skin topography measurement for use in cosmetology

Applications of Fringe Projection Technique cont..

- Cultural heritage and preservation

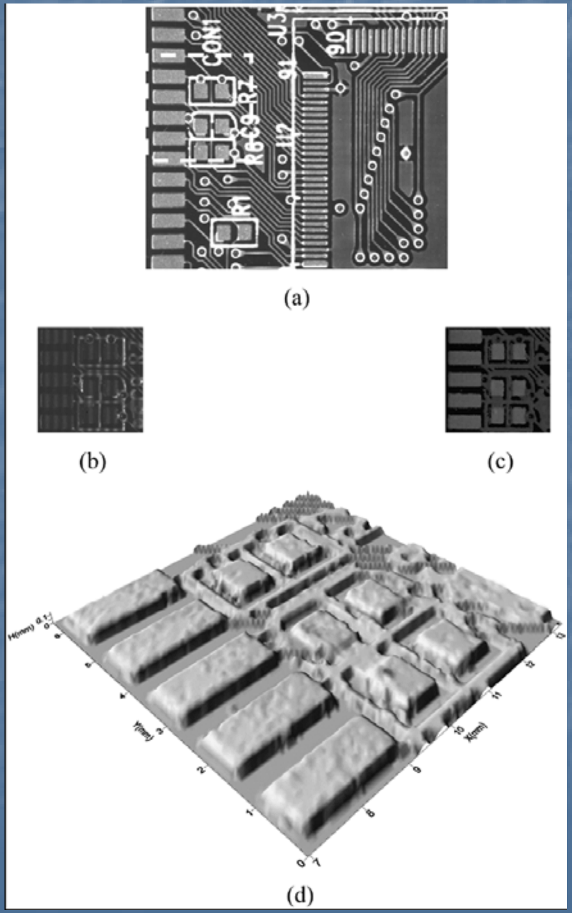


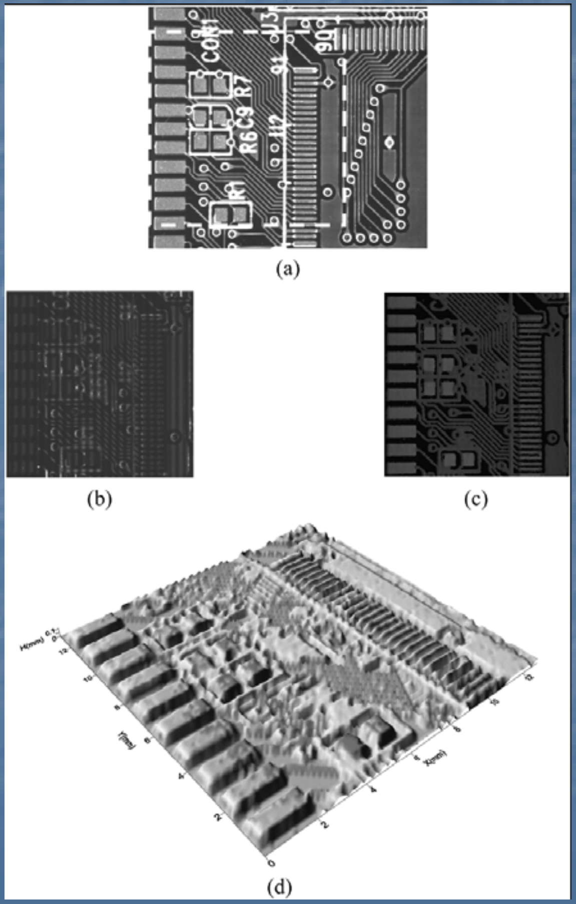


Sansoni G et al., IEEE Trans. Instrumentation and Measurement 54(1), 359, 2005

Applications of Fringe Projection Technique cont..

- Quality control of printed circuit board manufacturing

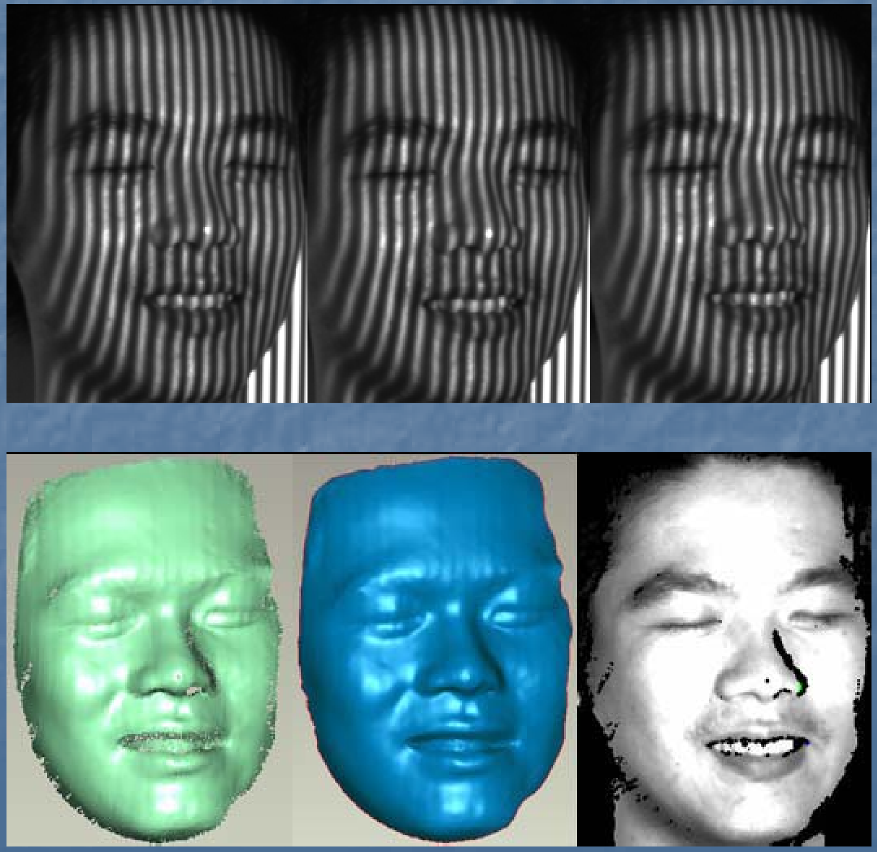




Yen H et al., IEEE Trans. Electron Packaging Manuf 29(1), 50, 2006

Applications of Fringe Projection Technique cont..

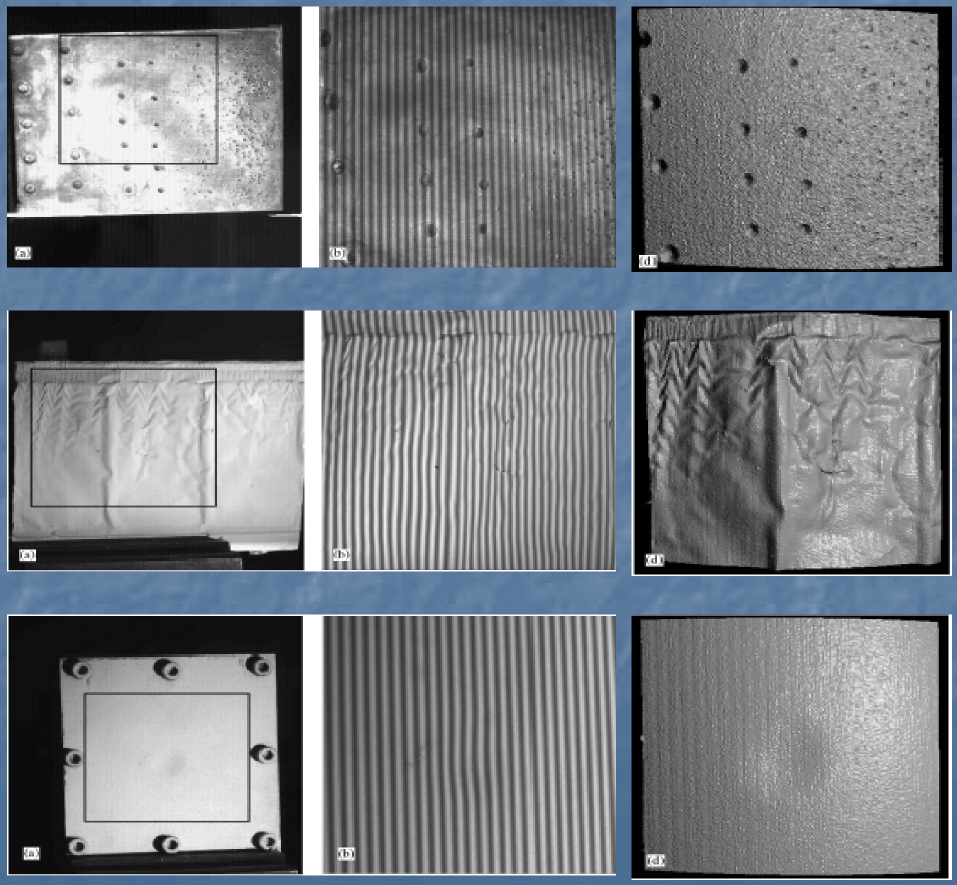
- 3D face reconstruction: Applications in security systems (face recognition systems), gaming, virtual reality etc.



Zhou G et al., Tsinghua Sci Technol 14, 62, 2009

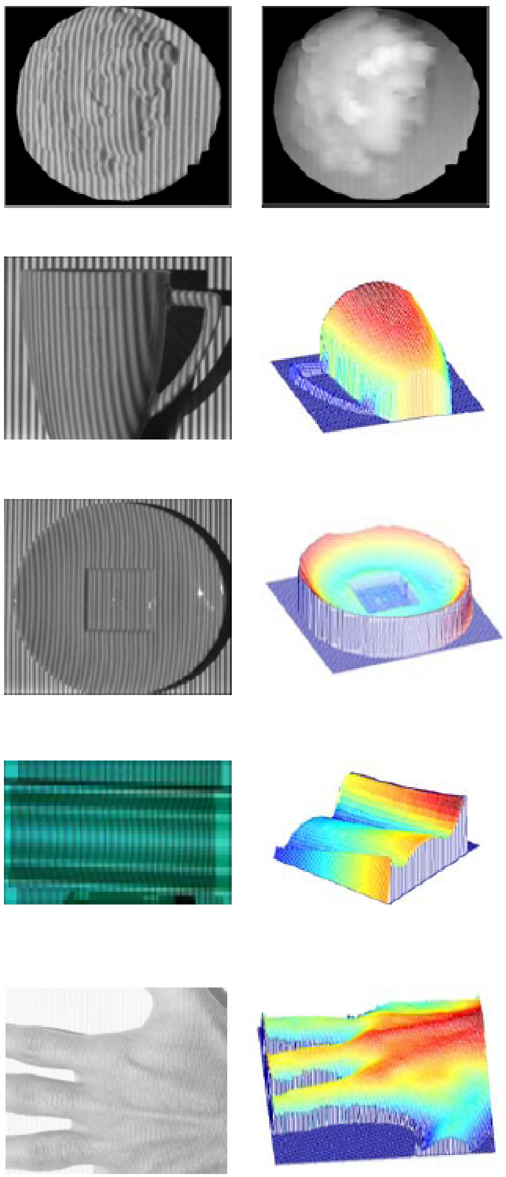
Applications of Fringe Projection Technique cont..

- Industrial and scientific applications
  - Corrosion analysis

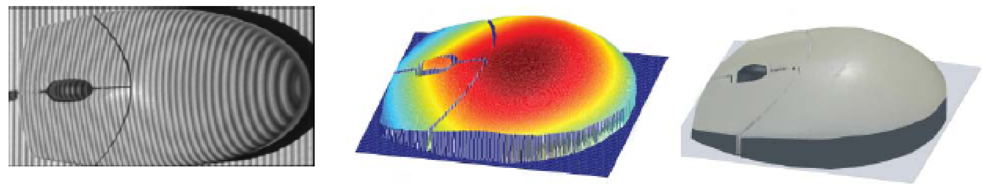


Huang PS et al., Optics and Lasers in Engineering 31(5), 371, 1999

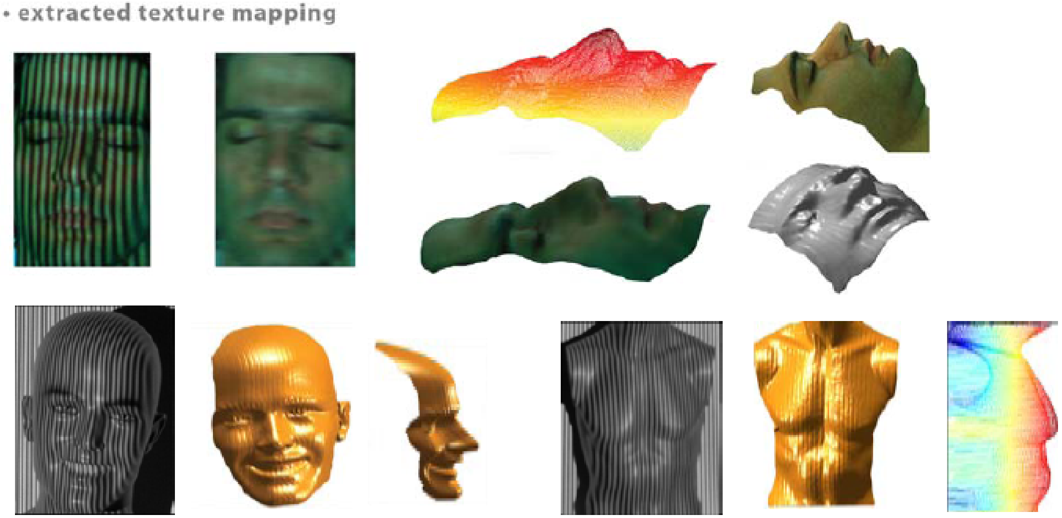
Experimental work at IMAC



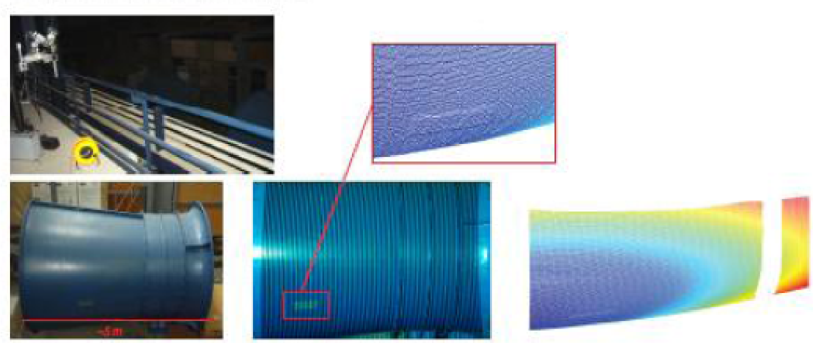
• real texture mapping



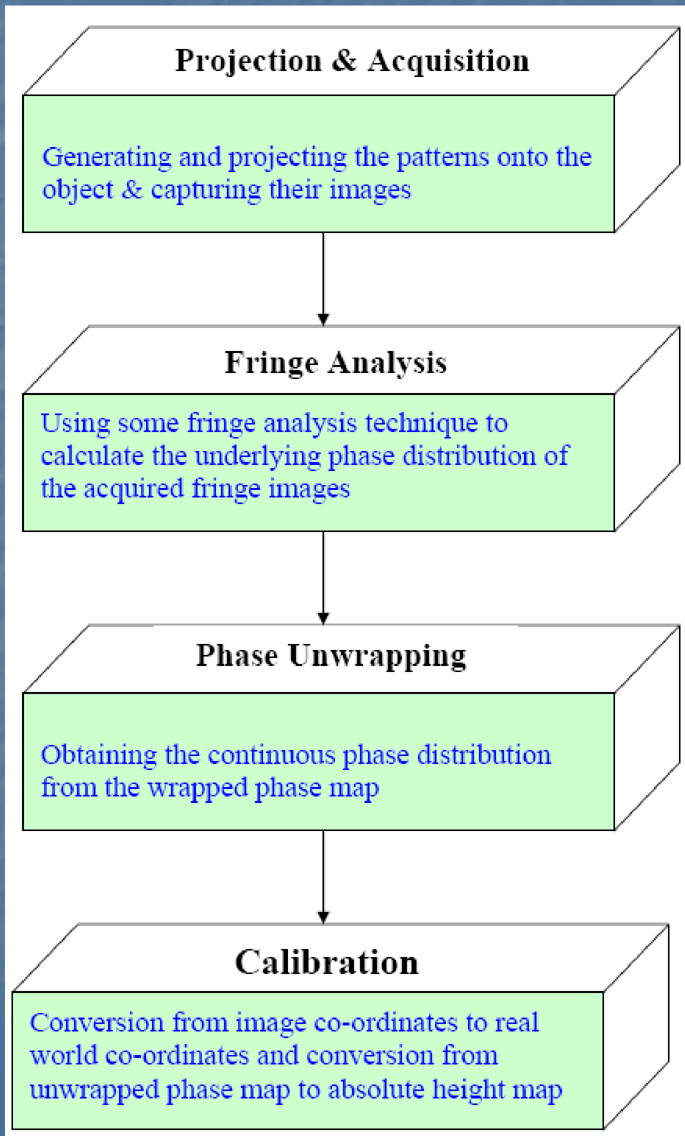
• extracted texture mapping

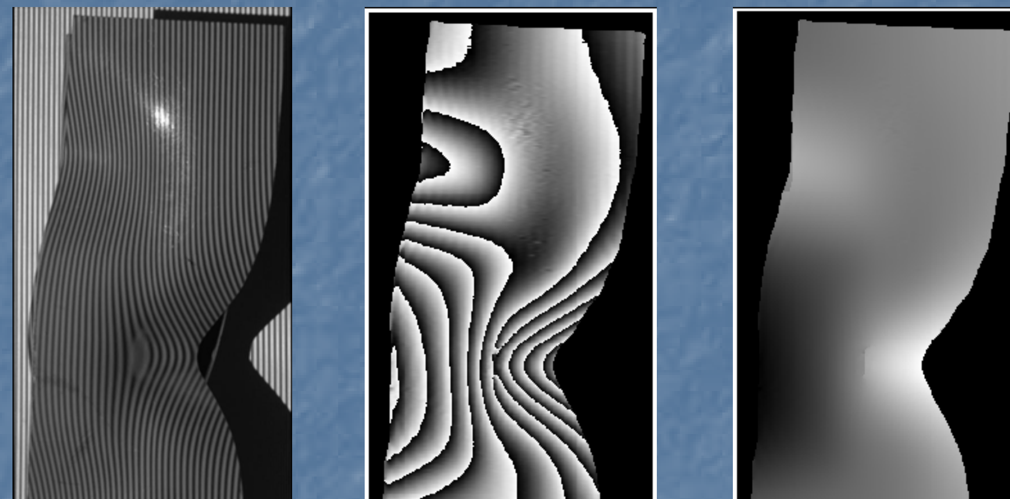


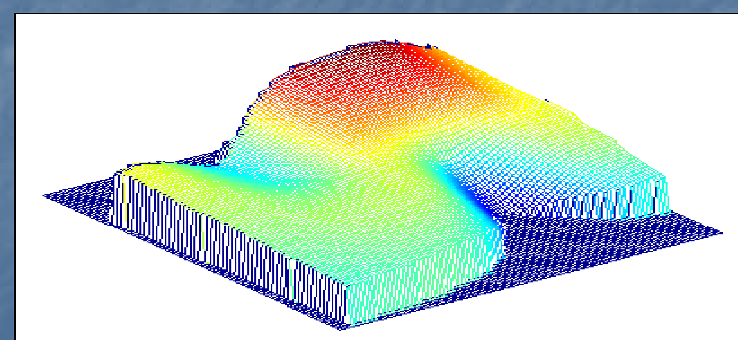
• non-accessible object



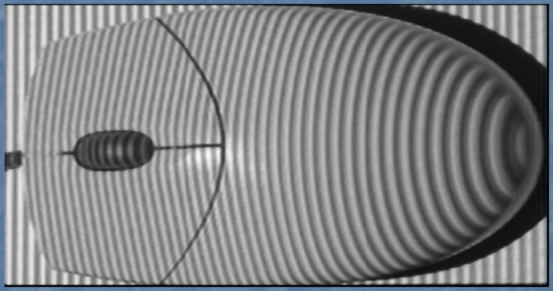
3D shape measurement of objects using fringe projection technique: Overview of measurement methodology

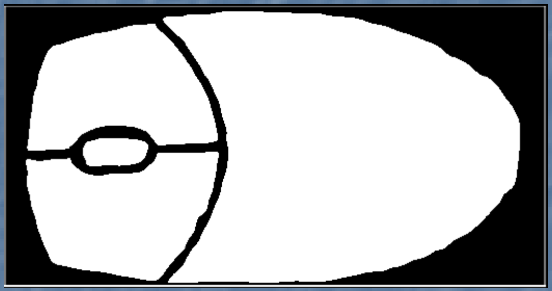


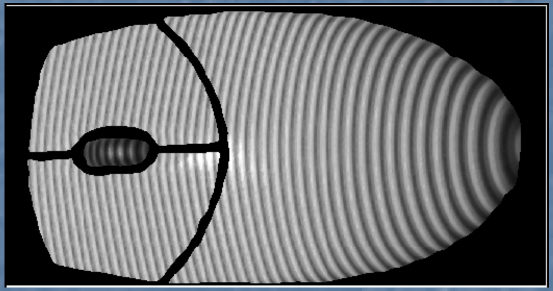


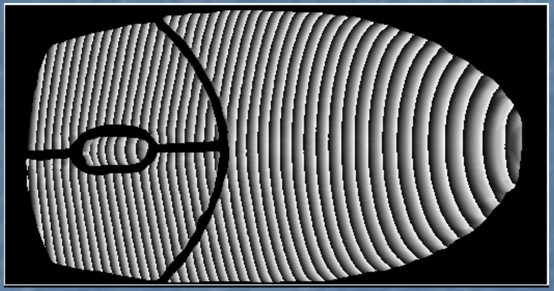


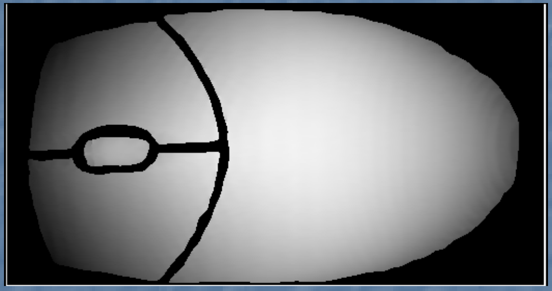
3D shape measurement of objects using fringe projection technique: Overview of measurement methodology

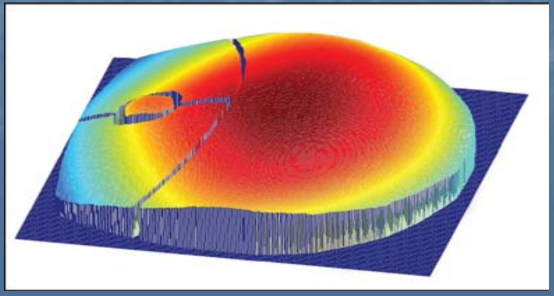




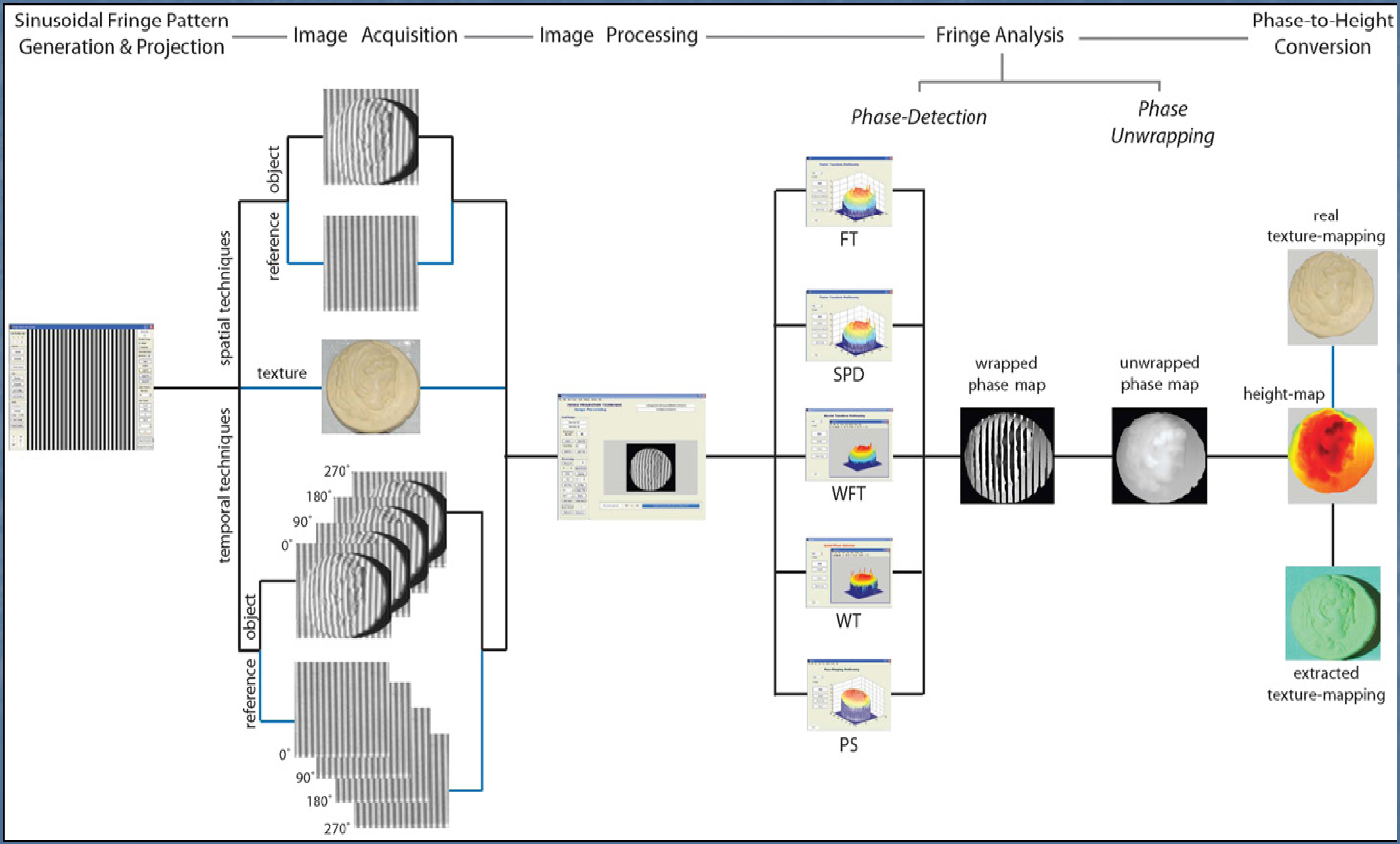








Work-flow in fringe projection profilometry



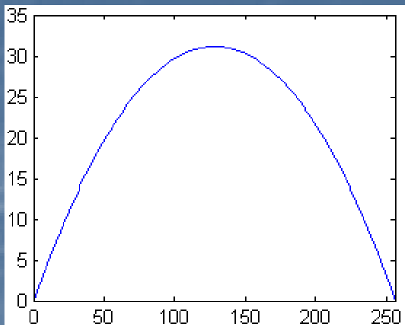
Fringe Analysis

$$g(x, y) = a(x, y) + b(x, y) \cos[2\pi f_0 x + \phi(x, y)]$$

- *a(x, y)* represents the intensity variations of the background (related to the object's texture)
- *b(x, y)* represents non-uniform reflectivities of the object surface (fringe modulation term)
- 2пf0x represents the spatial carrier
- $\phi(x, y)$ is the phase term which contains the information of the object's shape
- Fringe analysis methods aim at extracting $\phi(x, y)$ from g(x, y)

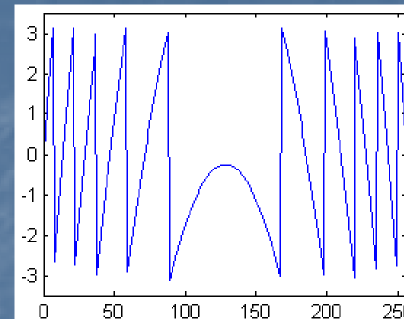
- Most commonly used fringe analysis methods are:
  - Fourier transform method
  - Wavelet transform method
  - Windowed Fourier transform method
  - Phase shifting method

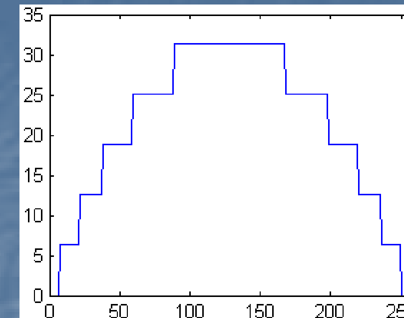
Phase Unwrapping



$$h(x) = ae^{j\phi(x)}$$

$$\hat{\phi}(x) = \tan^{-1}\left\{\frac{\mathrm{Im}[h(x)]}{\mathrm{Re}[h(x)]}\right\}$$

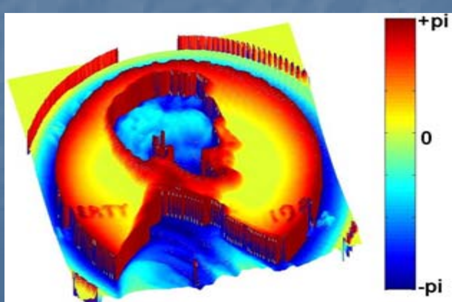


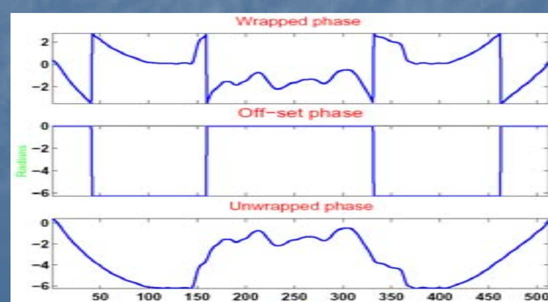


Phase $\phi(x)$ **Wrapped Phase** $\hat{\phi}(x)$ **Offset**

The process of determining the unknown integral multiple of 2pi to be added at each pixel of the wrapped phase map to make it continuous by removing the artificial 2pi discontinuities is referred to as phase unwrapping.

$$\phi_{unwrap}(x, y) = \phi_{wrap}(x, y) + 2\pi n$$





Wrapped phase map **Phase unwrapping** **Unwrapped phase**

Phase Unwrapping Cont..

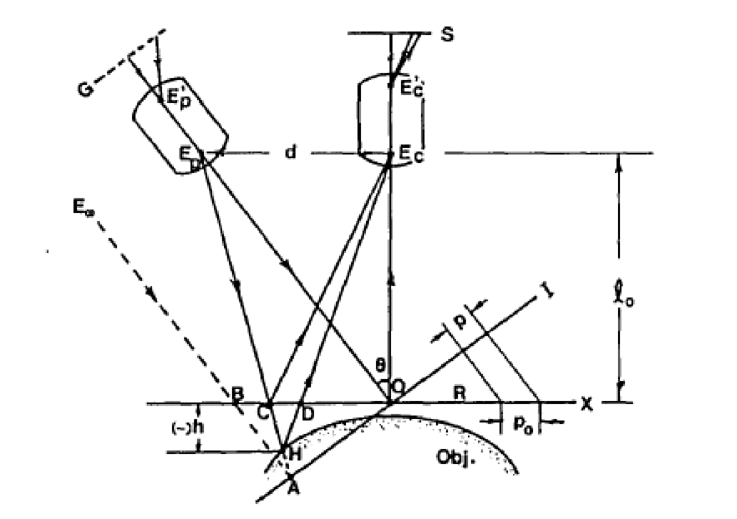
- Phase unwrapping is a trivial task if the wrapped phase map is ideal.
- In practice, the presence of the following makes unwrapping a difficult and path-dependent problem:
  - Shadows
  - Low fringe modulations
  - Non-uniform reflectivities of the object surface
  - Fringe discontinuities
  - Noise etc.
- Some of the most commonly used unwrapping algorithms are:
  - Goldstein’s unwrapping algorithm
  - ZpiM unwrapping algorithm
  - Quality guided phase unwrapping algorithm

System Calibration

$$g_T(x,y) = \sum_{n=-\infty}^{\infty} A_n \exp(2\pi i n f_0 x)$$

$$g_0(x,y) = \sum_{n=-\infty}^{\infty} A_n \exp\{2\pi i n f_0 [x + s_0(x)]\}$$

$$g_0(x,y) = \sum_{n=-\infty}^{\infty} A_n \exp\{i[2\pi n f_0 x + n\phi_0(x)]\}$$



Takeda M and Kazuhiro M, Applied optics 22 (24), 3977, 1983

Crossed-optical-axes geometry

$$g(x,y) = r(x,y) \cdot \sum_{n=-\infty}^{\infty} A_n \exp\{2\pi i n f_0 [x + s(x,y)]\}$$

$$g(x,y) = r(x,y) \cdot \sum_{n=-\infty}^{\infty} A_n \exp\{i[2\pi n f_0 x + n\phi(x,y)]\}$$

$$\overline{CD} = -dh(x,y)/[l_0 - h(x,y)]$$

$$h(x,y) = \frac{l_0 * \Delta\varphi(x,y)}{\Delta\varphi(x,y) - 2\pi f_0 d}$$

Linear calibration

$$h(x,y) = \frac{l_0\ \Delta\phi(x,y)}{2\pi\ f_0\ d} = K(x,y)\,\Delta\phi(x,y)$$

Non-linear calibration

$$h(x,y) = \frac{\Delta\phi(x,y)}{C_1(x,y) + C_2(x,y)\,\Delta\phi(x,y)}$$