Metrology and Sensing

Lecture 4: Fringe projection
2017-11-09
Herbert Gross
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Content

- Moire effect
- Illumination coding
- Fringe projection
- Deflectometry
Moire Effect

- Special pattern by using two identical but inclined gratings

Sinusoidal grating  Rotated grating  Overlay: Moiré interference

Ref: R. Kowarschik
Moire Effect

- Improved accuracy by two inclined gratings
- The new period is given by

\[ p = \frac{p_0}{\sin(\theta)} \]

- Improved accuracy by two gratings with slightly different periods \( p_1 / p_2 \)
- The new period is given by

\[ p = \frac{p_1 p_2}{2\Delta p} \]
Moire

- Point grating Moire

- Moire effect for two circular fringe systems
Moire
Shape Measurement by Structured Illumination

- **Main idea:**
  - light pattern projected onto the scene under investigation
  - deformation of the pattern due to 3D shape of the body
  - detection of the changed pattern by camera
  - analysis of the geometry to reconstruct the shape

- **Physics:**
  - incoherent illumination, light diffuse scattered into all directions
  - incoherent illumination, light specular reflected by polished surface (deflectometry)
  - coherent illumination, interferometry or holography

- **Special coding/decoding strategies gives fast and unique shape reconstruction:**
  coded structured light (CSL)
  Single shot: phase unwrapping is critical

- **Classification of methods:**
  - single/multiple shots
  - sparse/dense pattern (discretized, binary pattern/continuous grayscales)
  - spatial/time multiplexing (binary encoding / phase shifting)
  - black/white vs colored pattern
  - number of cameras
  - axis codification:
    - 1D vs 2D pattern
Shadow Moire

- Typical formation of fringes
- Moire period quite longer than grating constant $p$: small angle between illumination and observation
- Master grating projected onto the sample
- Observation under modified angle
- Shift depends on the height $z$

Ref: R. Kowarschik/Wyant
Shadow Moire Setup

- **Shadow Moire**
- **Illumination and observation propagated through the same grating (multiplicative Moire)**
- **Illumination:**
  transmission at position A
  \[ t_A(x, y) = 1 + \cos\left(\frac{2\pi}{p} x_A\right) \]
- **Observation:**
  transmission at position B
  \[ t_B(x, y) = 1 + \cos\left(\frac{2\pi}{p} x_B\right) \]
- **Total signal**
  \[ I(x, y) = \left[ 1 + \cos\left(\frac{2\pi}{p} x_A\right) \right] \cdot \left[ 1 + \cos\left(\frac{2\pi}{p} x_B\right) \right] \]
  with geometry
  \[ x_A = \frac{l \cdot x_p}{l + h_p}, \quad x_B = \frac{s \cdot h_p + l \cdot x_p}{l + h_p} \]
- **Finally gives**
  \[ I(x, y) = K(x, y) \cdot \left[ 1 + \cos\left(\frac{2\pi}{p} \cdot \frac{s \cdot h}{l + h}\right) \right] \]
  and allows to reconstruct the height \( h(x,y) \)
- **High frequencies are filtered out:**
  smoothed Moire signal, frequency depends on parameters \( s, h \)

Ref: T. Yoshizawa
Moire

- Shadow Moire for different viewing angles

- Shadow Moire filtering of the elementary period frequency

Ref: R. Kowarschik
Shadow Moire

- Serat fringe projection
- Filtering out the high frequencies

$t_1(x, y)$

$t_2(x, y)$

$t_1(x, y)t_2(x, y)$

$128(1 + \cos 2\pi\psi(x, y))$

Ref: R. Kowarschik

Object surface

Slide projector

Camera
Moire by Time-Multiplexing

- Fast going horse buggy
- Stroboskopical illumination by discrete flashes (or TV image sequencing):
  wheel spokes seems to rotate slowly or backwards
Measurement by Fringe Projection

- Projection of a light sheet onto a deformed surface

- Corresponds to one fringe in more complicated pattern projection
Linear Encoders

- Main idea:
  - linear scale as reference, linear pattern of fringes
  - reading head with similar linear scale
  - comparison of scales due to changes by movement or deformation

- Optical encoding techniques by:
  - Moire
  - grating fringe projection
  - interferometry
  - holography

- Quantitative evaluation of length by counting the periods/fringes

- Unique demodulation by phase shifting techniques

- Similar technique:
  angle encoding
Coded Illumination

- **Time** multiplexing:
  - binary codes
  - n-ary codes
    (n discrete quantizations)
  - gray code with phase shift
  - hybrid methods

- **Spatial** codification:
  - non-formal codification
  - M-arrays
  - de Bruijn sequences

- **Direct** codification of amplitude or color:
  - gray levels
  - color coding
Coded Illumination

- Comparison:
  binary graycode vs phase shift

Ref: R. Kowarschik
Coded Illumination

- Binary graycode projection of different pattern in a time series

Ref: R. Kowarschik
Absolute Encoders

- Absolute decoding: simultaneously binary multi-track code

Ref: R. Kowarschik
Coded Illumination

- Phase shift technique: projection of the same periodic pattern for different phases (location of maxima are moving)
- At least three phases are needed to guarantee a unique reconstruction
- To relax noise influence: 4 or 5 phase values measured (redundance)

Ref: R. Kowarschik
Encoding with Moire

- Linear encoders: slightly different period in projection / observation
Wrapping

- Full surface height $h$: $z(x, y)$
- Wrapped onto a limited height $\Delta h$
- Typical for recovery of angle/phase information onto the elementary interval $2\pi$
- The phase determination is not unique for multiples of $2\pi$
- Recovery possible by corresponding algorithms to get the smooth surface
- Shape measurement of a surface
- Projection of a fringe pattern onto the surface
- Observation of the fringe deformation by a camera, mostly by Scheimpflug geometry
- A shift corresponds to a change in depth
- Non-trivial image processing
Pattern Projection

- Checkerboard projection pattern instead of simple linear fringes
Pattern Projection Setups

- General setup of a pattern projection
Fringe Projection

- Illumination:
  1. telecentric / collimated
  2. central / source point
Fringe Projection

- Observation methods
  1. structured detector
  2. Moire
Fringe Projection

- Problems with shadowing
- Partly missing information possible
- Solution: diversification by movements and multiple images

Ref: R. Kowarschik
Visibility and unvisible regions in projection
Here: measurement of a sphere
Signal Evaluation of Telecentric Fringe Projection

- Fringe period in projection
  \[ p_x = \frac{p}{\cos \theta_1} \]

- Lateral shift due to height \( z \)
  \[ u = z \cdot (\cos \theta_1 + \cos \theta_2) \]

- Corresponding depth value \( z(x) \) from measured phase of fringes
  \[ f(x) = \frac{u}{p_x} = \frac{z(x) \cdot (\cos \theta_1 + \cos \theta_2)}{p} = \frac{z(x)}{p} \cdot \frac{\sin (\theta_1 + \theta_2)}{\cos \theta_2} \]
Measurement by Central Projection

- Evaluation in only 2 dimensions for central projection
- Mapping transform

\[ Z = \frac{c \cdot t - d \cdot (x + x')}{x + x'} \]

\[ X = \frac{x}{c} \left( d + \frac{c \cdot t - d \cdot (x + x')}{x + x'} \right) \]
Fringe Projection

- Systems

Setup of the 3D-shape measurement system

3D sensorhead

Measuring of a seat with kolibriROBOT

Ref: R. Kowarschik
Example Fringe projection

- Monochromatic illuminated technical surface
Fringe Projection

- Examples

- Sheetmetal workpiece
- Measuring result; Comparison with CAD model
- Prepared stump, 4 different perspectives
- tooth
- Complete jaw

Ref: R. Kowarschik
Shape Measurement

- Reverse engineering:
  from body to digital 3D data

Ref: W. Osten
3D Shape Measurement for Biometry

- Colored biometric fringe projection
- Projection of a 2D triangular pattern
3D Shape Measurement for Biometry

- Biometric 3D mesh of a human face
- Error-free identification of people

Ref: S. Zhang
Deflectometry

Principle of deflectometry:

- measurement of the deflection of light rays for reflective polished surfaces under the specular direction
- nature of the light source is known
- measured object is a “part of the imaging system”
- observation of the light source over the object

Ref: B. Fleck
Deflectometry

- General approach

structured illumination of the object

object phase image

gradient field

quantitative 3D surface topography

qualitative evidence of macroscopic defects

Additional information from system calibration, system geometry

Ref: B. Fleck
Deflectometry

- **Principle:**
  - an array of thin light pencils is incident on the surface under test
  - the ray positions are measured by a camera after reflection from the surface under test
  - the nominal locations of the ray centroids must be calibrated
  - to ensure a unique interpretation, several z-positions of the screen are measured
  - only works for polished surfaces
  - the pattern can be a 2D array or a line pattern

- **Accuracy:**
  - strongly depends on the size of the surface
  - rough estimation: 1 μm
    - for small pieces, 0.2 μm can be achieved

- **Problems:**
  - ranges of large curvature:
    - lateral resolution is poor
  - not usable before polishing
  - calibration and reconstruction algorithms complicated
Deflectometry

- Setup for reflective sample
- Setup for refractive/transmissive sample
Deflectometry

- **Calculation and evaluation**

  \[ \varphi = \frac{2\pi}{p} \cdot d \cdot \tan(2\alpha) \]

  - \( p \): stripe width
  - \( d \): distance focusing screen - surface

Ref: B. Fleck