数字莫尔三维测量及精度分析

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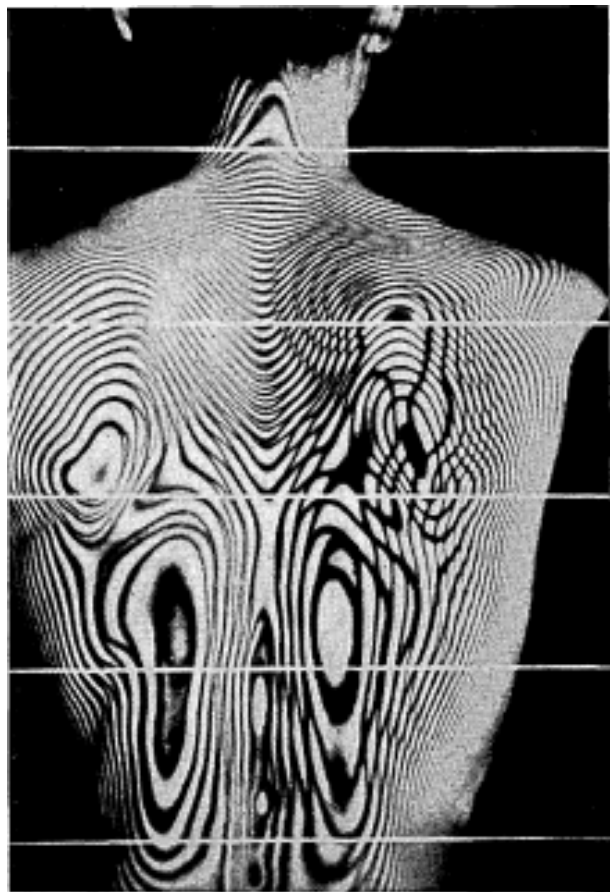
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① 莫尔三维测量发展

② 三角测量法

③ 数字莫尔条纹的产生

④ 高度分布的计算

⑤ 总结

莫尔三维测量发展

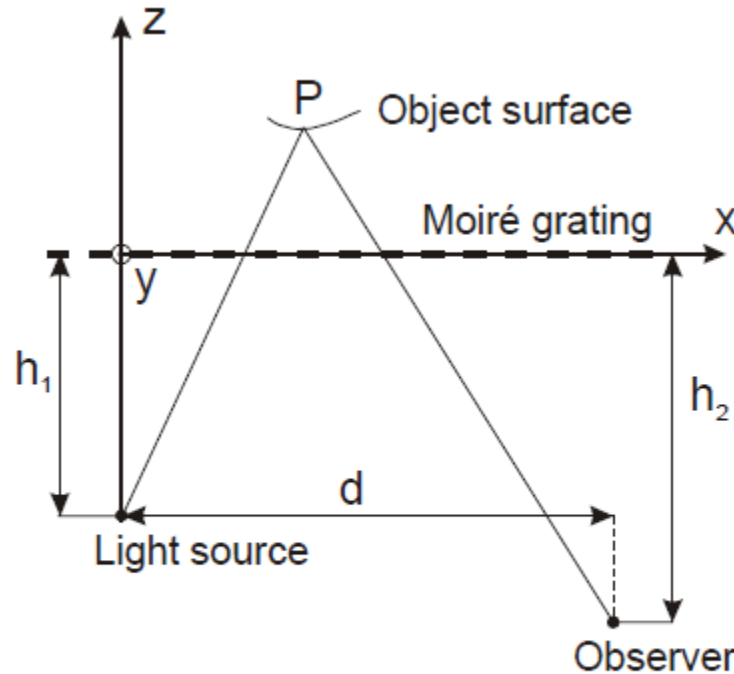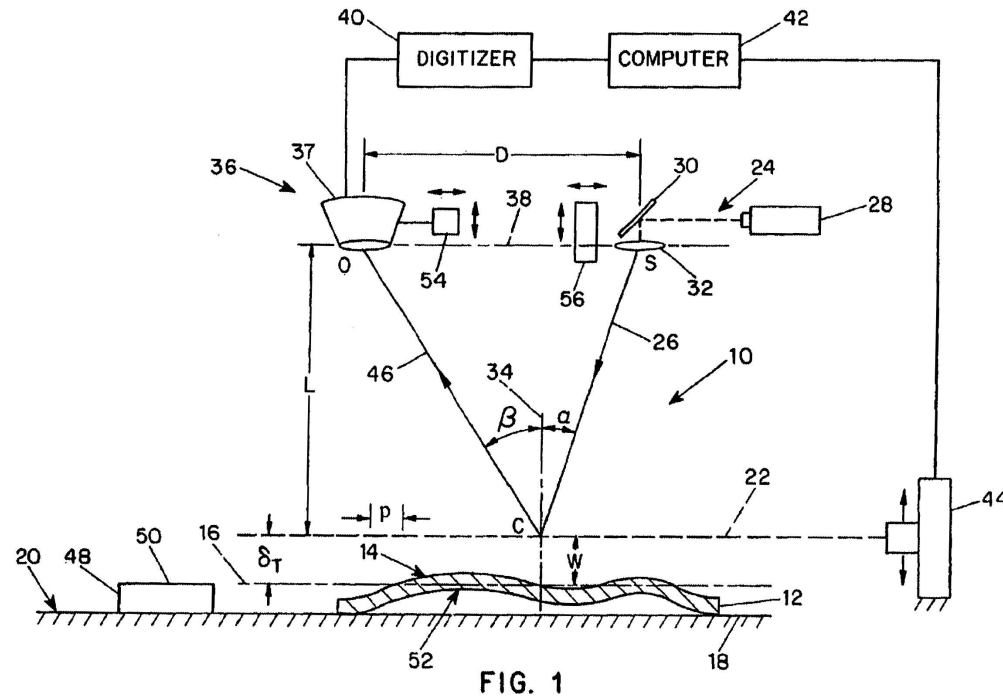Takasaki, H. (1970). "Moiré topography." Applied Optics **9**(6): 1467-1472.

阴影莫尔三维测量

Figure 1 Moiré contouring system with the light source and the observer at finite distances from the grating.

Degrieck, J., et al. (2001). "Application of digital phase-shift shadow moiré to micro deformation measurements of curved surfaces." Optics and lasers in engineering **36**(1): 29-40.
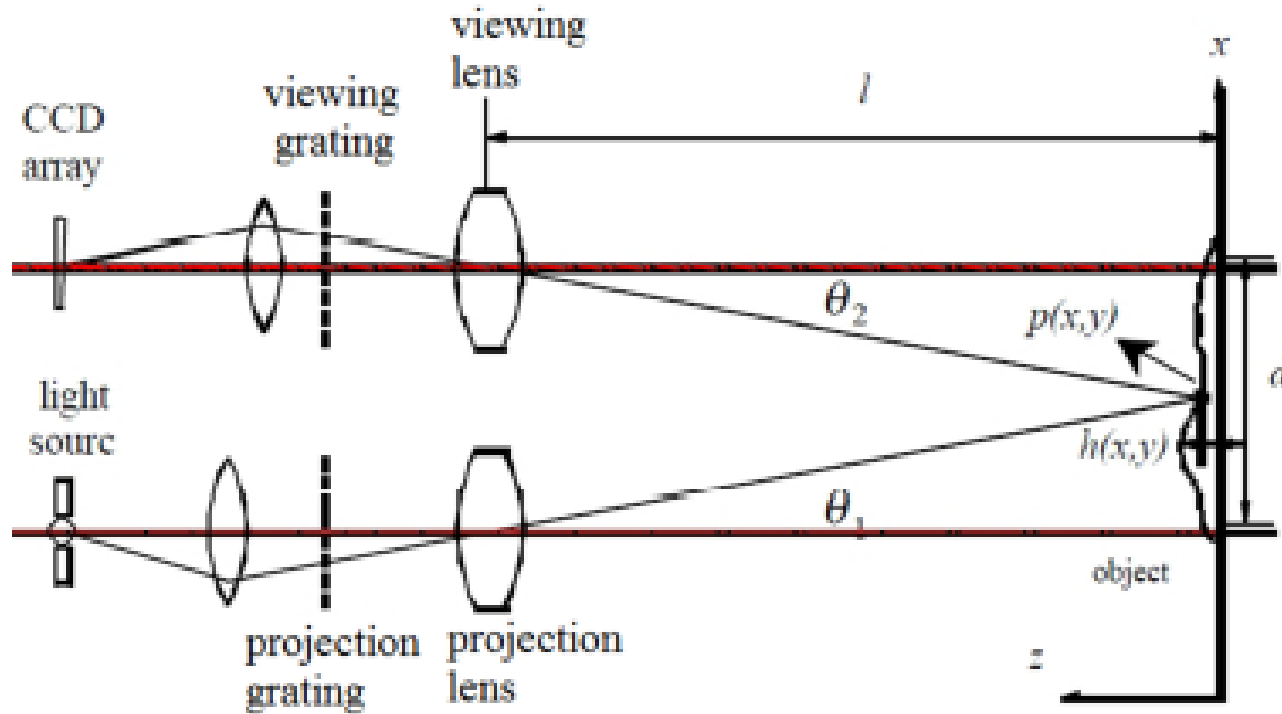
阴影莫尔三维测量

Kao, Imin, and Fu-Pen Chiang. "Shadow moire surface measurement using talbot effect." U.S. Patent No. 6,731,391. 4 May 2004.

投影莫尔三维测量

(b)

Mohammadi, Fatemeh. "3D optical metrology by digital moiré: Pixel-wise calibration refinement, grid removal, and temporal phase unwrapping." (2017).
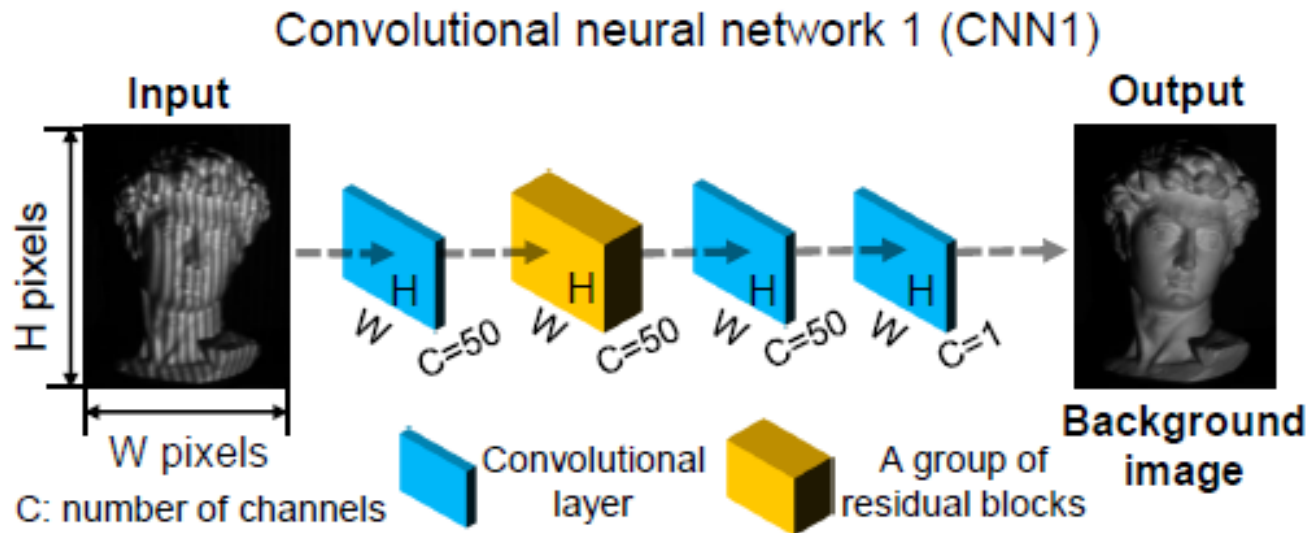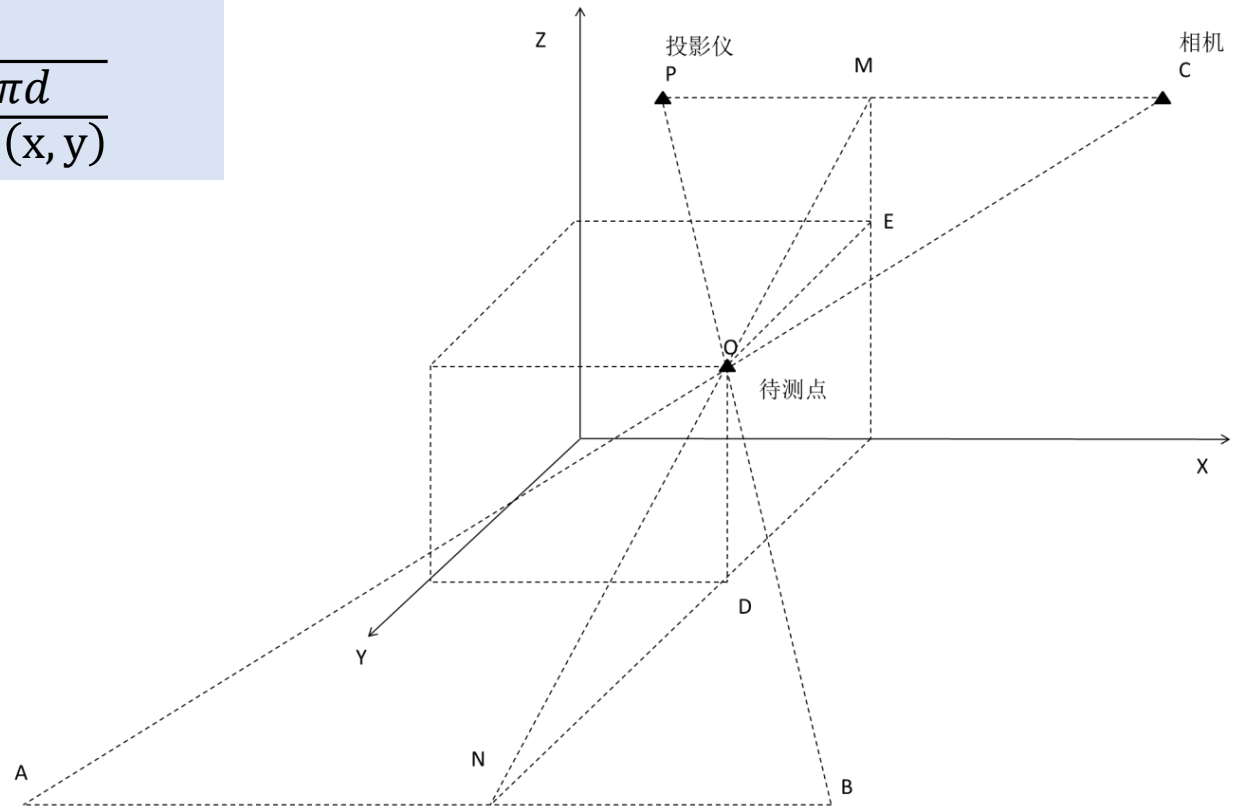
深度学习和莫尔三维测量的结合

Figure 2. Schematic of our first convolutional network (CNN1).

Feng, Shijie, et al. "Fringe pattern analysis using deep learning." *Advanced Photonics* 1.2 (2019): 025001.

$$h(x, y) = \cfrac{H}{1 + \cfrac{2\pi d}{L\Delta\varphi(x, y)}}$$

被测点在X-Z平面之外的三角测量法

$$h(x, y) = \frac{H}{1 + \frac{2\pi d}{L\Delta\varphi(x, y)}}$$
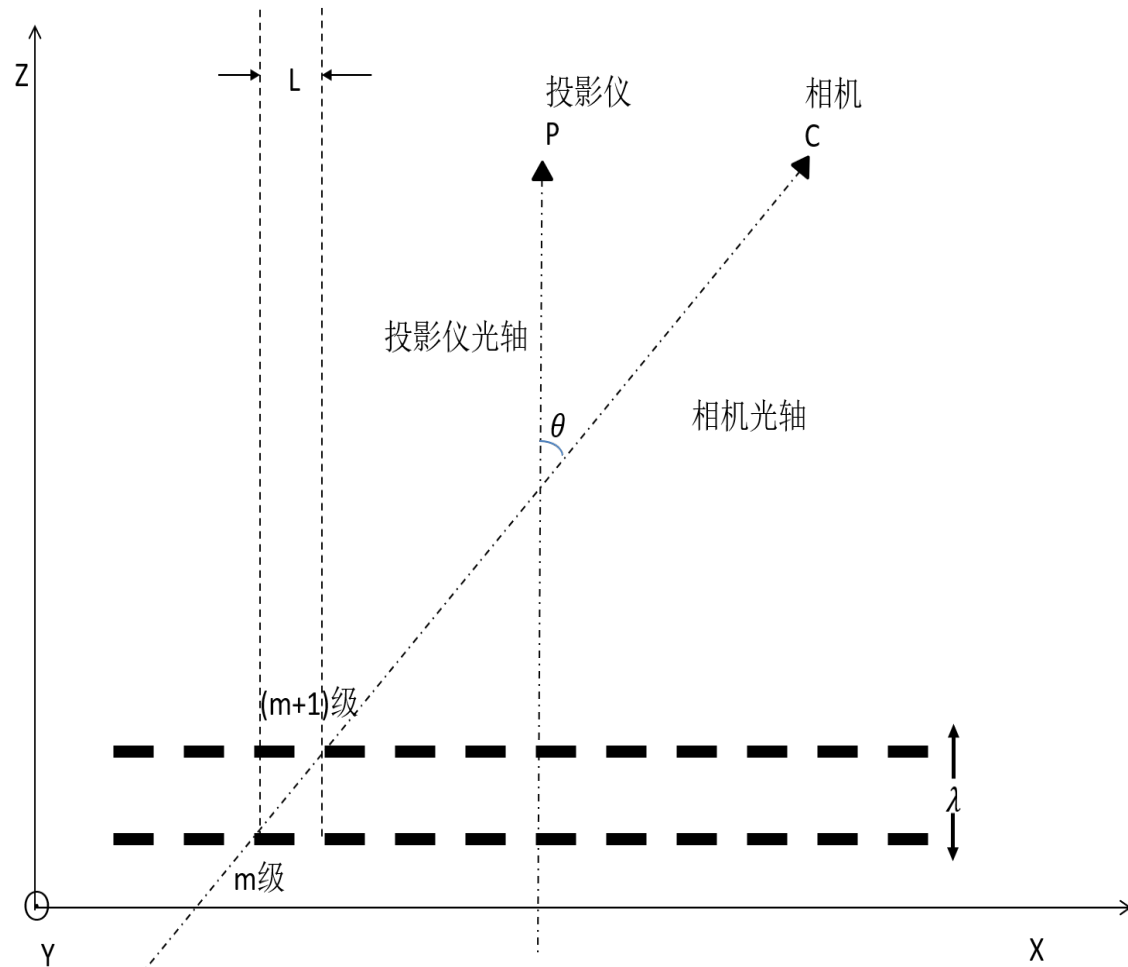
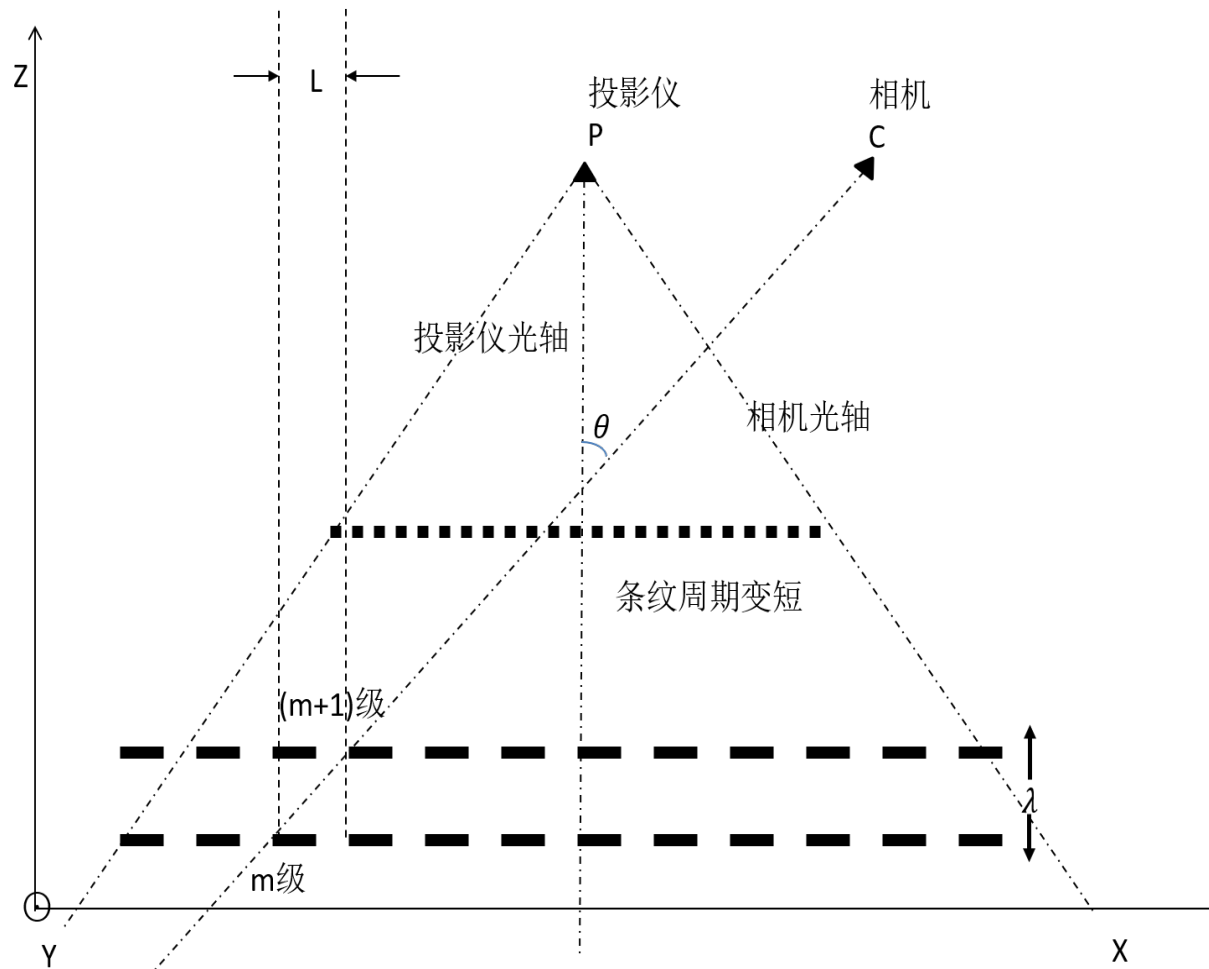$$h(x, y) = \frac{LH}{2\pi d}\Delta\varphi$$

$$h(x, y) = K\Delta\varphi$$

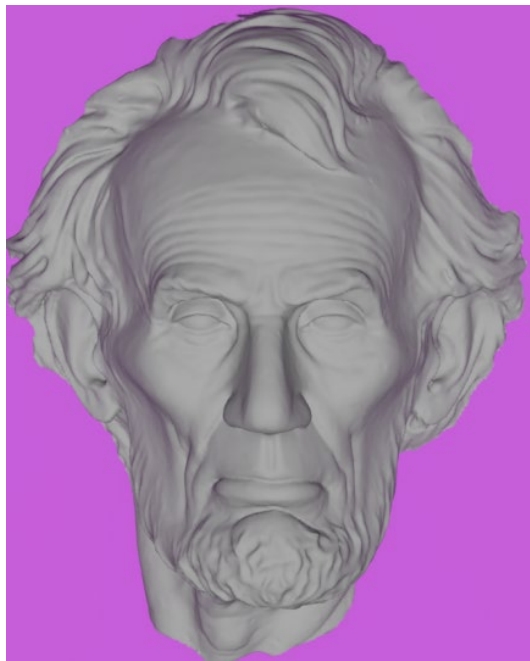$$K = \frac{\lambda}{2\pi}$$

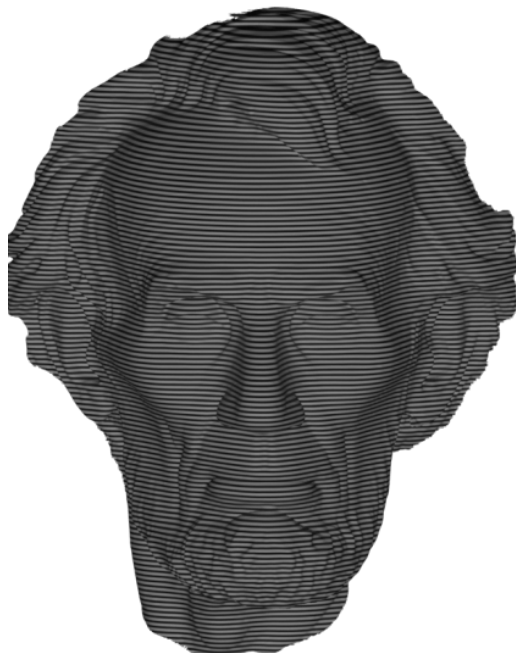$$\lambda = \frac{L}{tan\theta}$$

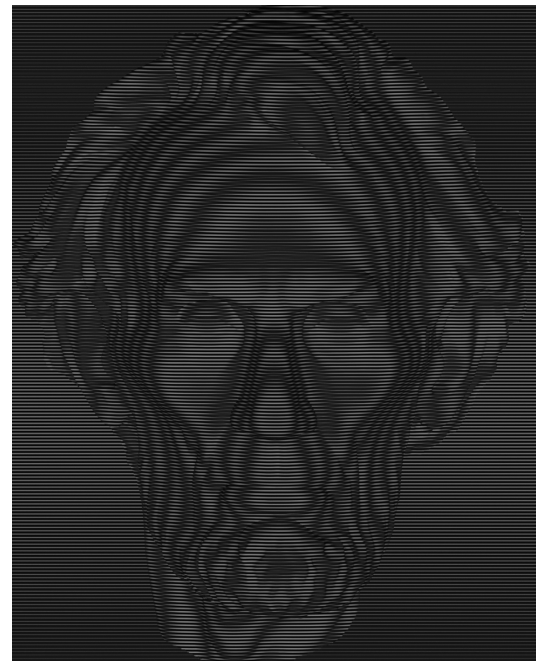当高度变化较小时，莫尔波长可由投影仪-相机光轴夹角和投影条纹周期确定

高度变化范围过大，条纹周期L减小，莫尔波长不能
视为恒定值

数字莫尔条纹的产生

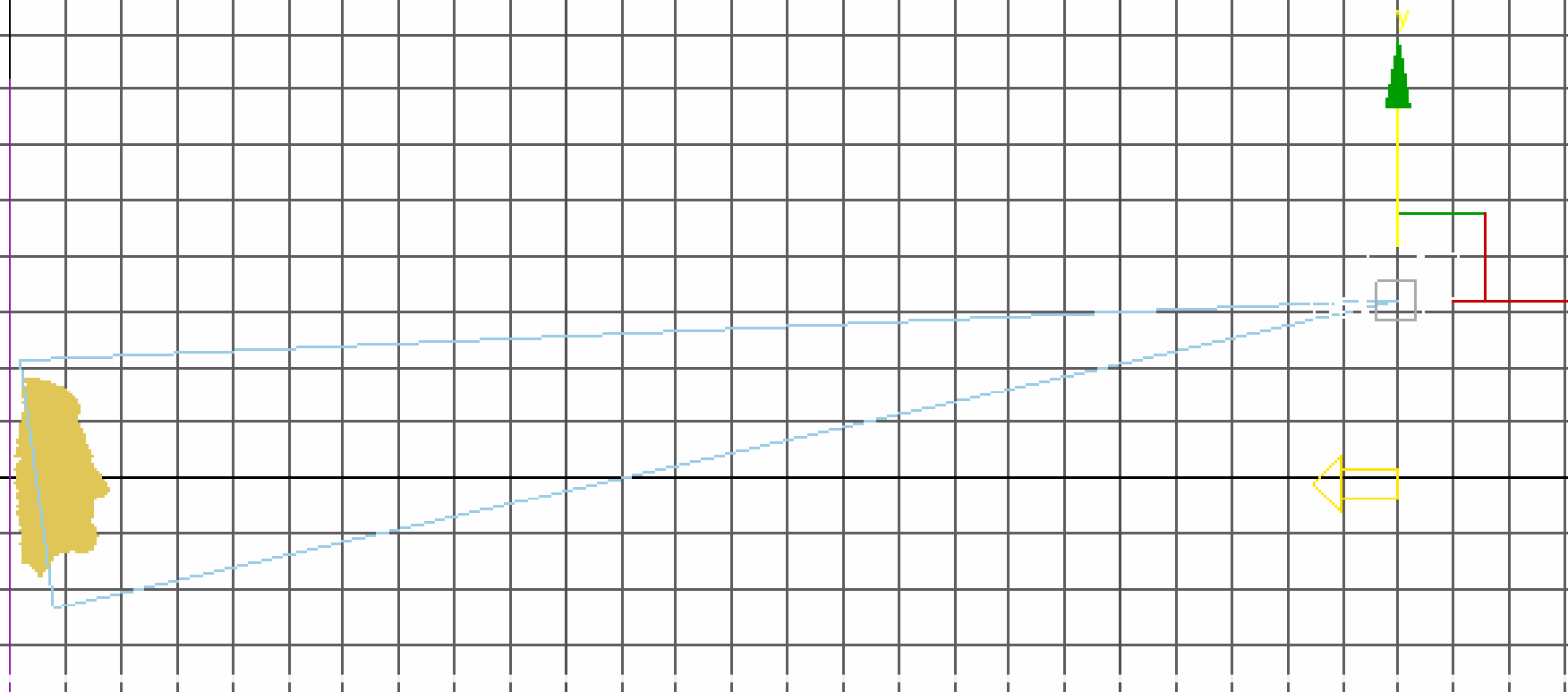数字莫尔条纹的产生：(a)待测物体原型；(b)经过物体高度分布扭曲的投影条纹；(c)和同频率条纹叠加产生的含有高频噪声的莫尔图样
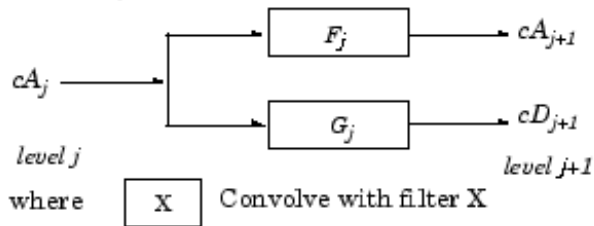
3ds Max设置图

(a)

(b)

(c)

(d)

叠加条纹初始相位为0，π，δ，δ + π的，含有高
频条纹的莫尔图样

一维和二维平稳小波变化

One-Dimensional SWT

Decomposition step

$cA_j \longrightarrow F_j \longrightarrow cA_{j+1}$

$\longrightarrow G_j \longrightarrow cD_{j+1}$

level j   *level j+1*

where $\boxed{X}$ Convolve with filter X

Initialization $cA_0 = s$

$F_j \longrightarrow \boxed{\uparrow 2} \longrightarrow F_{j+1}$

Initialization $F_0 = Lo\_D$

$G_j \longrightarrow \boxed{\uparrow 2} \longrightarrow G_{j+1}$
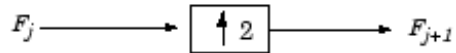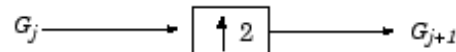
Initialization $G_0 = Hi\_D$

where $\boxed{\uparrow 2}$ Upsample

Two-Dimensional SWT

Decomposition step

$cA_j \longrightarrow$

rows $F_j \longrightarrow$ *columns* $F_j \longrightarrow cA_{j+1}$

columns $G_j \longrightarrow cD_{j+1}^{(h)}$ *horizontal*

rows $G_j \longrightarrow$ *columns* $F_j \longrightarrow cD_{j+1}^{(v)}$ *vertical*

columns $G_j \longrightarrow cD_{j+1}^{(d)}$ *diagonal*
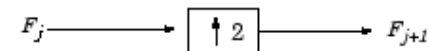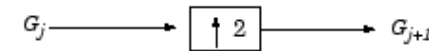
where

$\boxed{X}$ *rows*   Convolve with filter X the rows of the entry

$\boxed{X}$ *columns*   Convolve with filter X the columns of the entry

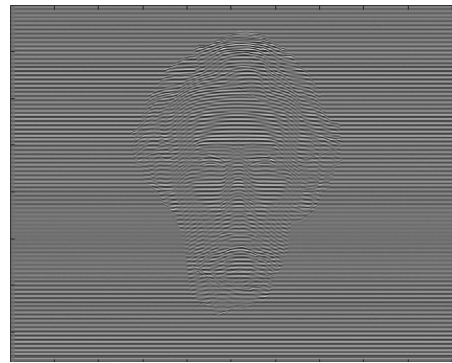**Initialization** $cA_0 = s$ for the decomposition initialization

$F_j \longrightarrow \boxed{\uparrow 2} \longrightarrow F_{j+1}$

Initialization $F_0 = Lo\_D$

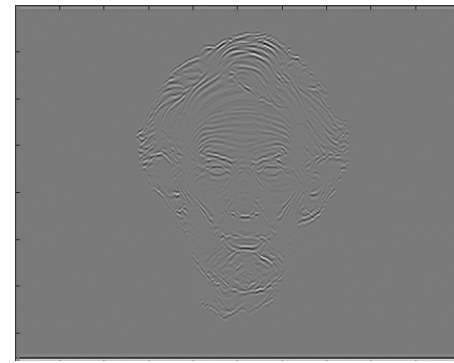$G_j \longrightarrow \boxed{\uparrow 2} \longrightarrow G_{j+1}$

Initialization $G_0 = Hi\_D$

where $\boxed{\uparrow 2}$ Upsample

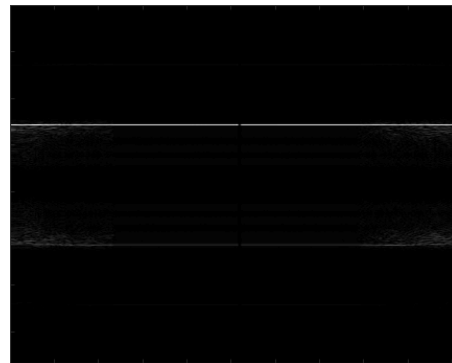**Note** $size(cA_j) = size(cD_j^{(h)}) = size(cD_j^{(v)}) = size(cD_j^{(d)}) = s$

where $s = size\ of\ the\ analyzed\ image$
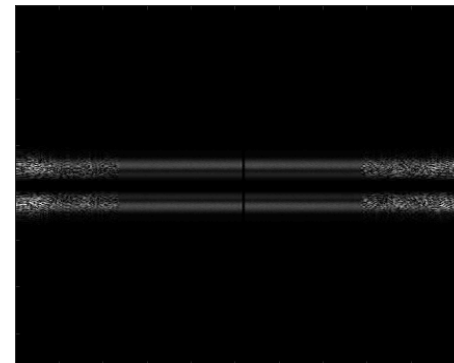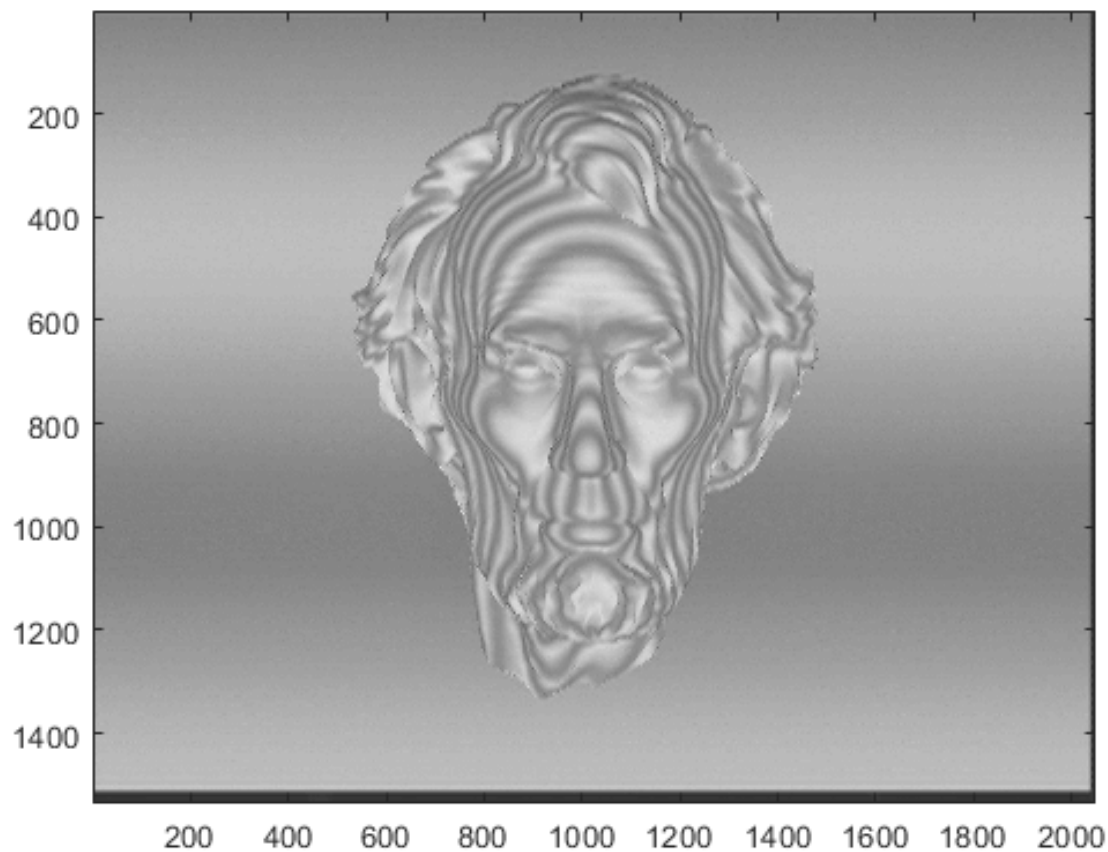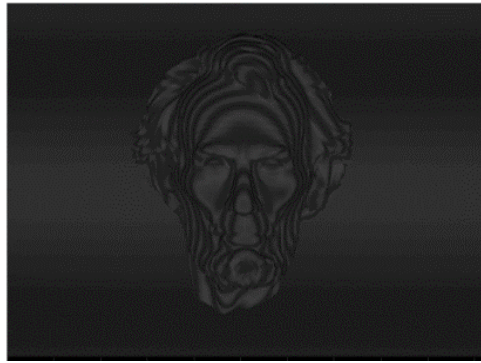
(a)　　　　　　　　　　　　(b)

(c)　　　　　　　　　　　　(d)

平稳小波傅立叶滤波林肯脸条纹叠加图：(a)第三层水平分解系数；
(b)滤波后第三层分解层水平系数；(c)图(a)中系数傅立叶变化后的频
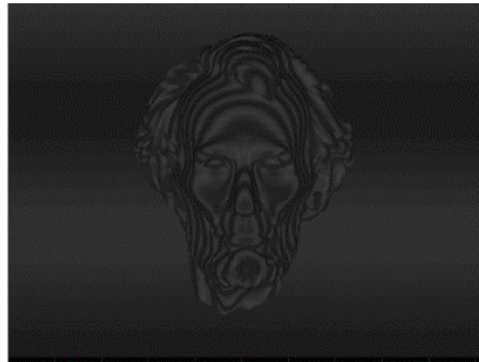谱幅度；(d)图(c)中频谱经过低通滤波后的频谱幅度

经过平稳小波变换-傅里叶滤波后的莫尔图样，已无高频条纹

(a)
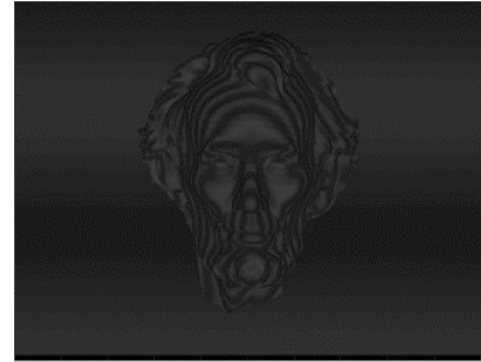
(b)

(c)

(d)

叠加条纹初始相位为0，π，δ，δ＋π的，
已滤除高频条纹的莫尔图样

$$I_1(x, y) = a(x, y) + b(x, y)\sin\Phi(x, y)$$

$$I_2(x, y) = a(x, y) + b(x, y)\sin(\Phi(x, y) + \pi)$$

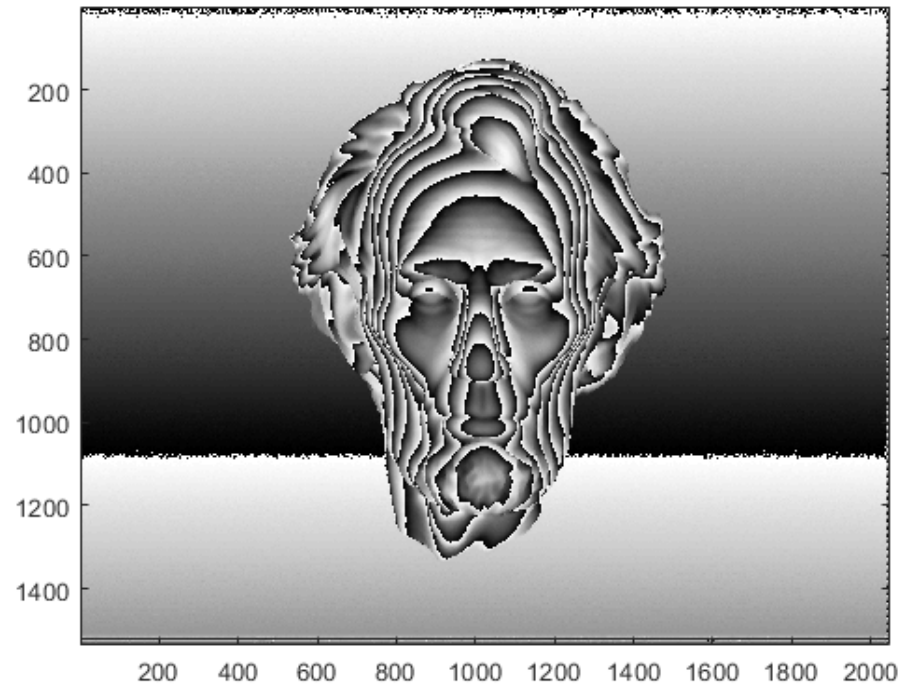$$I_3(x, y) = a(x, y) + b(x, y)\sin(\Phi(x, y) + \delta)$$

$$I_4(x, y) = a(x, y) + b(x, y)\sin(\Phi(x, y) + \delta + \pi)$$

$$\Phi(x, y) = \text{artan}\left(\frac{\left(I_2(x, y) - I_1(x, y)\right)sin\delta}{\left(I_4(x, y) - I_3(x, y) - I_2(x, y) + I_1(x, y)\right)sin\delta} \right)$$

$$\Phi(\mathrm{x}, y) \in [-\pi, \ \pi]$$
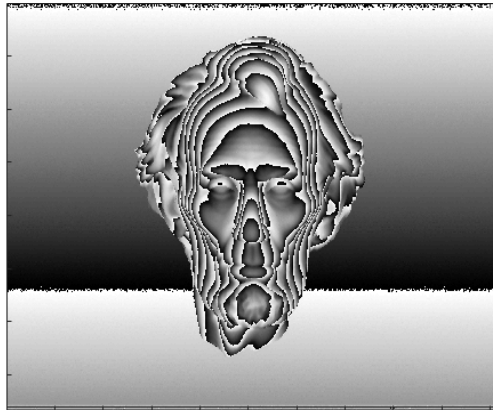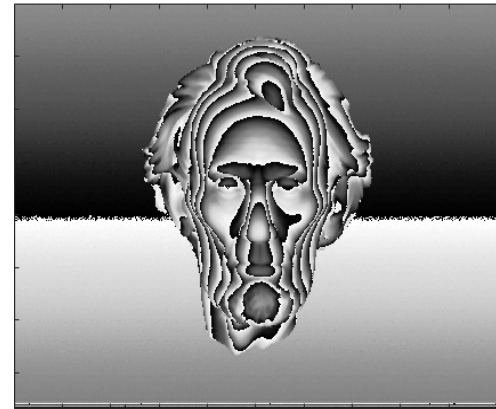

由四张不同相位的莫尔条纹代入相位计算公
式得到的折叠相位

$$\Phi_{12} \begin{cases} \Phi_1(x,y) - \Phi_2(x,y), & \Phi_1 > \Phi_2 \\ \Phi_1(x,y) - \Phi_2(x,y) + 2\pi, & \text{其他} \end{cases}$$
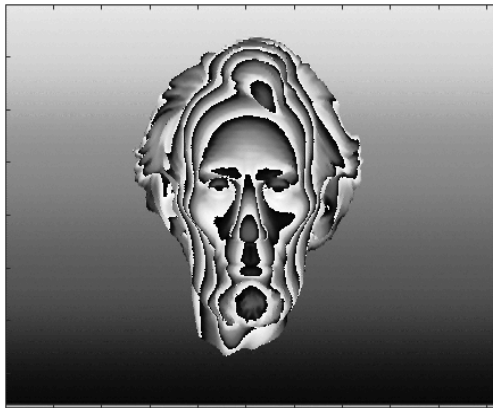
$$\varphi(x,y) = \Phi_1(x,y) + (2\pi)Round\left(\frac{\left(\frac{\lambda_{12}}{\lambda_1}\right)\Phi_{12}(x,y) - \Phi_1(x,y)}{2\pi}\right)$$
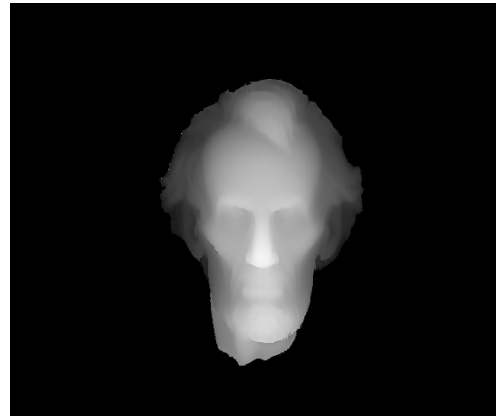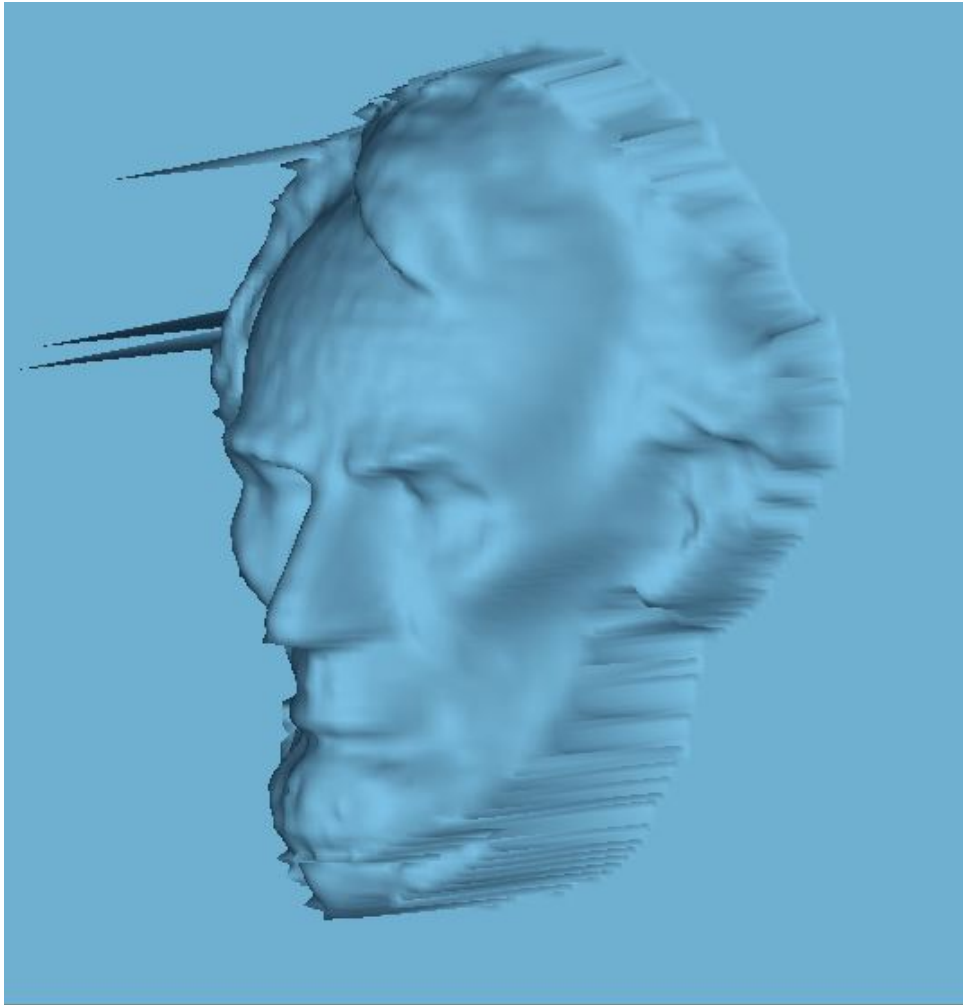
(a)

(b)

(c)

(d)

林肯脸测量结果：(a)条纹周期6个像素的折叠相位；(b)条纹周期8个像素的折叠相位；(c)条纹周期10个像素的折叠相位；(d)利用莫尔波长得到的展开相位；

$$h(x, y) = \frac{\lambda_1}{2\pi} \varphi(x, y)$$

数字莫尔三维测量方法得到的林肯脸
三维重建模型

总结

✓ 相位-高度映射关系

✓ 数字莫尔条纹的生成：叠加；高频条纹滤除；

✓ 高度的计算：相位提取；相位展开；高度转换；

❑ MATLAB自带GPU array 加速

❑ 多种滤波方法的尝试