

High-resolution, high-speed 3D perception and sensing data streaming

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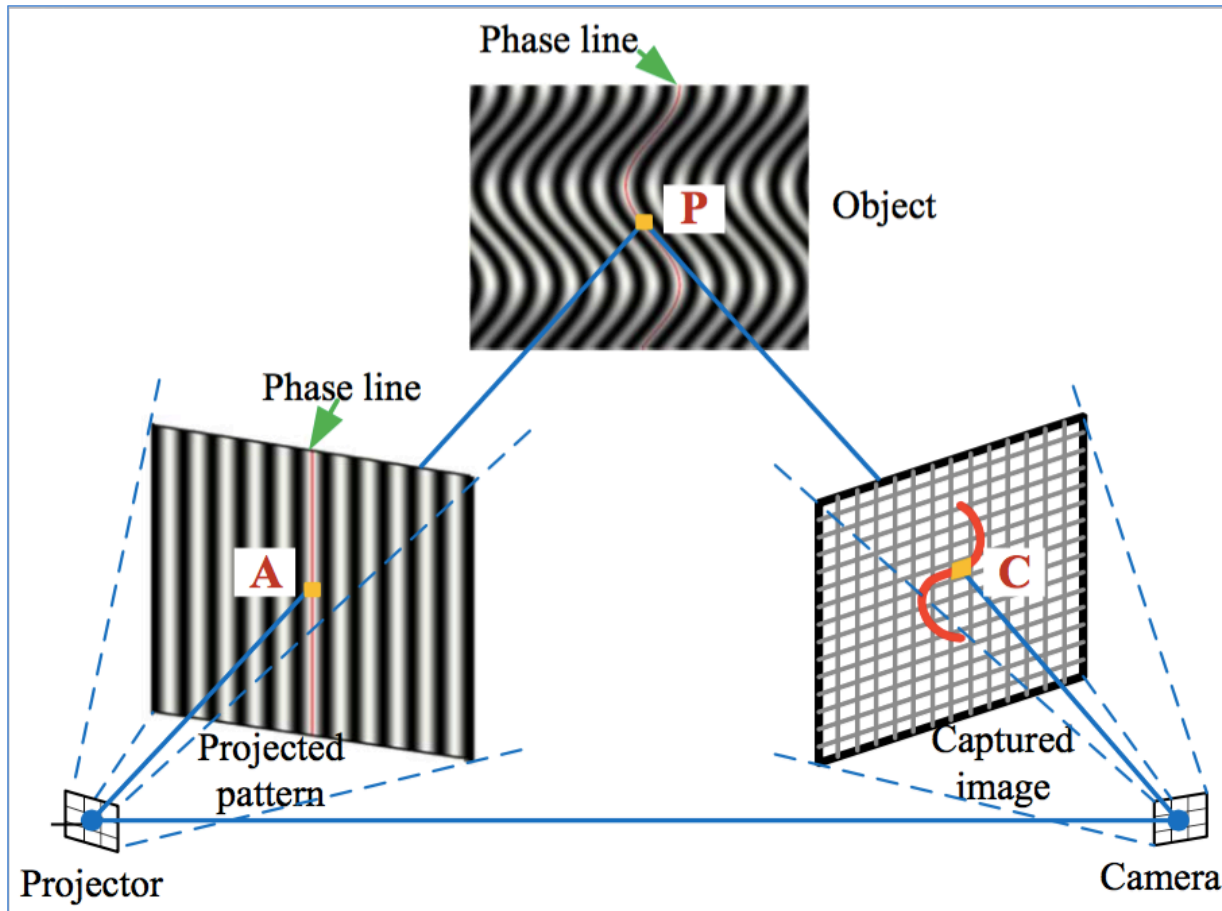
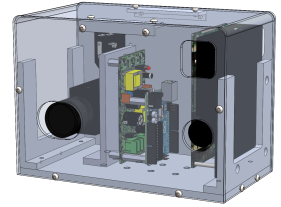
December 3, 2019

Outline

- High-speed, high-resolution 3D sensing
- Holostream: 3D video streaming
- Applications



Structured light technology



Three-step phase shifting algorithm

- Phase shifted fringe images

$$I_1(x, y) = I'(x, y) + I''(x, y) \cos[\phi(x, y) - 2\pi / 3]$$

$$I_2(x, y) = I'(x, y) + I''(x, y) \cos[\phi(x, y)]$$

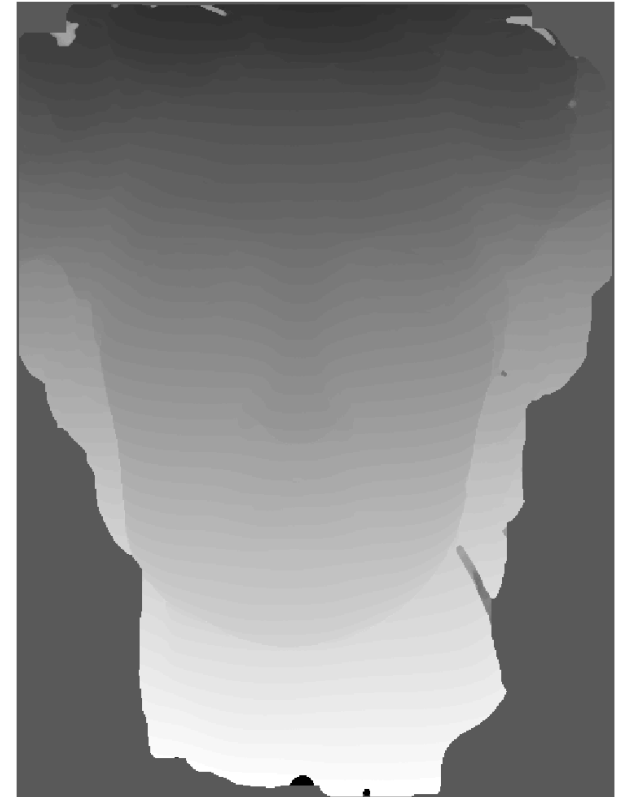
$$I_3(x, y) = I'(x, y) + I''(x, y) \cos[\phi(x, y) + 2\pi / 3]$$

- Wrapped phase

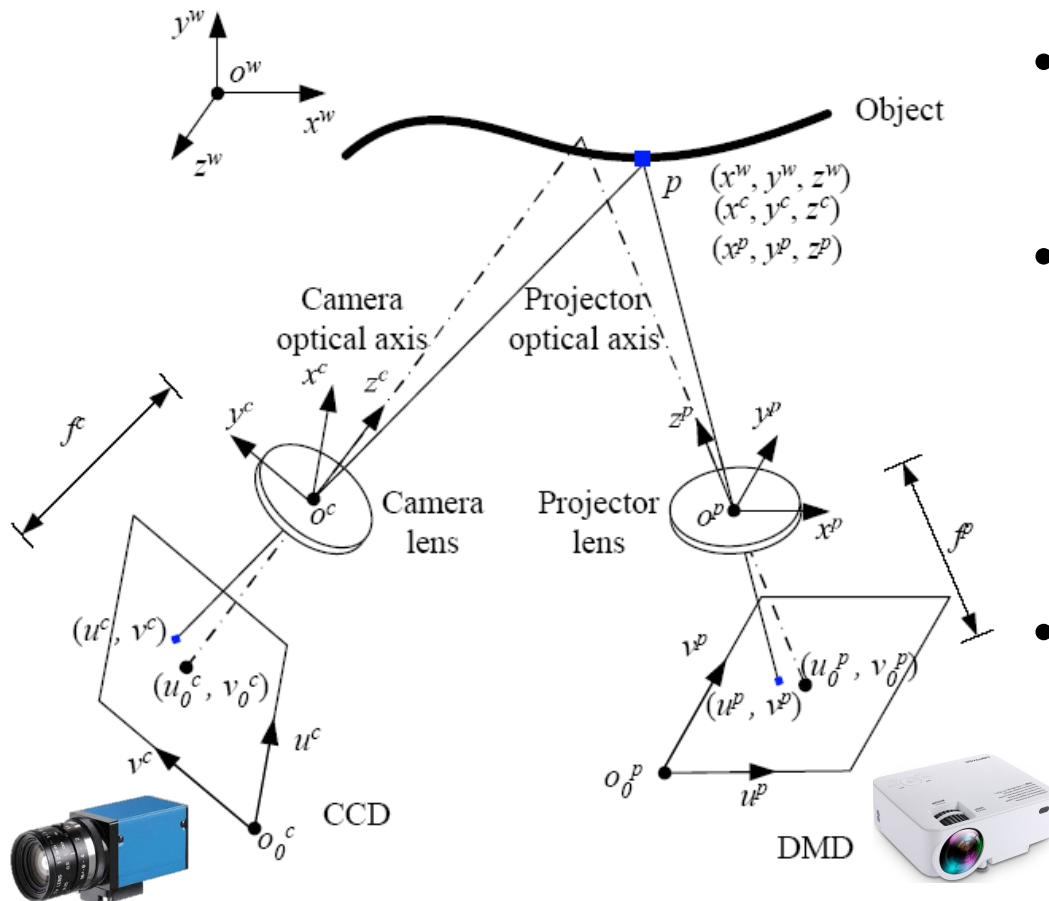
$$\phi(x, y) = \tan^{-1} \frac{\sqrt{3}[I_1(x, y) - I_3(x, y)]}{2I_2(x, y) - I_1(x, y) - I_3(x, y)}$$

- 2D texture

$$I'(x, y) = [I_1(x, y) + I_2(x, y) + I_3(x, y)] / 3$$



Structured light system calibration



S. Zhang and P. S. Huang, Opt. Eng. 45(8), 2006.

- Perspective transformation

$$s\{u, v, 1\}^T = A[R, t]\{x^w, y^w, z^w, 1\}^T$$

- Extrinsic parameters

$$R = \begin{bmatrix} r_{00} & r_{01} & r_{02} \\ r_{10} & r_{11} & r_{12} \\ r_{20} & r_{12} & r_{22} \end{bmatrix}, \quad t = \begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix}$$

- Intrinsic parameters

$$A = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \quad \begin{array}{l} \alpha, \beta: \text{focal lengths} \\ \gamma: \text{skew effect} \\ (u_0, v_0): \text{principal point} \end{array}$$

3D coordinate calculation

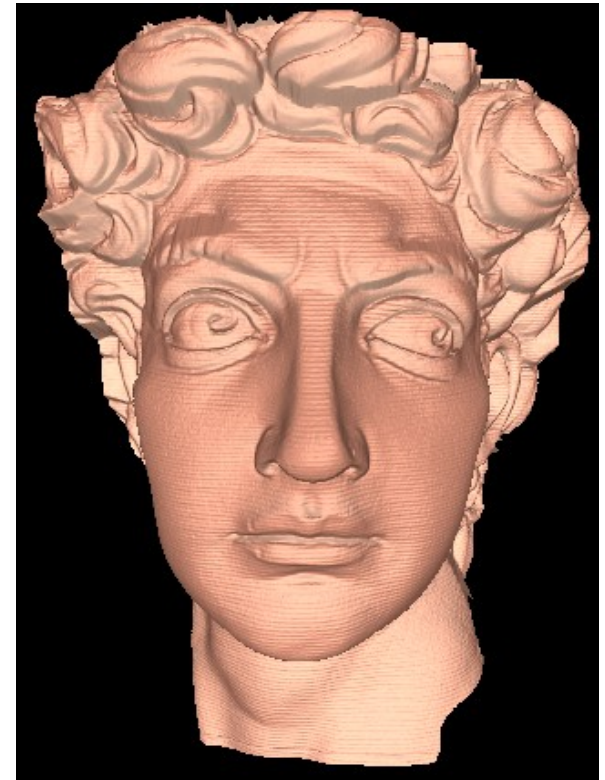
- From world to camera image coordinates

$$s^c \begin{Bmatrix} u^c \\ v^c \\ 1 \end{Bmatrix} = \begin{bmatrix} \alpha^c & \gamma^c & u_0^c \\ 0 & \beta^c & v_0^c \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{00}^c & r_{01}^c & r_{02}^c & t_x^c \\ r_{10}^c & r_{11}^c & r_{12}^c & t_y^c \\ r_{20}^c & r_{21}^c & r_{22}^c & t_z^c \end{bmatrix} \begin{Bmatrix} x^w \\ y^w \\ z^w \\ 1 \end{Bmatrix}$$

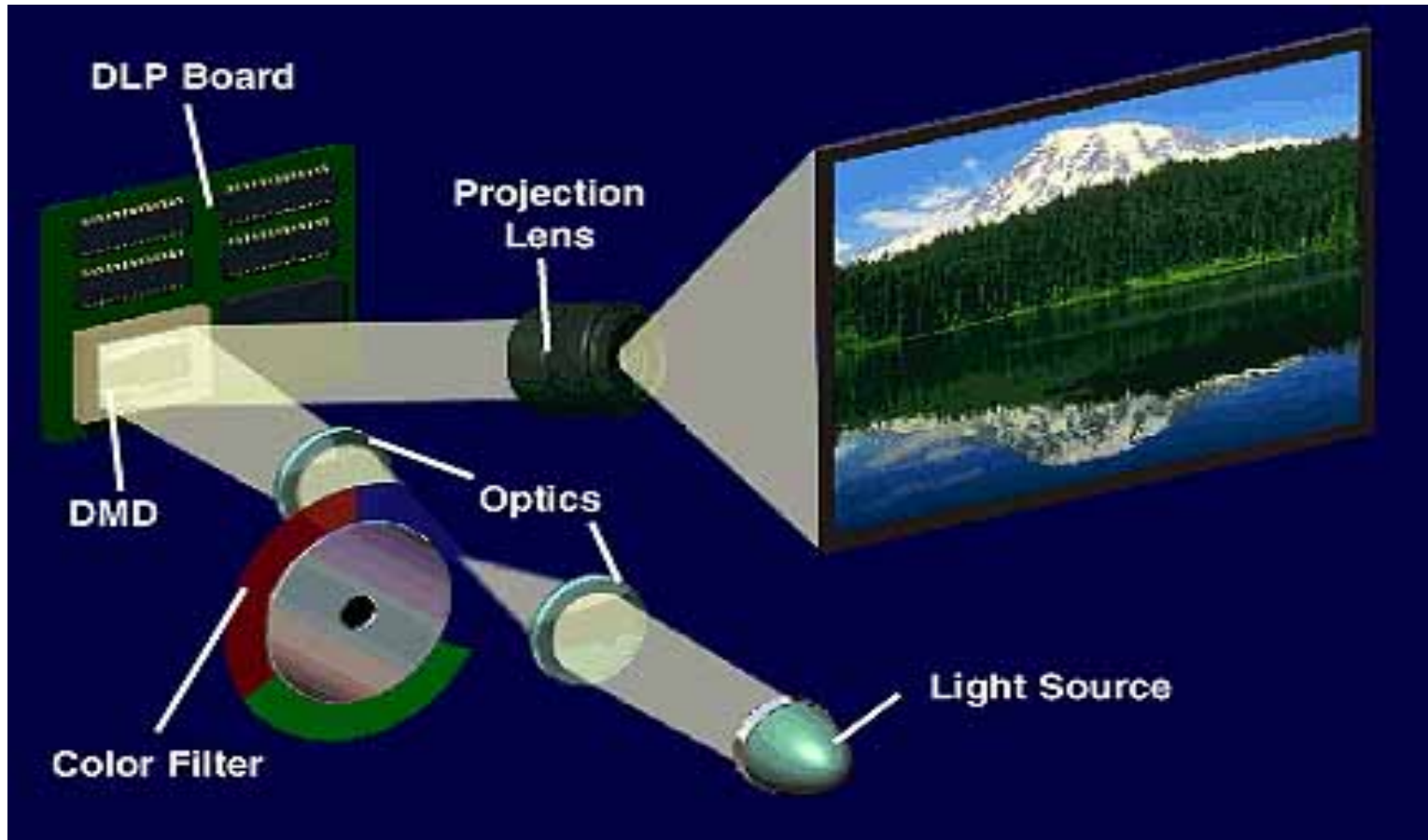
- From world to projector image coordinates

$$s^p \begin{Bmatrix} u^p \\ v^p \\ 1 \end{Bmatrix} = \begin{bmatrix} \alpha^p & \gamma^p & u_0^p \\ 0 & \beta^p & v_0^p \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{00}^p & r_{01}^p & r_{02}^p & t_x^p \\ r_{10}^p & r_{11}^p & r_{12}^p & t_y^p \\ r_{20}^p & r_{21}^p & r_{22}^p & t_z^p \end{bmatrix} \begin{Bmatrix} x^w \\ y^w \\ z^w \\ 1 \end{Bmatrix}$$

- Absolute phase constraint: $u^p = f[\Phi_a(u^c, v^c)]$
- 7 equations
- 7 unknowns: $(x^w, y^w, z^w), u^p, v^p, s^c, s$

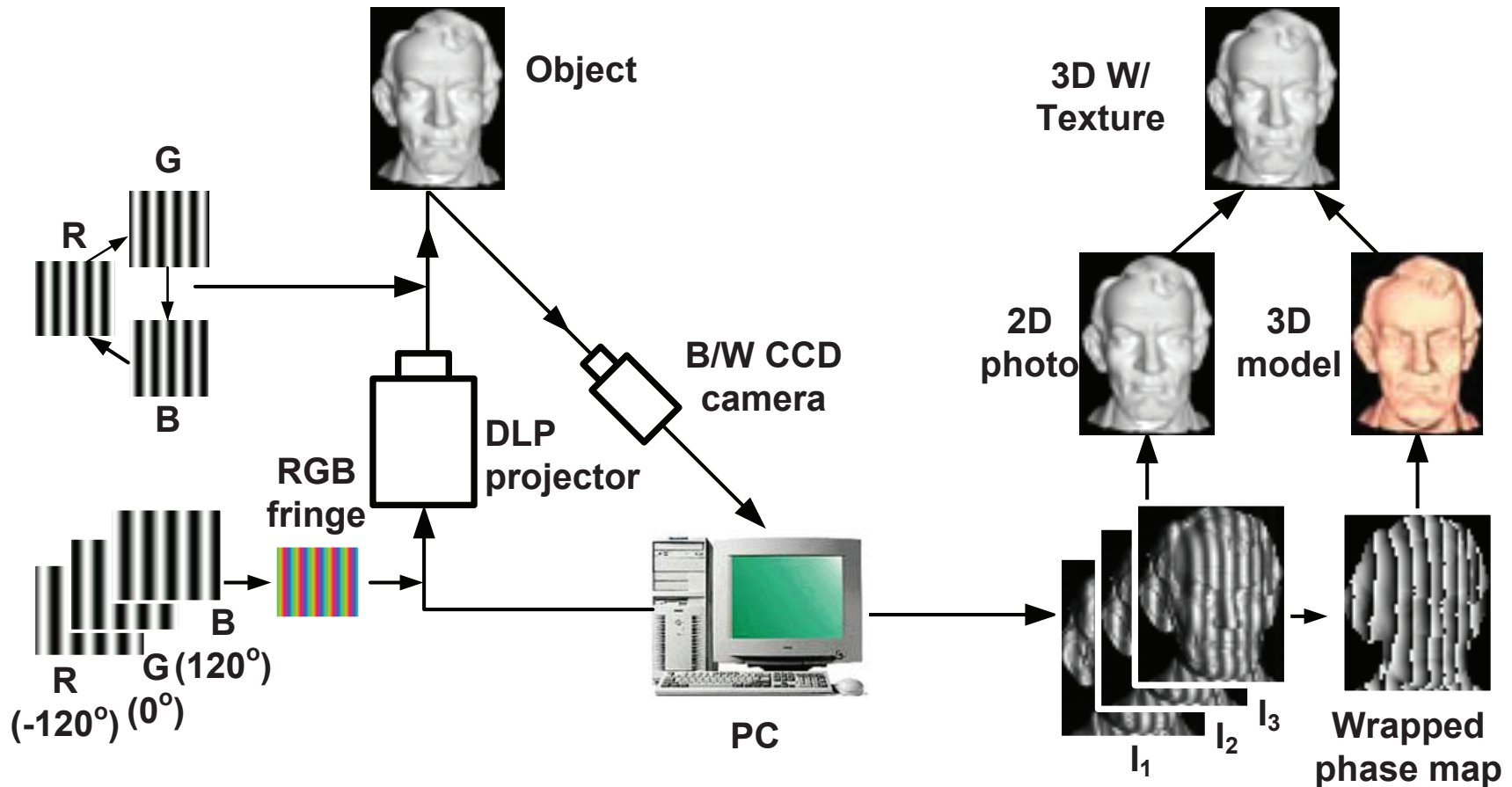


Single-chip DLP projector



Pictures from www.ti.com

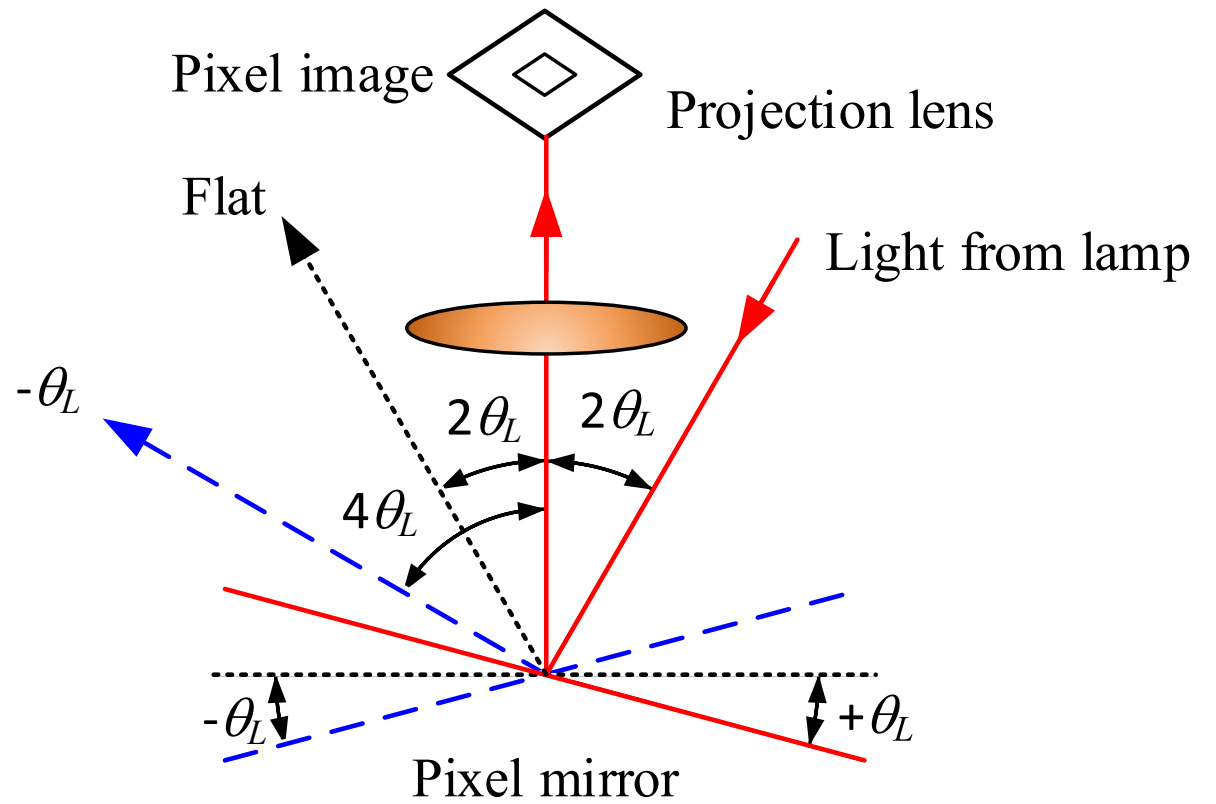
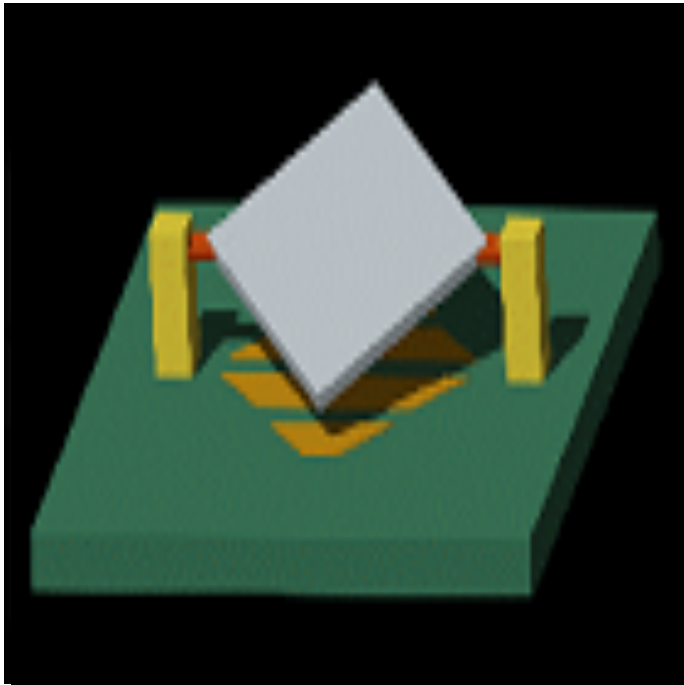
Real-time 3D sensing



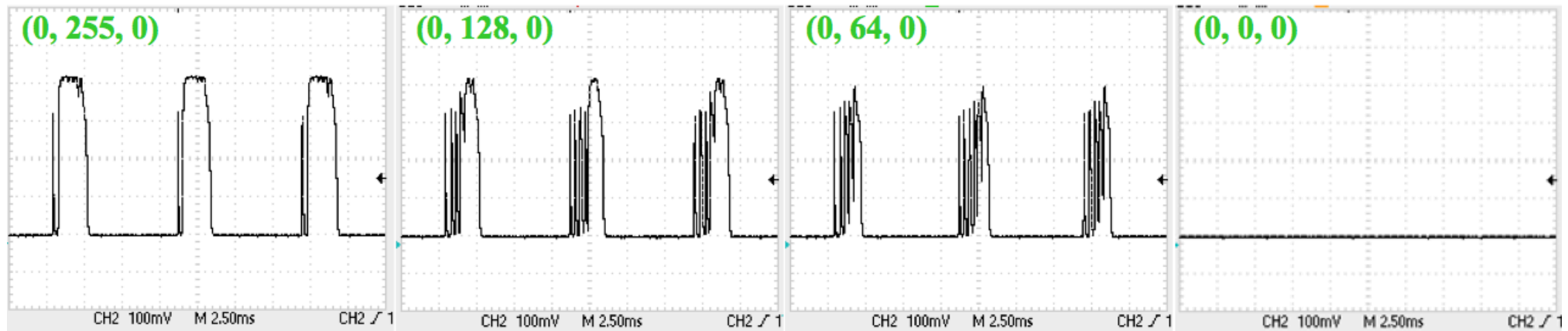


Video was created for Irish rock band U2

DLP technology



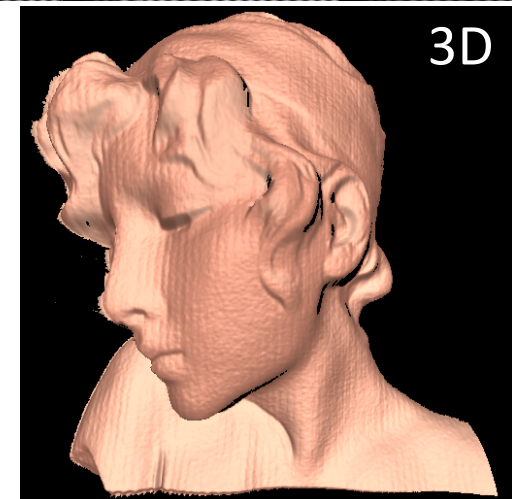
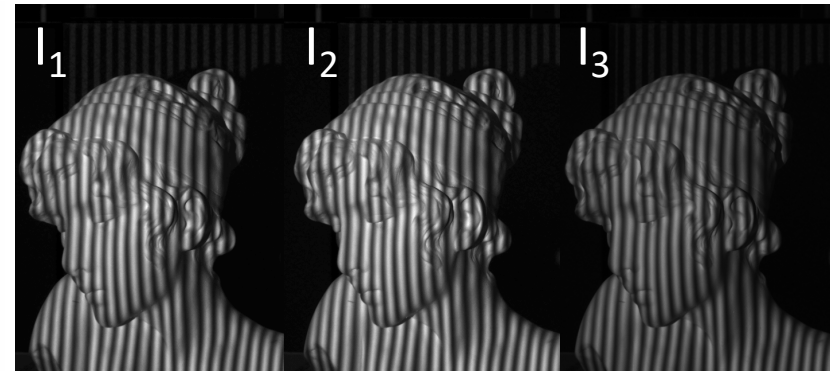
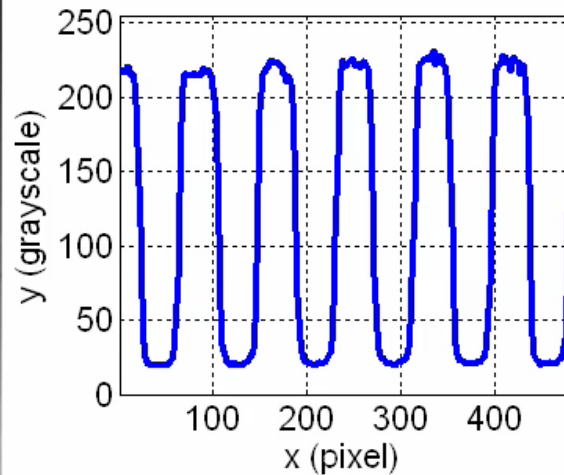
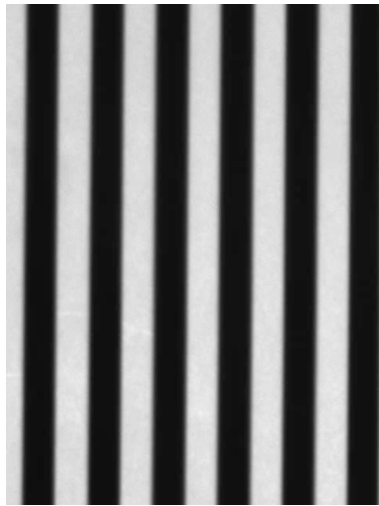
Limitations of using sinusoidal patterns



Projected timing signals with different grayscale input

- Precise synchronization requirement
- Speed limit of 120 Hz
- Projector's nonlinear gamma effect

Binary defocusing method



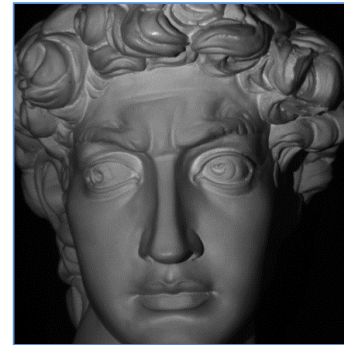
- DLP Discovery 4100 (0.7")
 - Resolution: 1024 X 768
 - 8-bit image switching rate: 291 fps
 - 1-bit binary image switching rate: **32,552** fps

Dithering/halftoning

- Dithering (halftoning)
 - Approximate an image with fewer colors or bits
 - Adopted extensively in printing (halftoning)



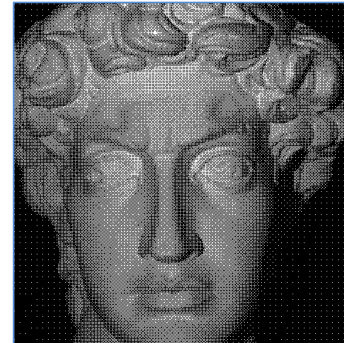
- Methods
 - Single thresholding
 - Random dithering
 - Ordered dithering (Bayer, 1973)
 - Error-diffusion dithering (Floyd & Steinberg, 1976; Stucki, 1981)



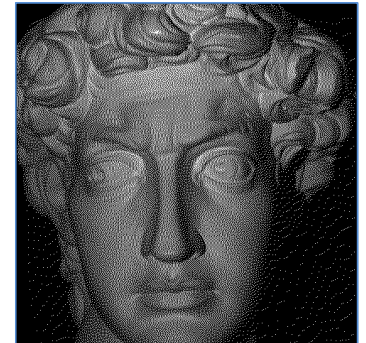
8-bit



Thresholding



Bayer



Error diffusion

Comparing results



Fringe pattern
(Square binary)



3D result
(Square binary)

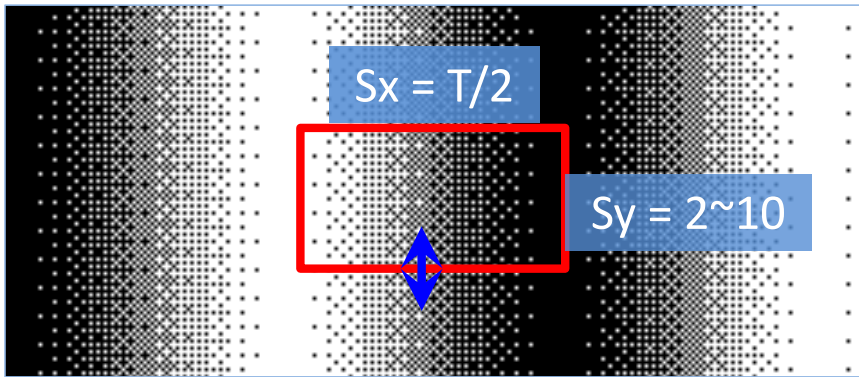


Fringe pattern
(Error diffusion)



3D result
(Error diffusion)

Dithering optimization



- Objective function

$$\min \| I(x, y) - G(x, y) \otimes B(x, y) \|$$

- $I(x, y)$: ideal sinusoidal
- $G(x, y)$: Gaussian filter
- $B(x, y)$ binary pattern

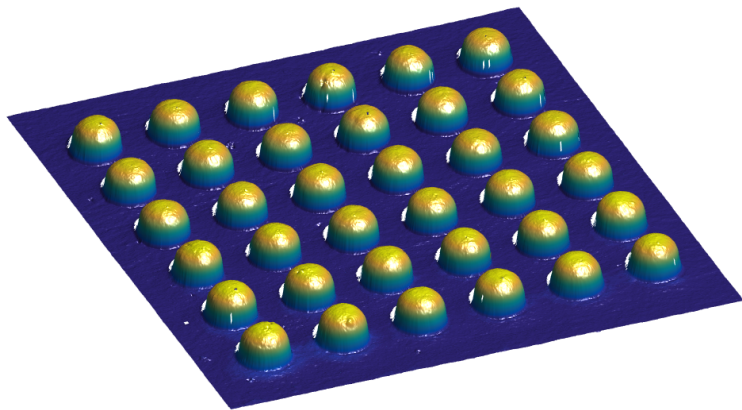


3D result
(Error diffusion)

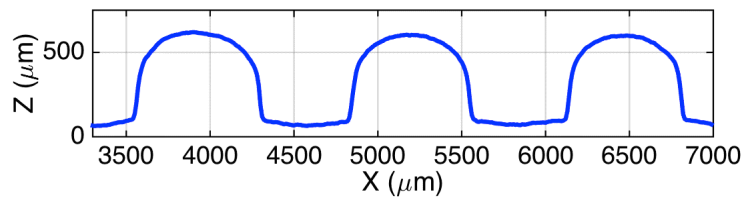


3D result
(Optimized dithering)

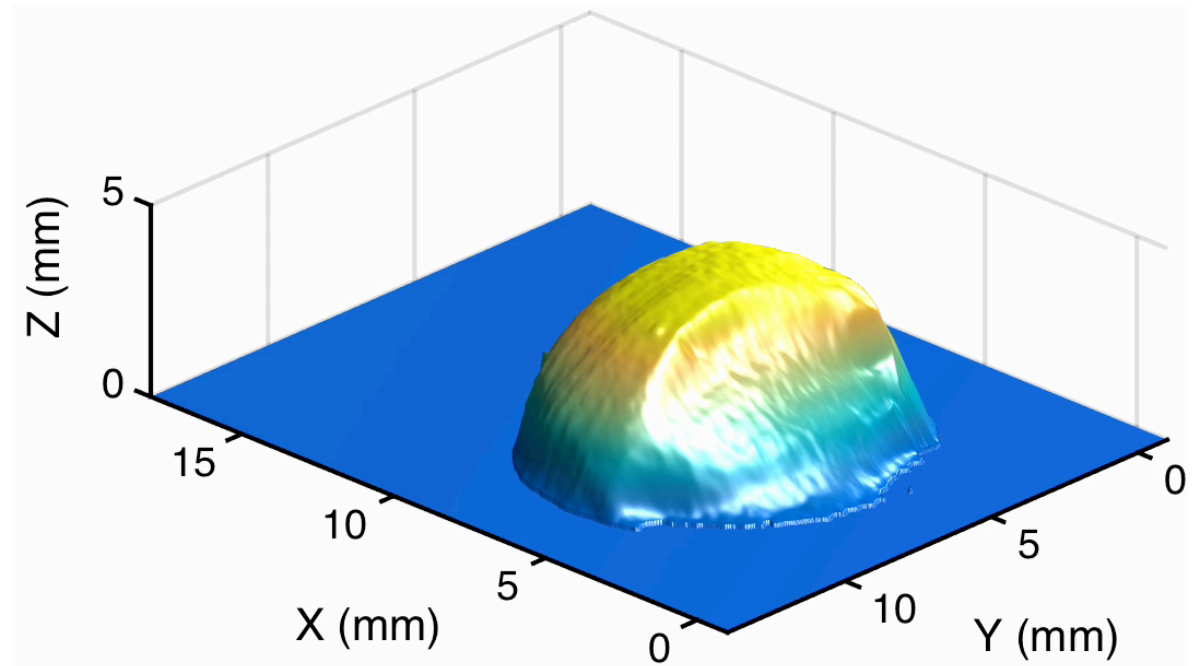
Microstructure imaging



3D

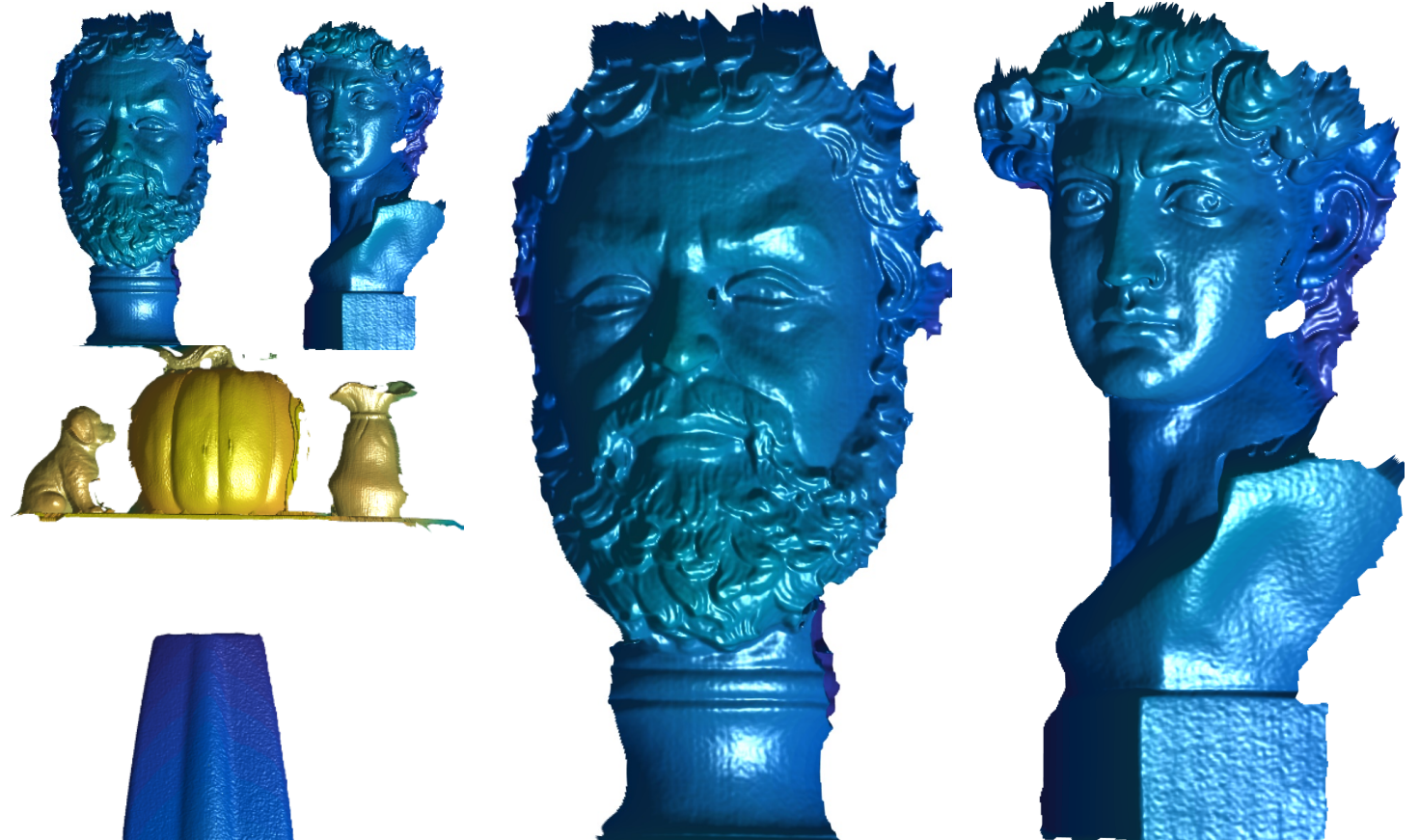
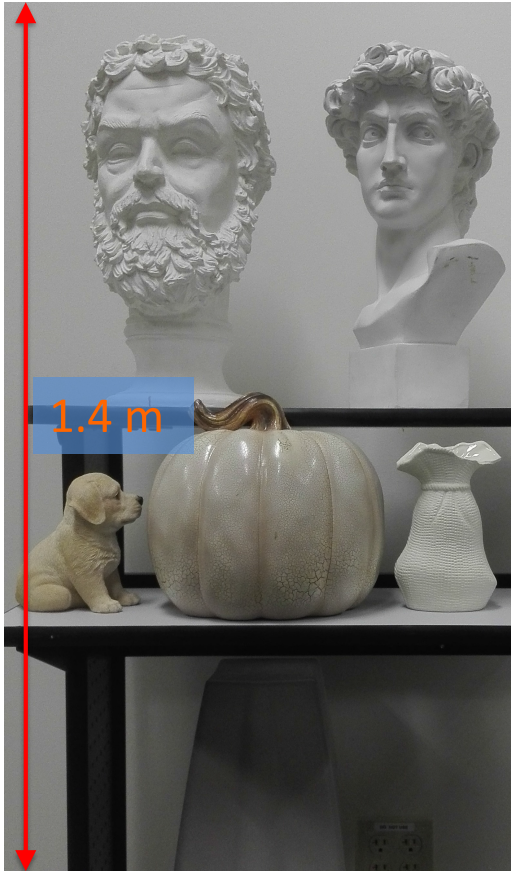


Cross section



- 3D imaging rate: 500 Hz
- Spatial resolution: $15 \mu\text{m}$
- Depth resolution: $2 \mu\text{m}$

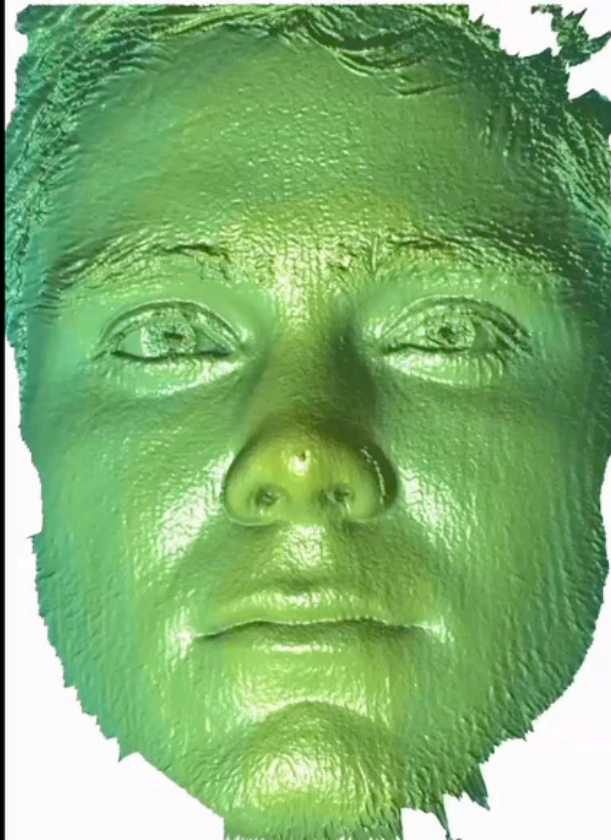
Large-scale imaging



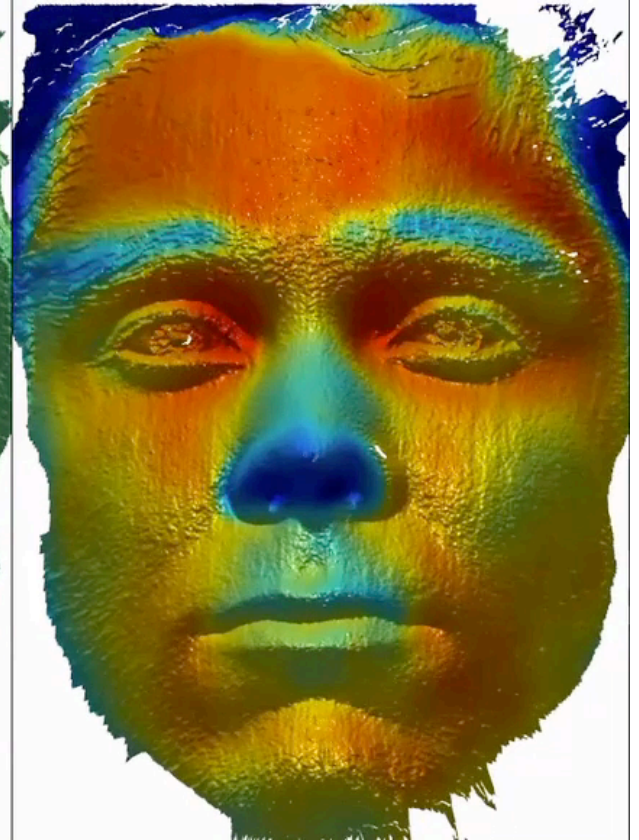
Multimodal imaging



2D texture



3D geometry



3D + temperature

Holostream: 3D video communication

Smart phones with 3D cameras



Apple



Samsung



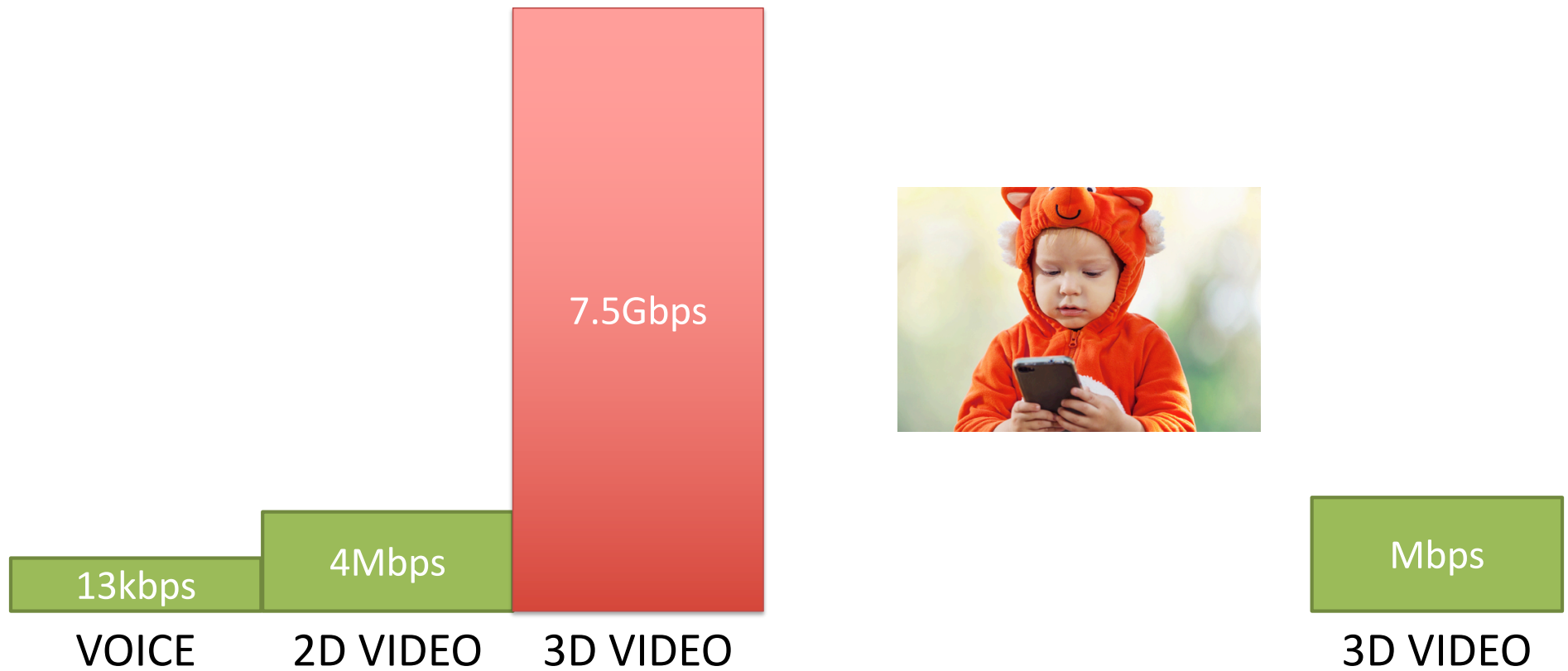
Huawei



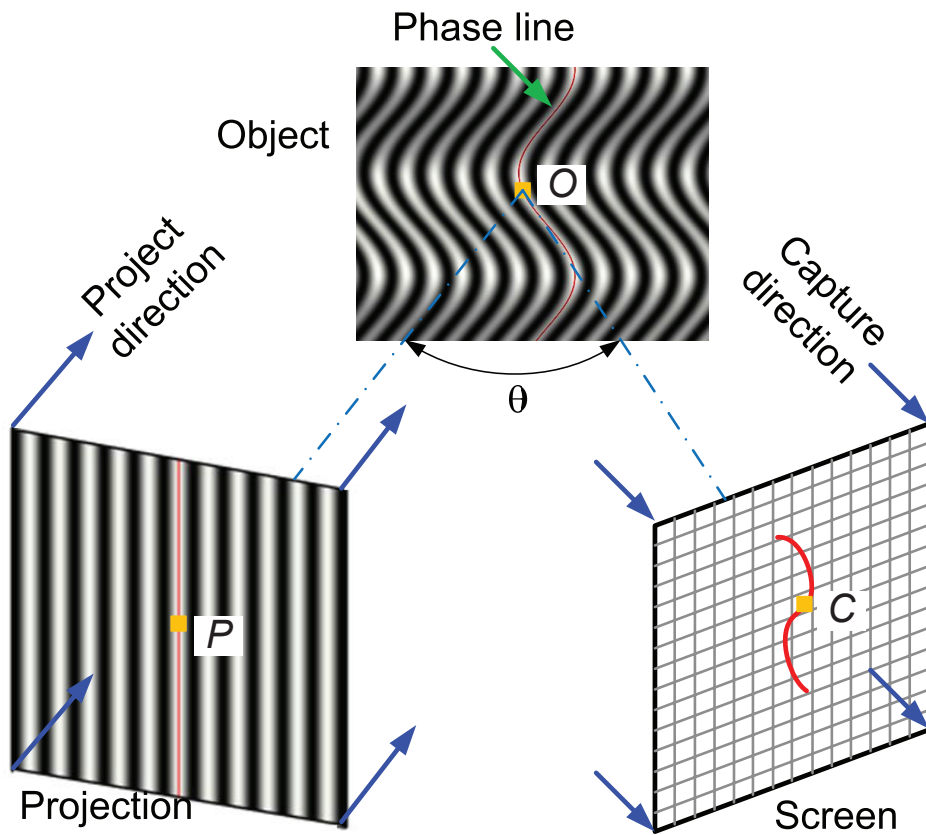
Xiaomi

Over 100M phones with a 3D sensor shipped in 2018

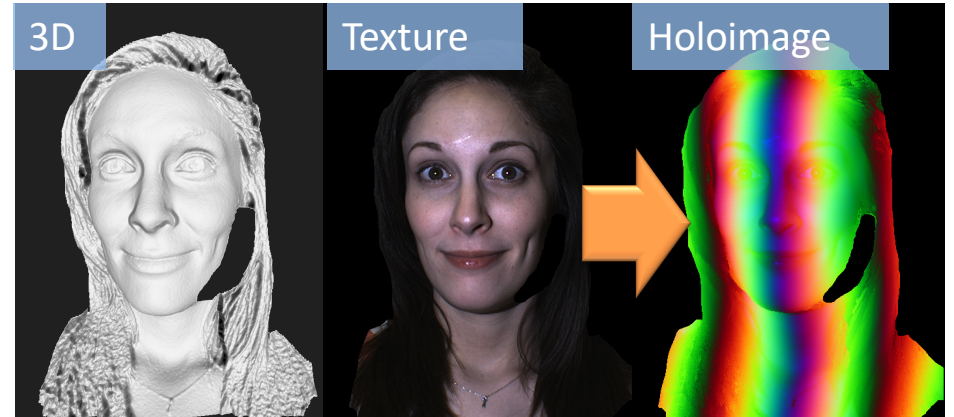
Why not 3D video communication?



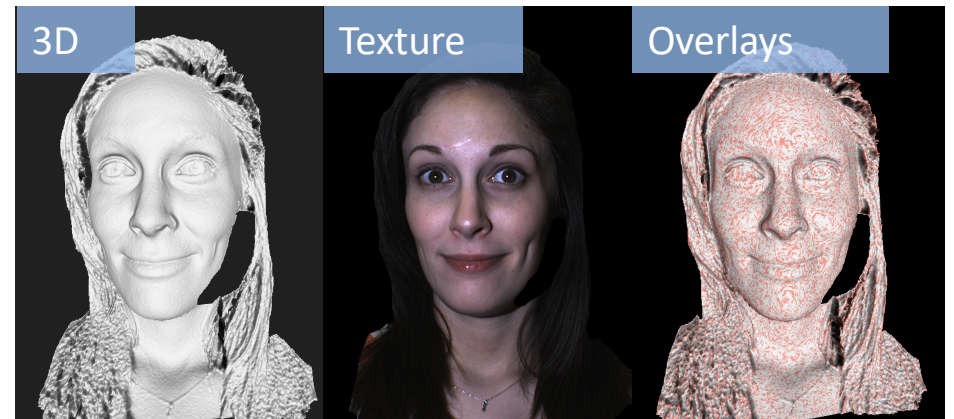
3D compression method



T. Bell et al., Appl. Opt. 56(33), (2017)



Encoding



Decoding

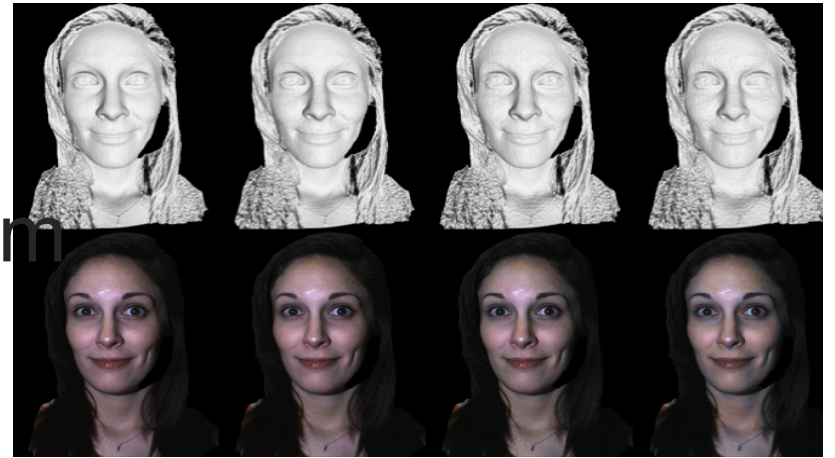


Original
7.5 Gbps

Lossless (129:1)
60 Mbps



Holostream



Purdue University

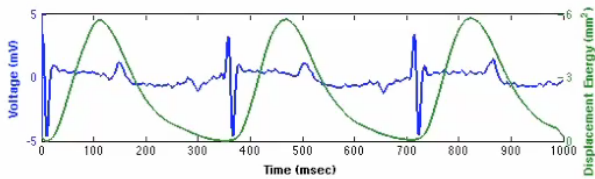
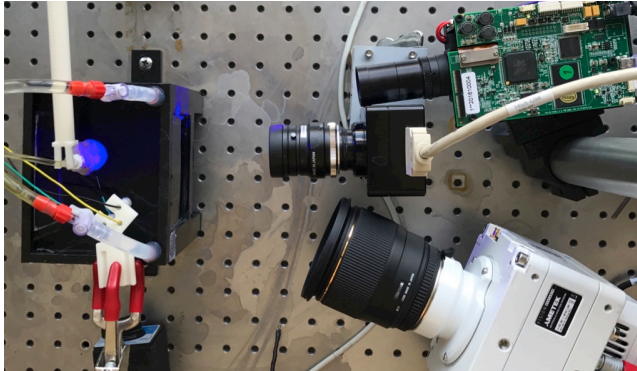
Mashable

**FaceTime is about to
become a relic**

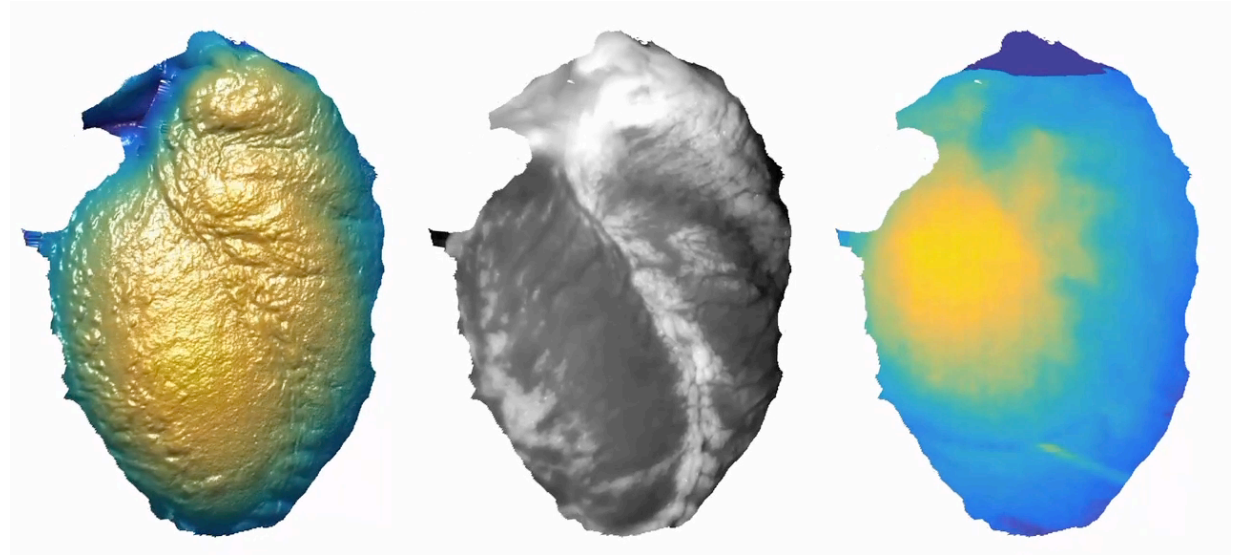


Applications

Cardiac imaging



Strain



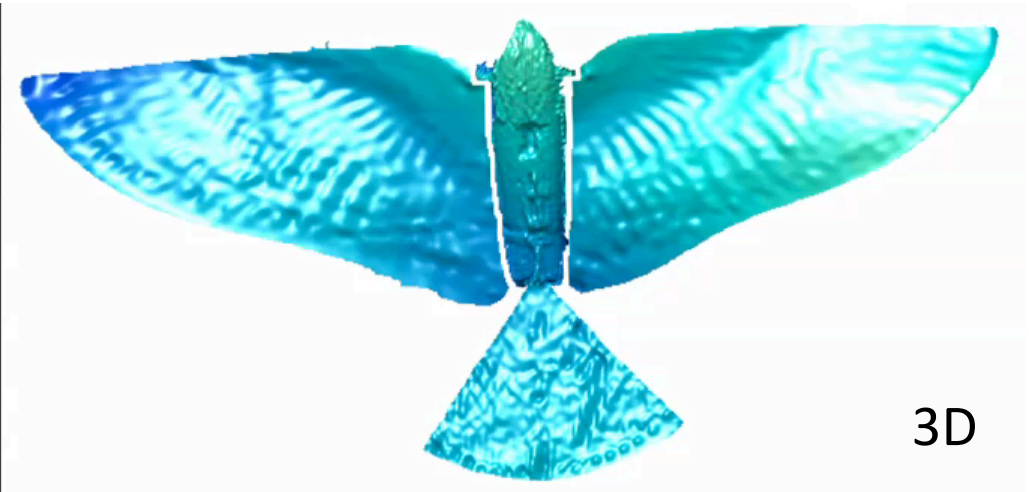
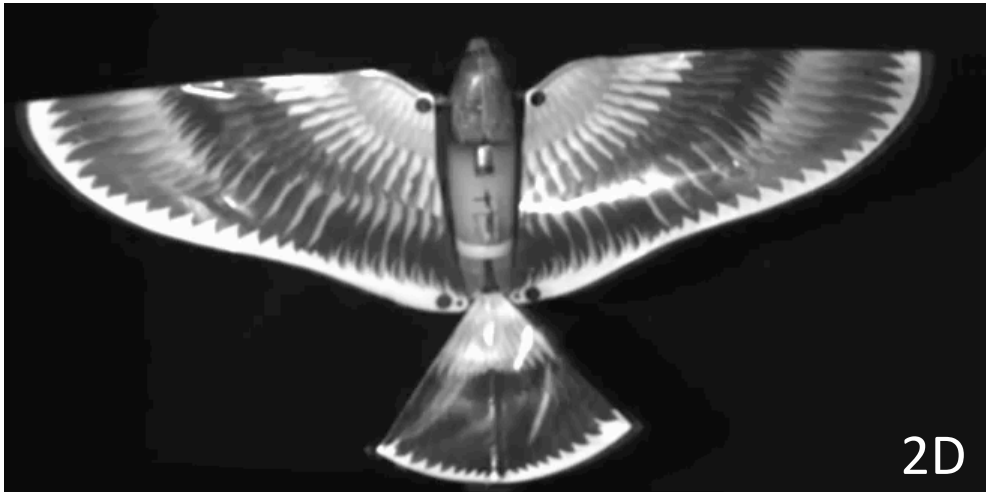
3D

2D texture

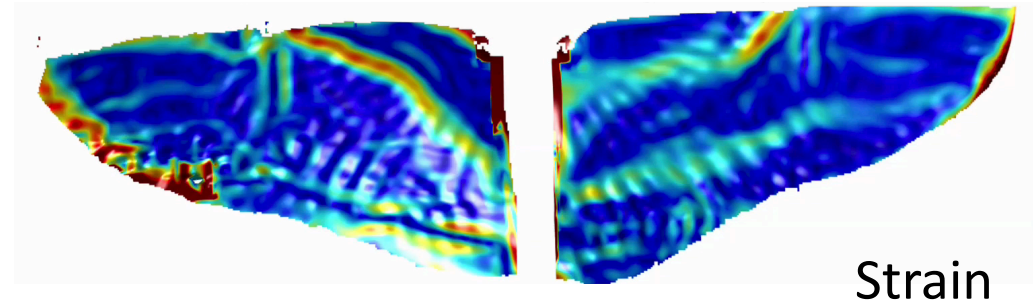
Fluorescence

- Rabbit heart rate: 180 beats/min
- 3D imaging rate: 2,000 Hz
- Image resolution: 800 x 600

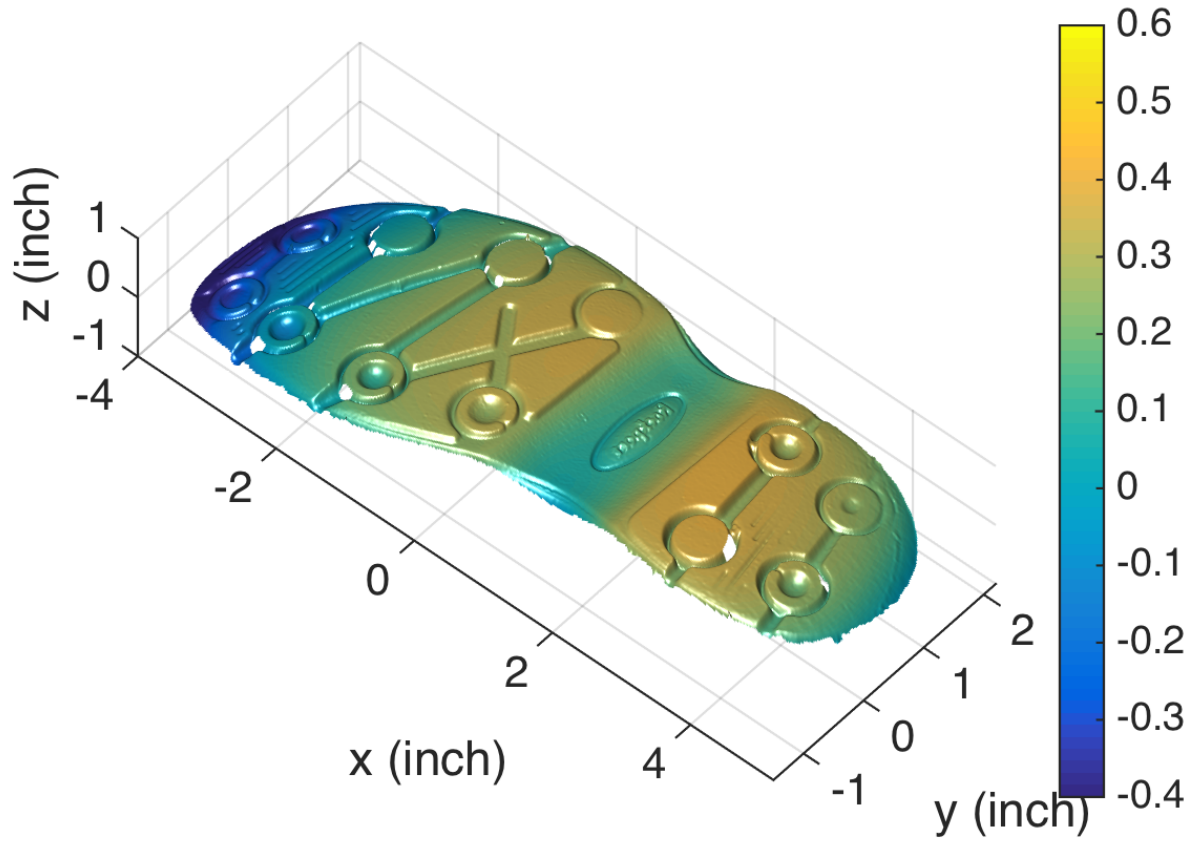
Flapping wing robot



- Flapping rate: 21 cycles/sec
- 3D imaging rate: 5,000 Hz
- Resolution: 800 x 600



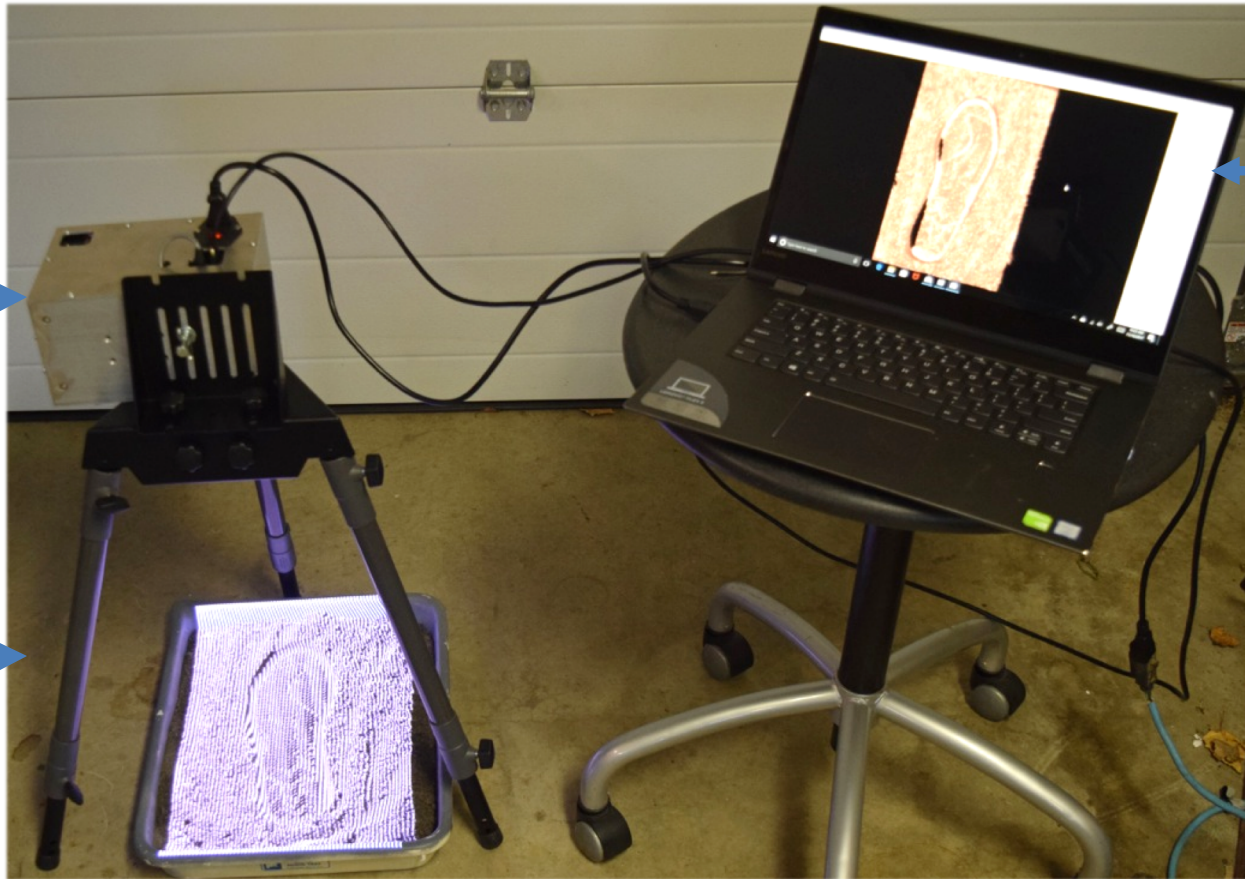
Forensic science



Forensic science

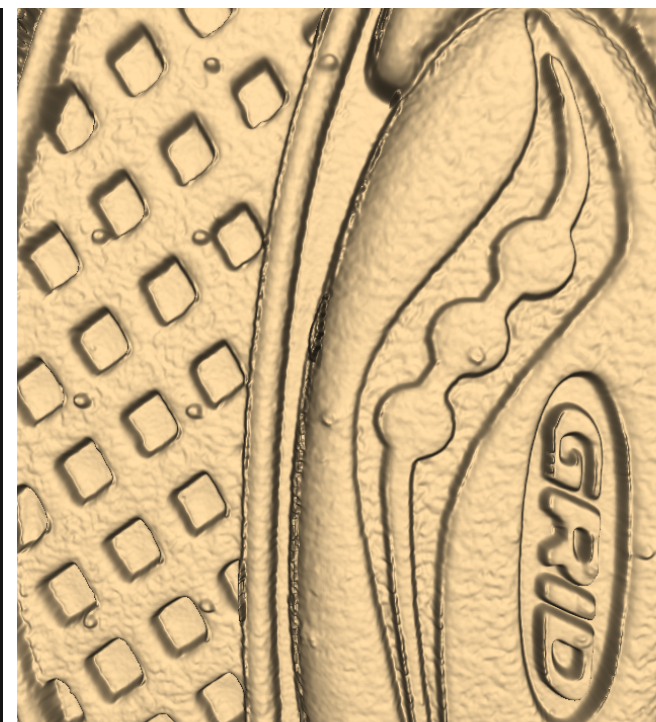
3D Scanner
USB Cable
Power Cable
Power Button

Tripod



Laptop
USB 3.0 Port

Forensic science





“House of Cards” created with English rock band Radiohead

Thank you!

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xyztlab.com