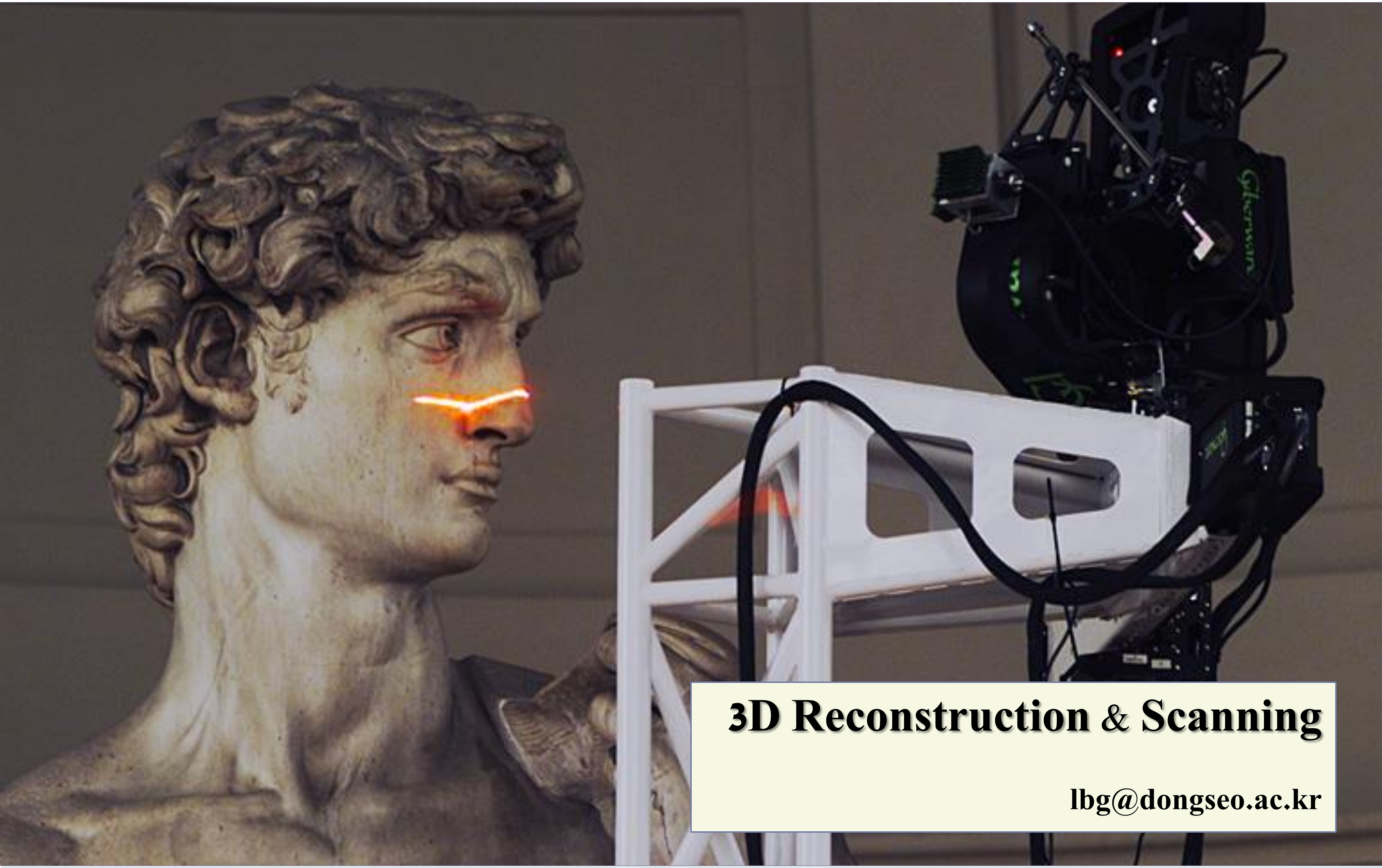
http://graphics.stanford.edu/projects/mich/

The Digital Michelangelo Project 1997~9



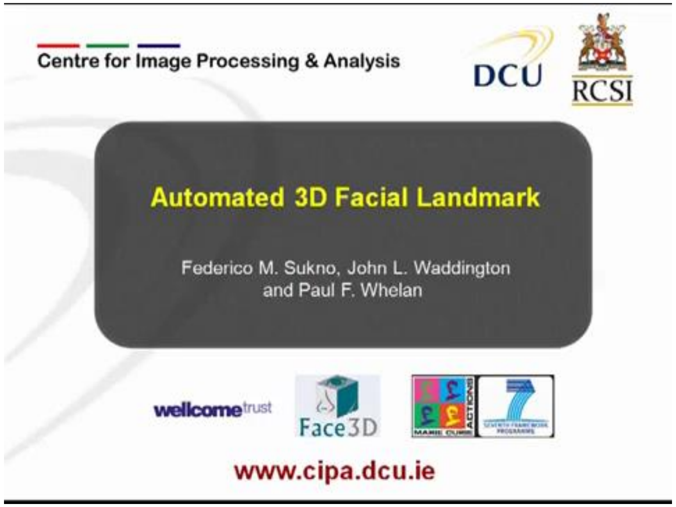
3D Reconstruction & Scanning

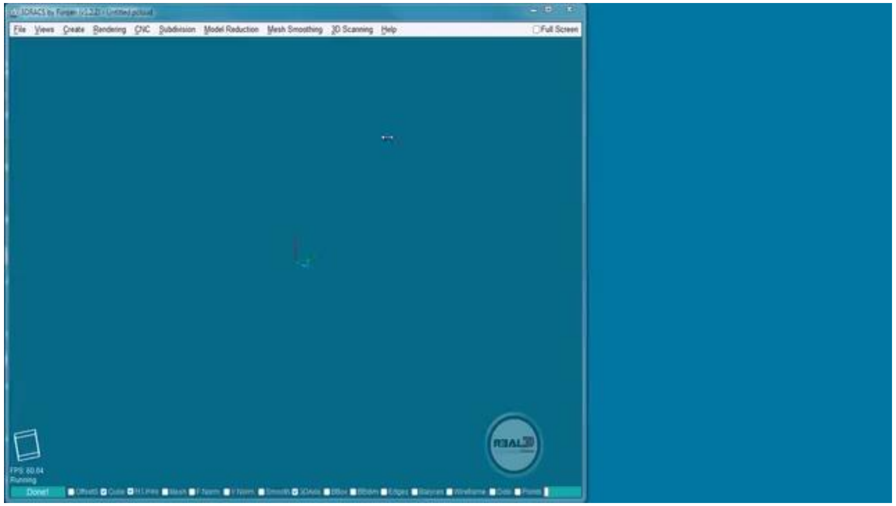
lbg@dongseo.ac.kr

http://www.ten24.info/
http://www.youtube.com/watch?v=j4waCVRgBWI
http://www.youtube.com/watch?v=Wgp0Cg3UFA4

Agenda

- Multiple View Geometry
- Depth Camera
- Structured Light
- Camera Calibration
- Projector Calibration





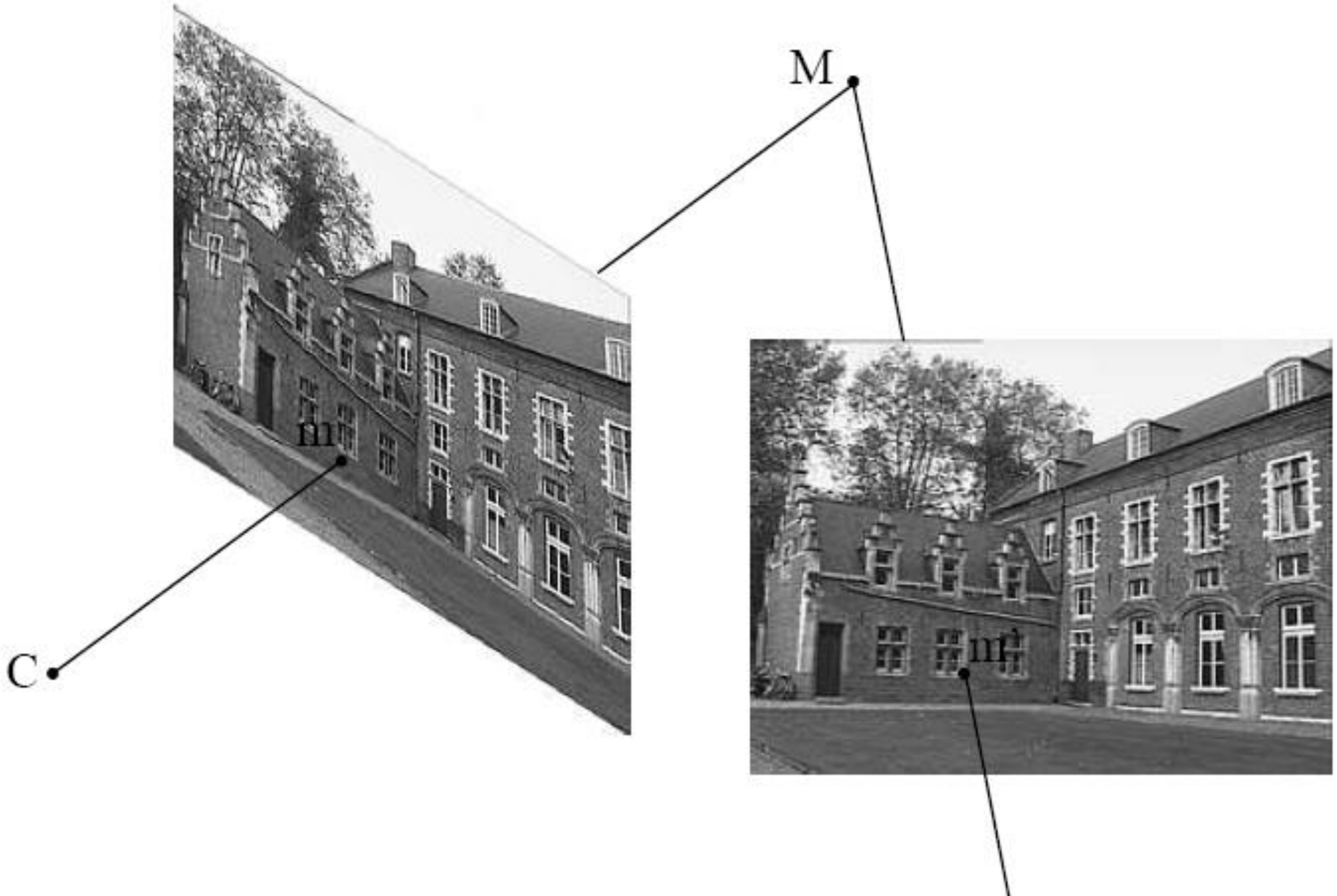
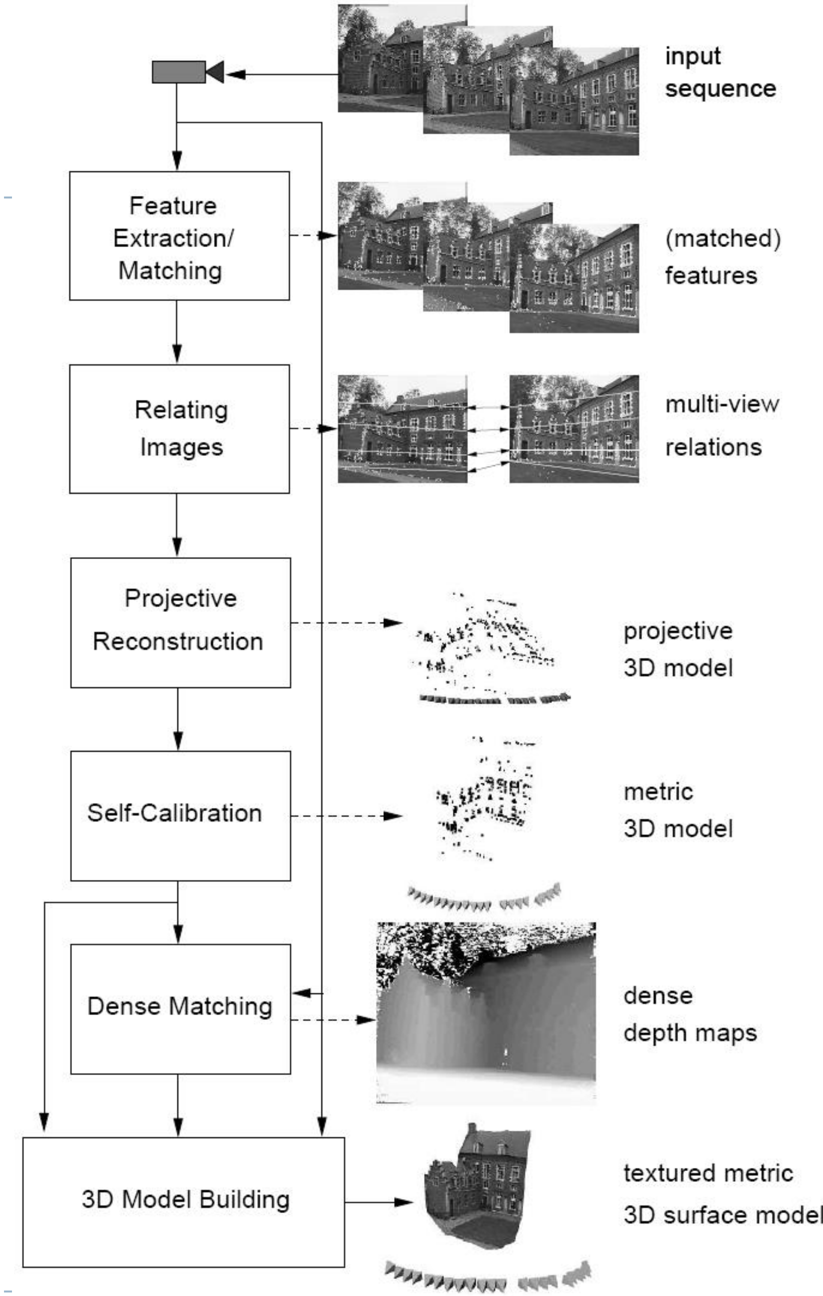


Figure 1.3: Reconstruction of three-dimensional point through triangulation.

- Projective Transformations
- Camera Calibration
- Epipolar Geometry
- Feature Points
- Correspondence Search
- RANSAC Algorithm
- 3D Reconstruction

- **SIFT&ASIFT**



Scale Invariant Feature Transform

Scale-invariant feature transform (or **SIFT**) is an algorithm in computer vision to detect and describe local features in images. The algorithm was published by David Lowe in 1999.

Applications include object recognition, robotic mapping and navigation, image stitching, 3D modeling, gesture recognition, video tracking, and match moving.

The algorithm is patented in the US; the owner is the University of British Columbia.

….

David Lowe
Computer Science Department
University of British Columbia

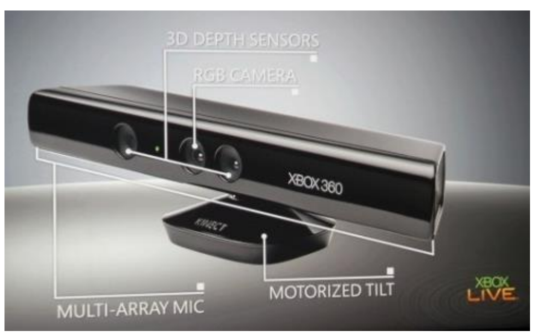
Depth Camera

lbg@dongseo.ac.kr

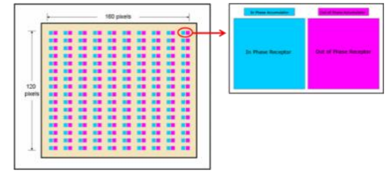
http://www.microsoft.com/en-us/kinectforwindows/discover/features.aspx

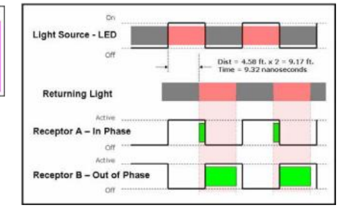
Microsoft Kinect

- Motion sensing input device by Microsoft
- Depth camera tech. developed by PrimeSense Invented in 2005
- Software tech. developed by Rare
- First announced at E3 2009 as “Project Natal”
- Windows SDK Releases



ToF 3D Camera

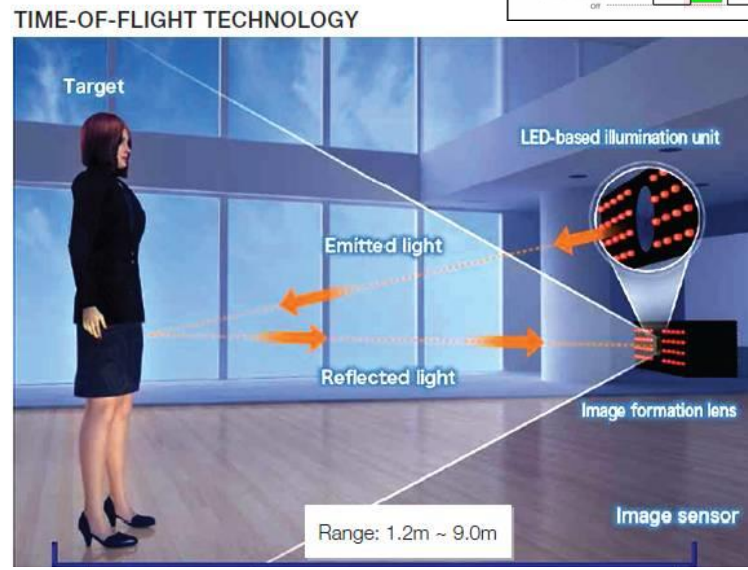




Time of flight cameras

3DV ZSense

3DV, Canesta (no-longer public)
PMD Technologies http://www.PMDTec.com
Mesa Technologies http://www.mesa-imaging.ch



The Mesa Imaging SwissRanger 4000 (SR4000) is probably the most well-known ToF depth camera. It has a range of 5-8 meters, 176 x 144 pixel resolution over 43.6° x 34.6° field of view. It operates at up to 54 fps, and costs about $9,000. I've seen these used in a number of academic laboratories.

The PMD Technologies CamCube 2.0 is a lesser-known, but equally impressive ToF depth camera. It has a range of 7 meters, 204 x 204 pixel resolution with 40.0° x 40.0° field of view. It operates at 25 fps, and last time I checked, it costs around $12,000.

http://www.cs.cmu.edu/afs/cs/academic/class/15385-s06/lectures/ppts/lec-17.ppt
http://www.sci.utah.edu/~gerig/CS6320-S2012/CS6320_3D_Computer_Vision.html

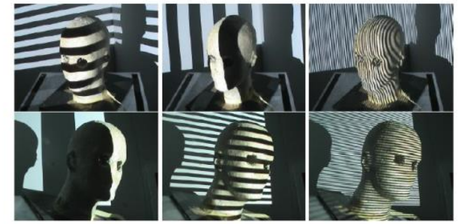
Computer Vision

Spring 2006 15-385,-685

Instructor: S. Narasimhan

Wean 5403
T-R 3:00pm – 4:20pm

Lecture #17



Structured Light II

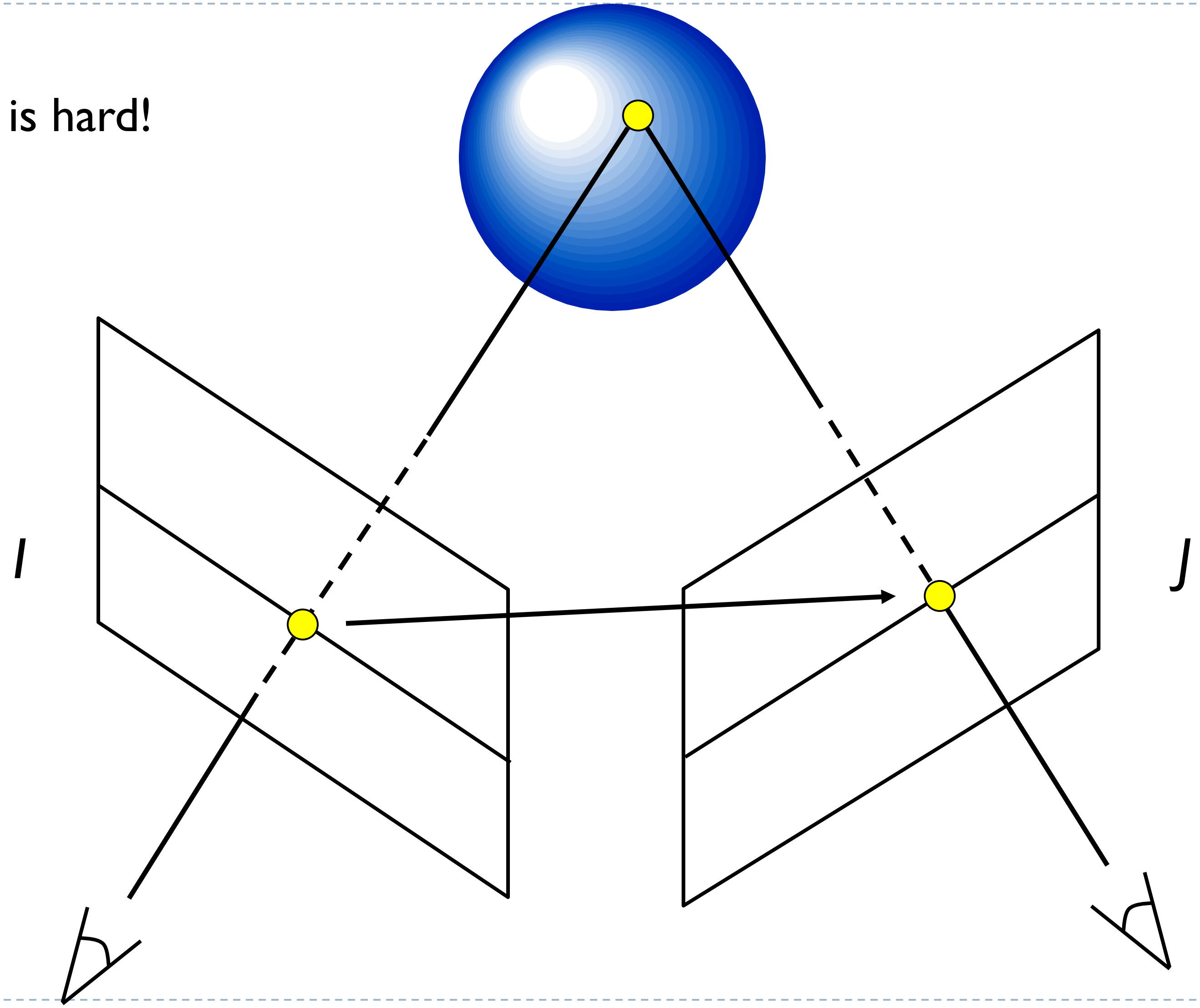
Guido Gerig
CS 6320, Spring 2012
(thanks: slides Prof. S. Narasimhan, CMU, Marc Pollefeys, UNC)
http://www.cs.cmu.edu/afs/cs/academic/class/15385-s06/lectures/ppts/lec-17.ppt

Structured Light + Range Imaging

lbg@dongseo.ac.kr

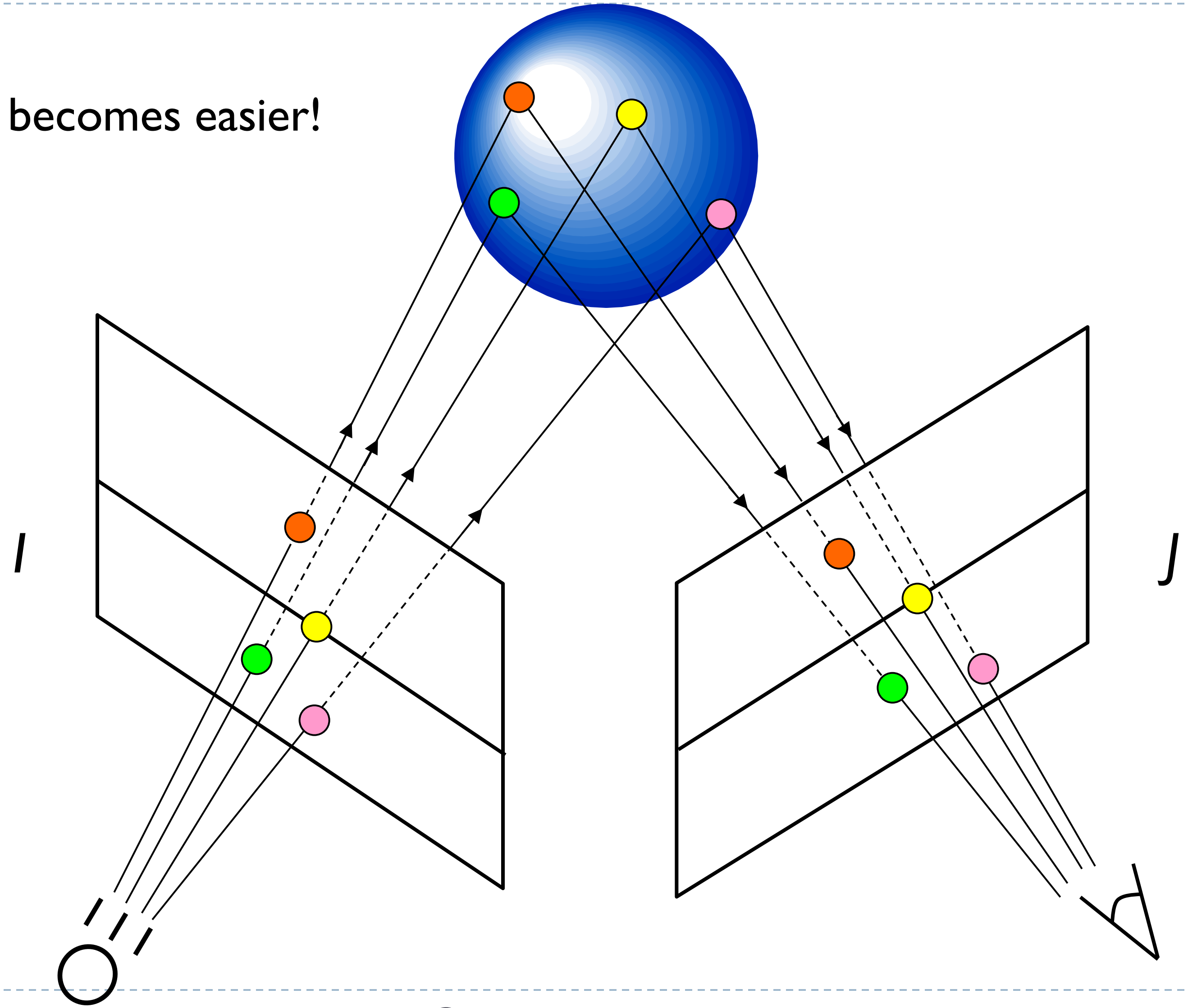
Stereo Triangulation

Correspondence is hard!

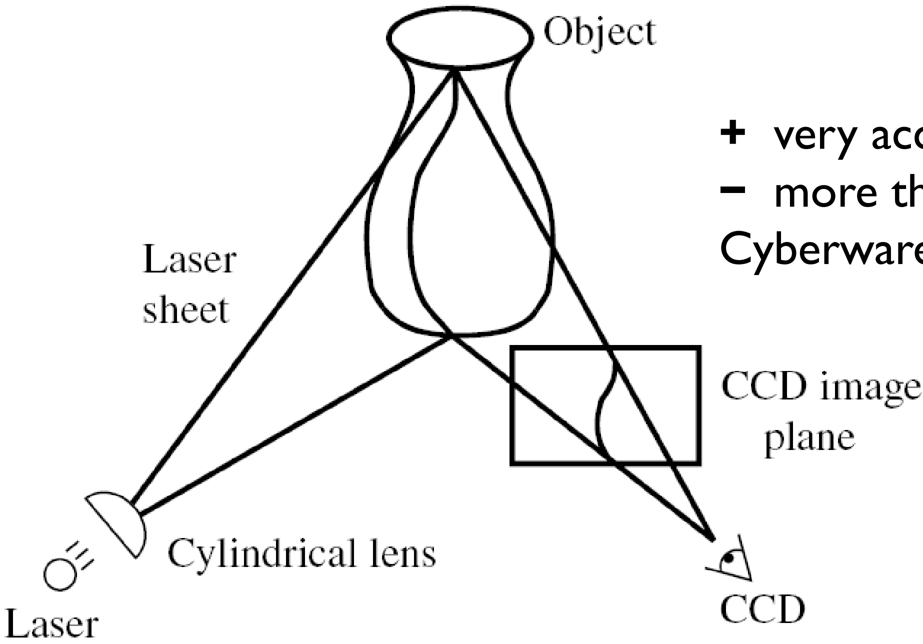


Structured Light Triangulation

Correspondence becomes easier!

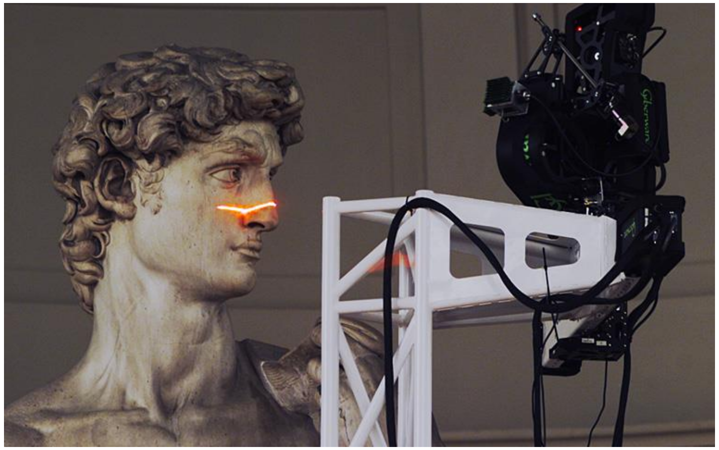


Example: Laser scanner



+ very accurate < 0.01 mm
− more than 10sec per scan

Cyberware® face and head scanner



Digital Michelangelo Project

http://graphics.stanford.edu/projects/mich/

http://www.youtube.com/watch?v=IqOg77liryg

Portable 3D laser scanner


2014. 12. 4.

KONICA MINOLTA

VIVID 910

NON-CONTACT 3-D DIGITIZER

3-D Digitizing - Breakthrough in Process Innovation

Konica Minolta's VIVID 910 the ideal 3D capture device for industrial applications in product design and manufacturing inspection.

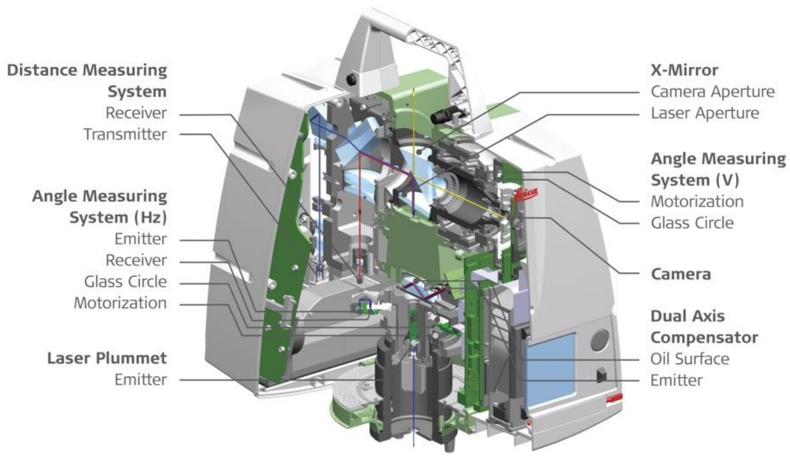
VIVID 910

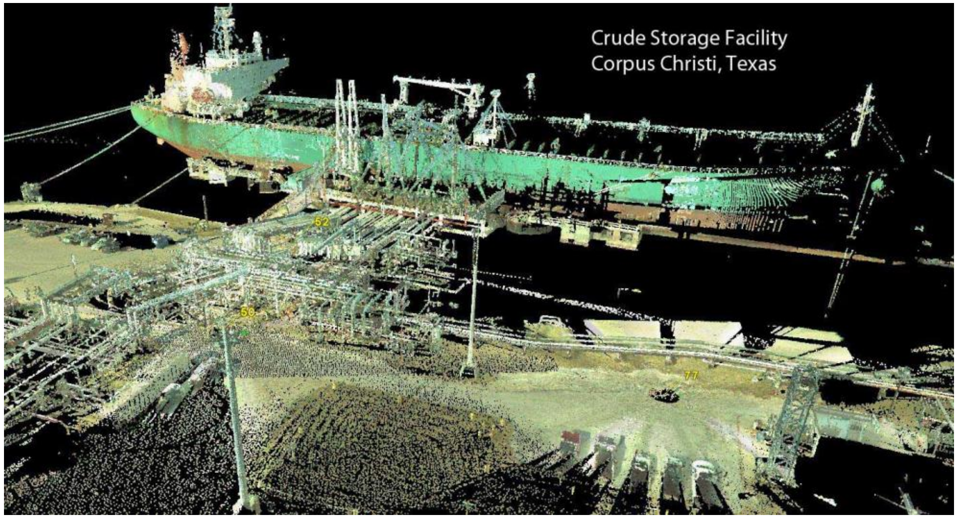
PET: Polygon editing software,
EAT: Easy alignment target-based registration
Compatible with all major 3D software for Modeling and CAD, CAM and CAT

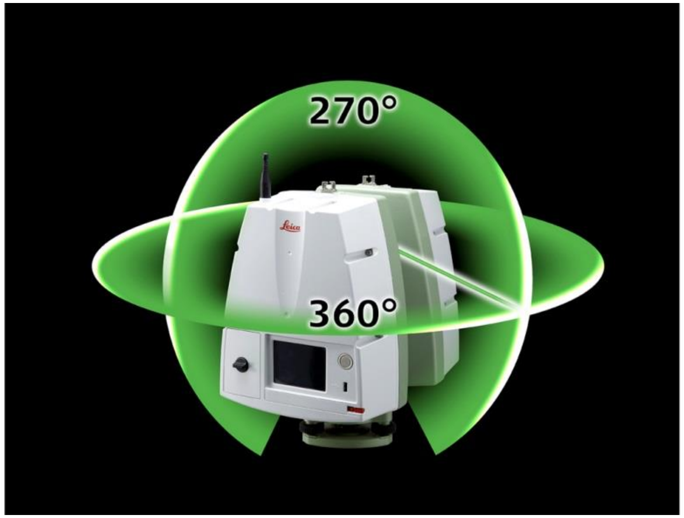
The essentials of imaging

http://pdf.directindustry.com/pdf/konica-minolta-sensing-americas/vivid-910/18425-140283.html 1/1

Leica ScanStation C10

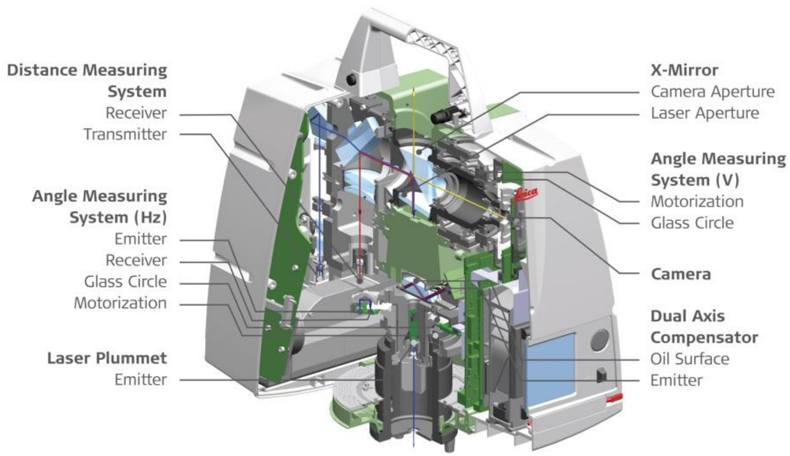






http://www.youtube.com/watch?v=cUI6HD_d89k
http://www.youtube.com/watch?v=1IDO1UevAJI
http://www.youtube.com/watch?v=cxTYYce_d_8

Leica ScanStation C10



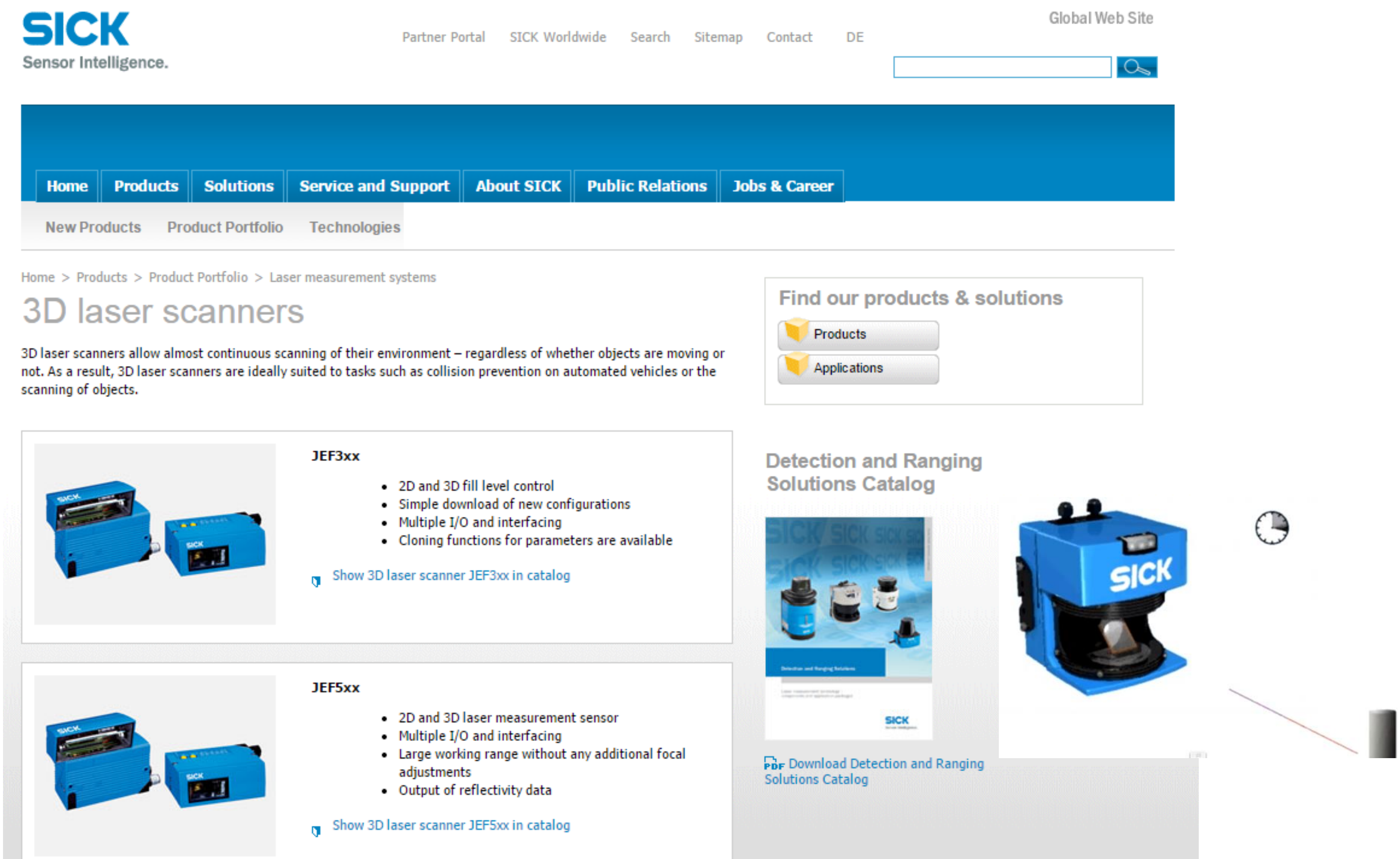
Leica ScanStation C10

System Performance		
Accuracy of single measurement		
Position*	6 mm	* At 1 m – 50 m range, one sigma
Distance*	4 mm	
Angle (horizontal/vertical)	60 μrad / 60 μrad (12" / 12")	
Modeled surface precision/noise**	2 mm	
Target acquisition***	2 mm std. deviation	
Dual-axis compensator	Selectable on/off, resolution 1", dynamic range +/- 5', accuracy 1.5"	

Laser Scanning System	
Type	Pulsed; proprietary microchip
Color	Green, wavelength = 532 nm visible
Laser Class	3R (IEC 60825-1)
Range	300 m @ 90%; 134 m @ 18% albedo (minimum range 0.1 m)
Scan rate	Up to 50,000 points/sec, maximum instantaneous rate
Scan resolution	
Spot size	From 0 – 50 m: 4.5 mm (FWHH-based); 7 mm (Gaussian-based)
Point spacing	Fully selectable horizontal and vertical; <1 mm minimum spacing, through full range; single point dwell capacity
Field-of-View	
Horizontal	360° (maximum)
Vertical	270° (maximum)
Aiming/Sighting	Parallax-free, integrated zoom video
Scanning Optics	Vertically rotating mirror on horizontally rotating base; Smart X-Mirror™ automatically spins or oscillates for minimum scan time

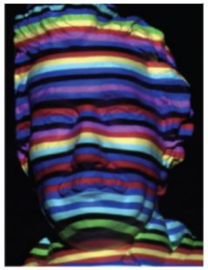
https://www.youtube.com/watch?v=yfQhEiq48YA
https://www.youtube.com/watch?v=aL-lhvu0ugo

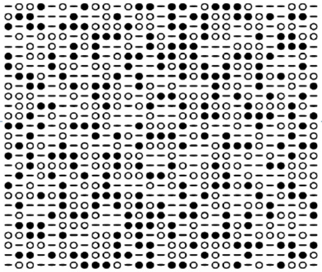
LMS LIDAR scanner from SICK



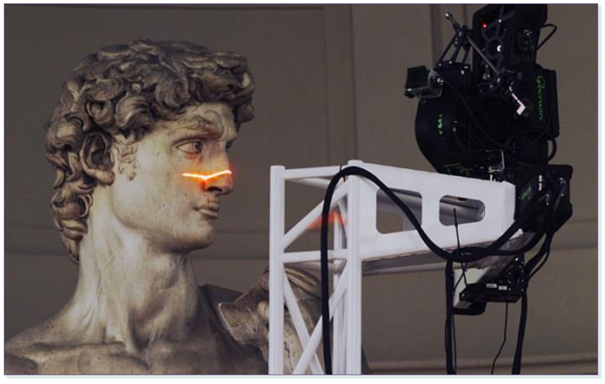
Structured Light 3D Surface Imaging

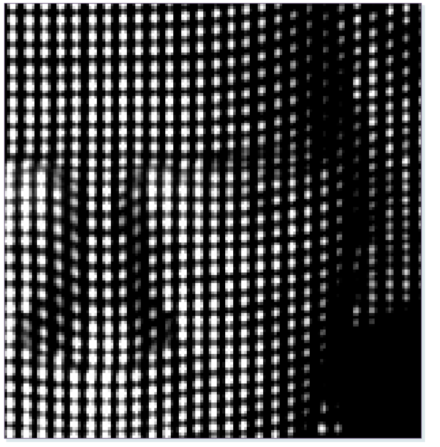
lbg@dongseo.ac.kr





Continuum of Triangulation Methods





Multi-stripe
Multi-frame

Single-stripe

Single-frame

Slow, robust

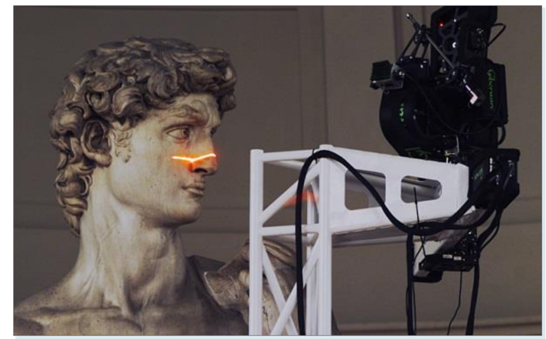
Fast, fragile

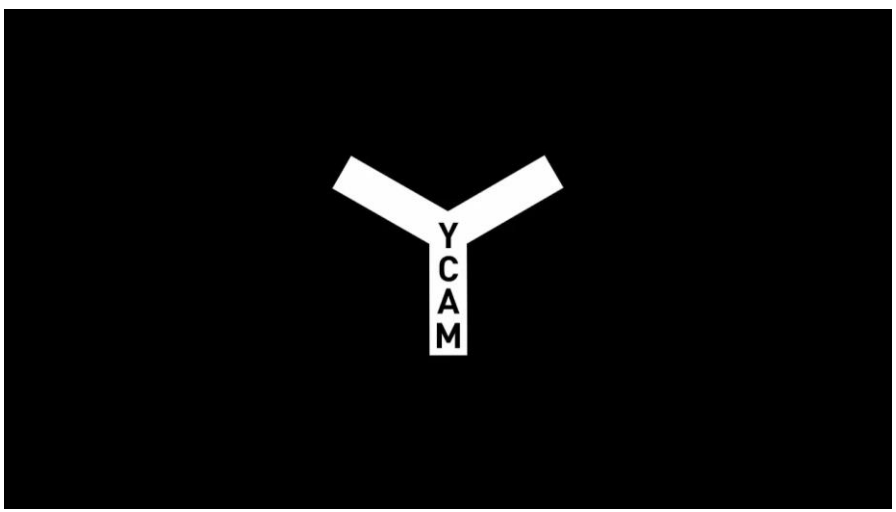
http://vimeo.com/37090394
http://www.youtube.com/watch?v=a6g17-4FmFo

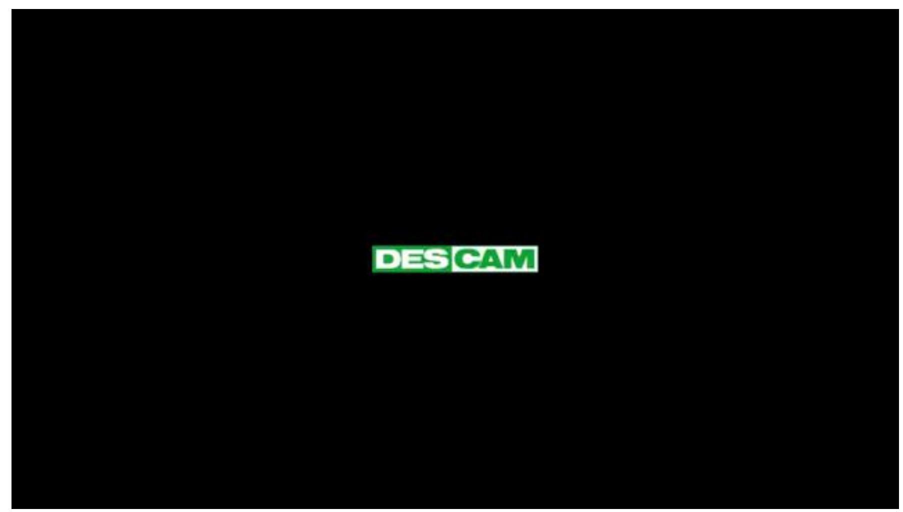
Faster Acquisition?

- Project multiple stripes simultaneously
- Correspondence problem: which stripe is which?

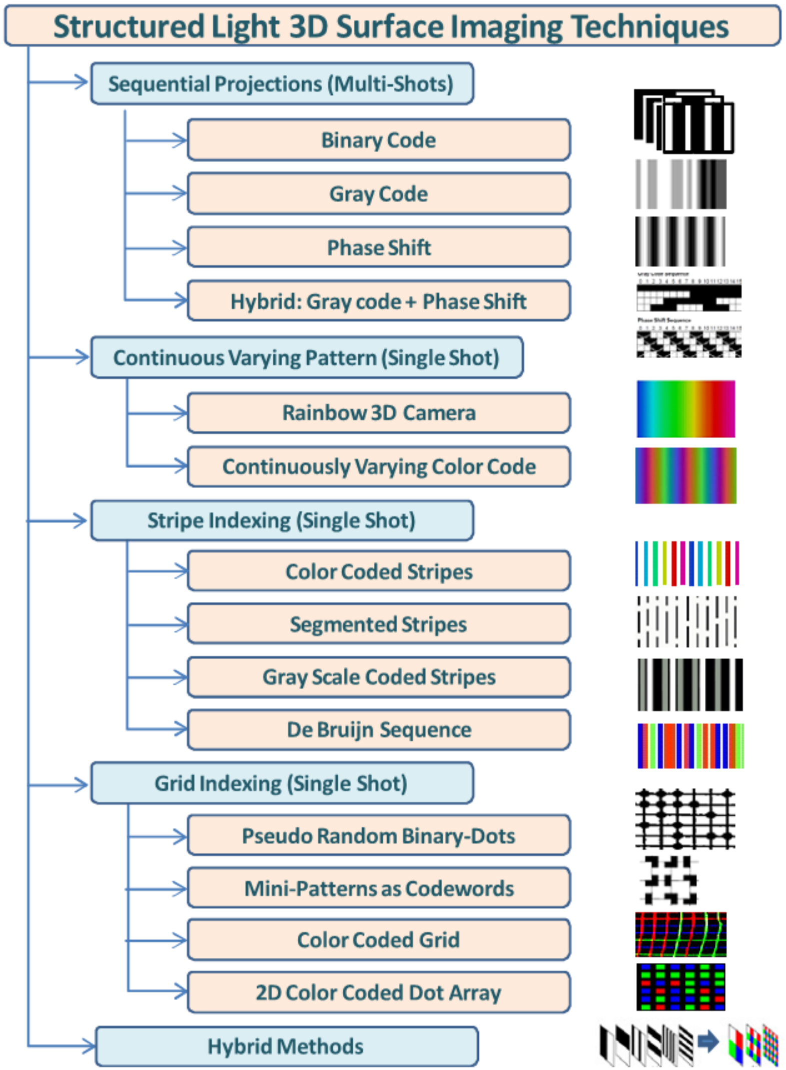
- Common types of patterns:
  - Binary coded light striping
  - Gray/color coded light striping





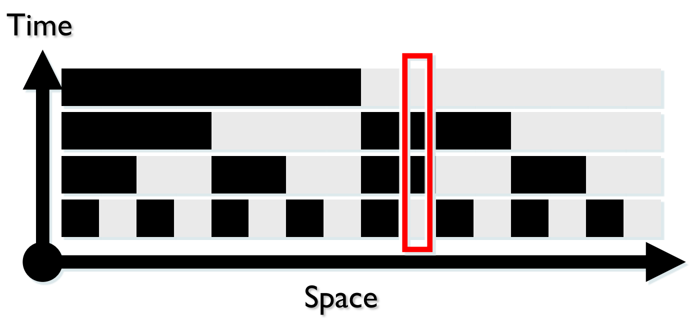


Structured Light Projection Classification

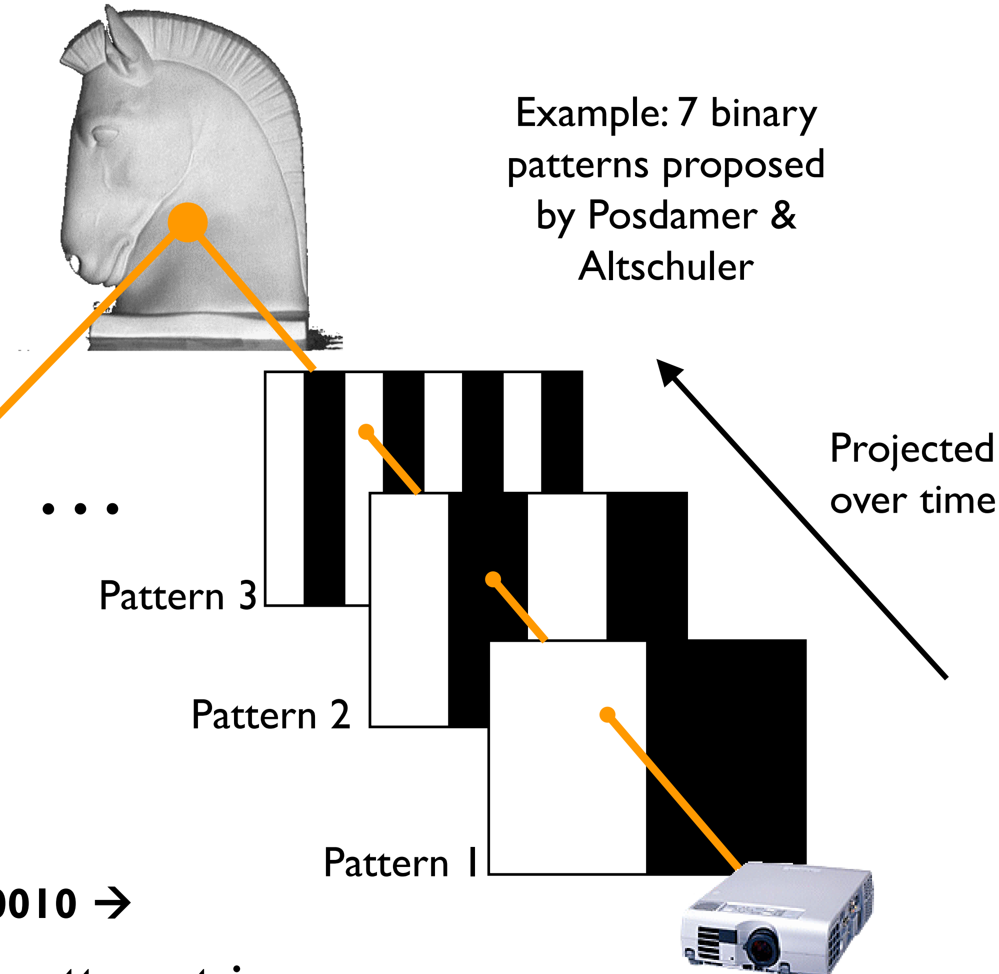


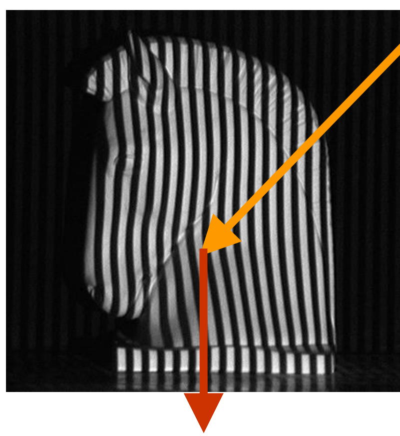
J. L. Posdamer and M. D. Altschuler. Surface measurement by space-encoded projected beam systems. *Computer Graphics and Image Processing*, 18:1–17, 1982.

Binary Coding



Example: 7 binary patterns proposed by Posdamer & Altschuler



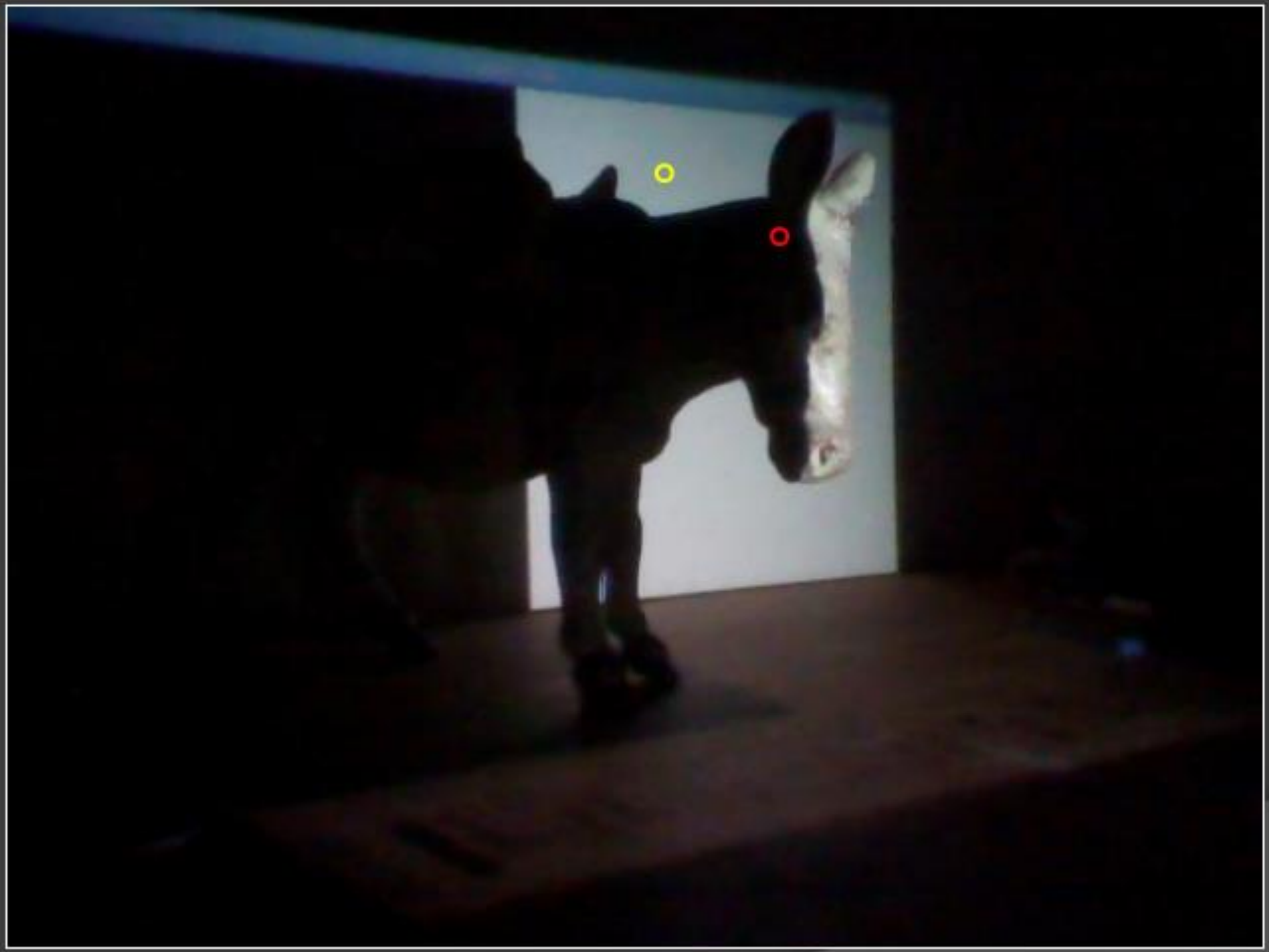


Codeword of this píxel: 1010010 →

identifies the corresponding pattern stripe

Example: A Tale of Two Pixels

Example: A Tale of Two Pixels

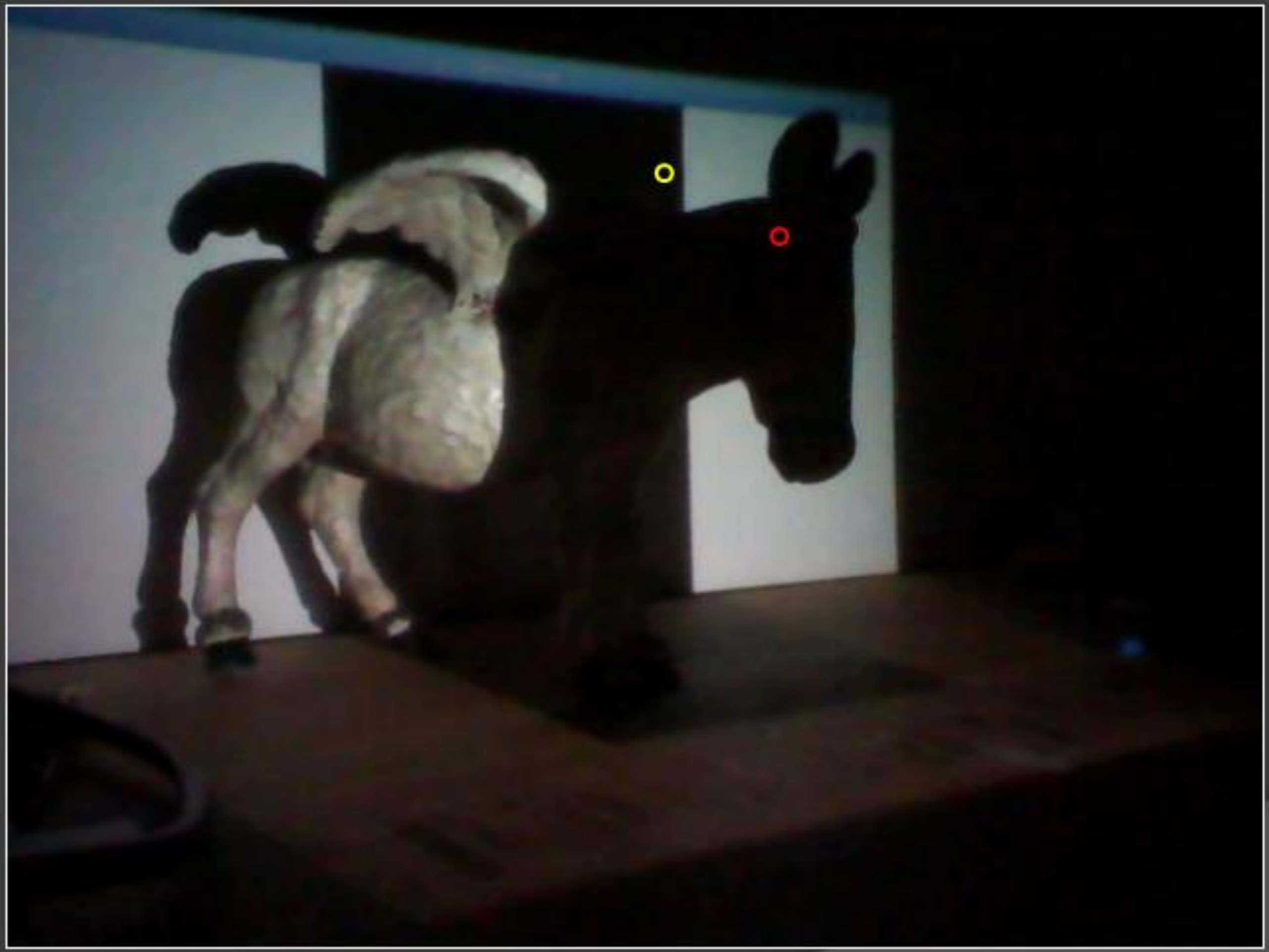


- 0
- 1

Example: A Tale of Two Pixels

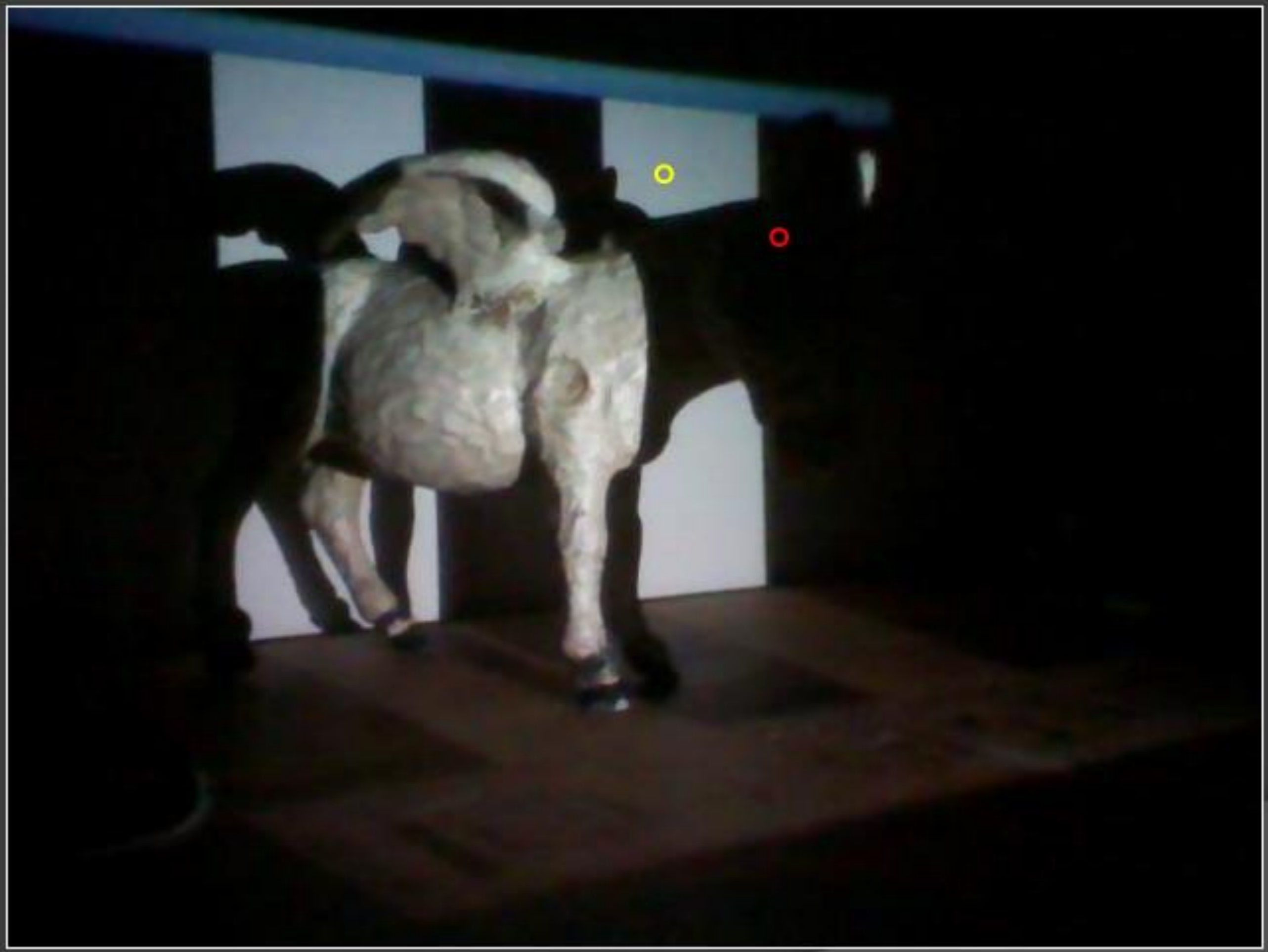
- 01
- 11

Example: A Tale of Two Pixels



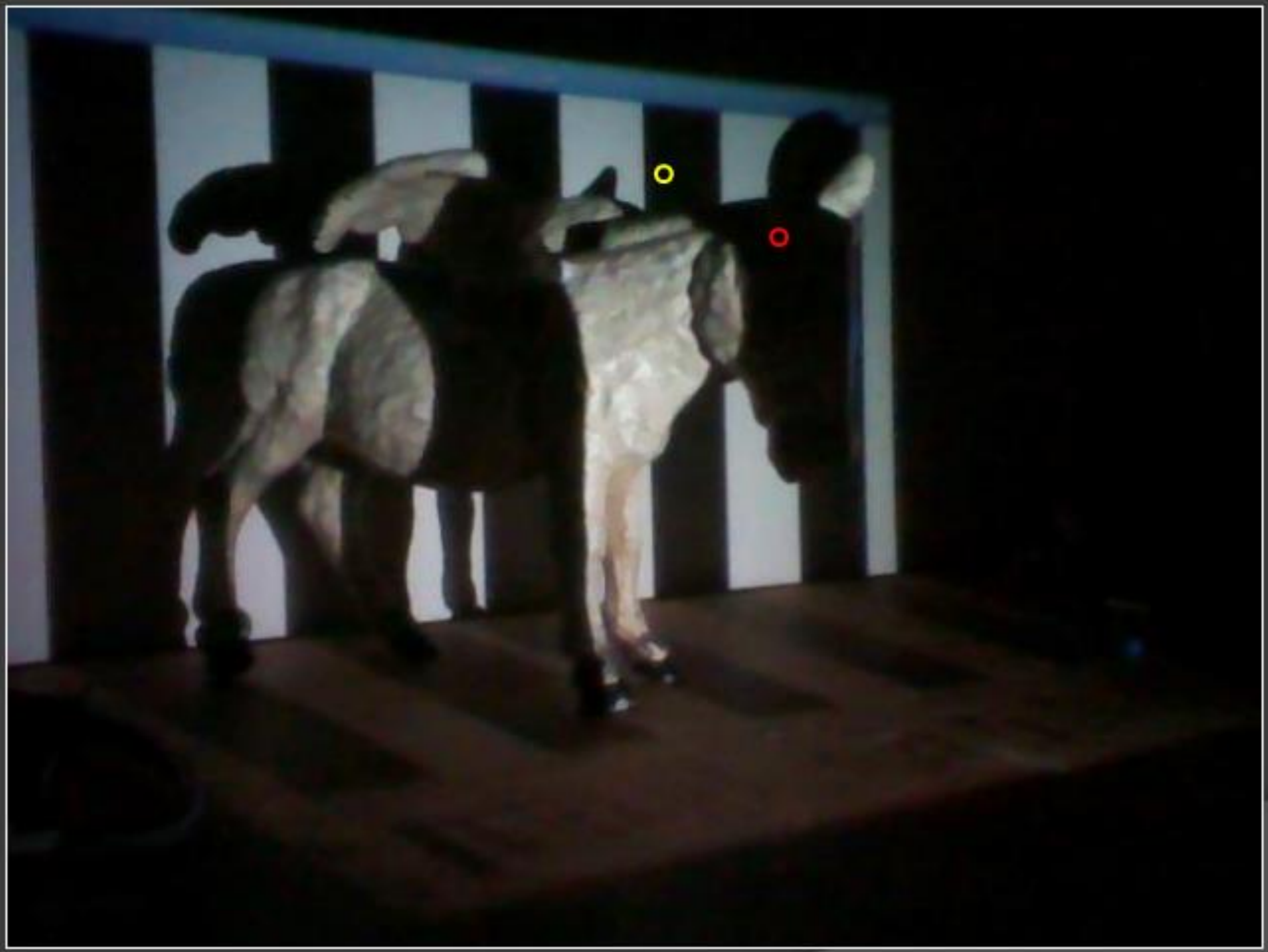
- 010
- 110

Example: A Tale of Two Pixels



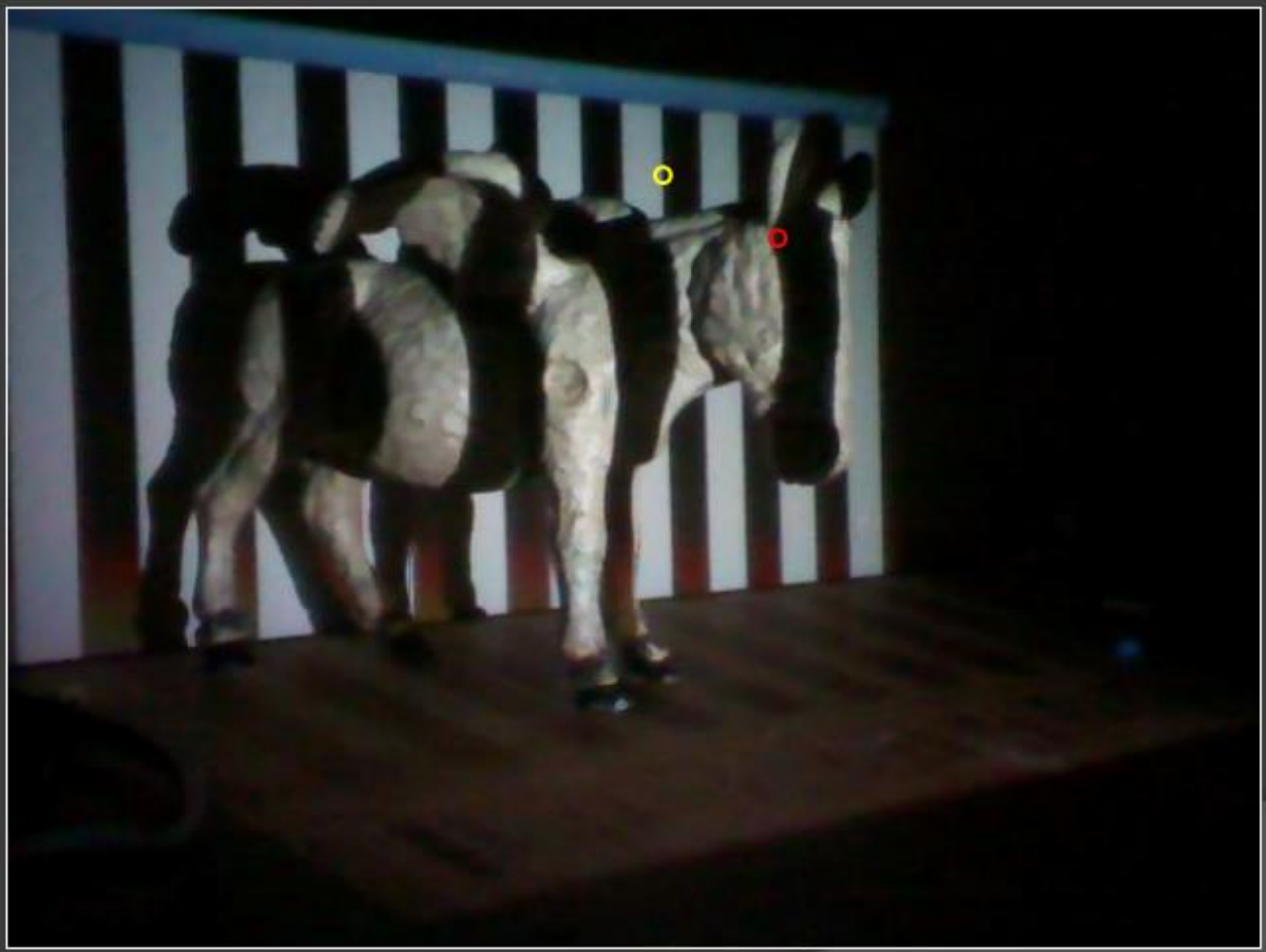
- 0100
- 1101

Example: A Tale of Two Pixels



- 01000
- 11010

Example: A Tale of Two Pixels

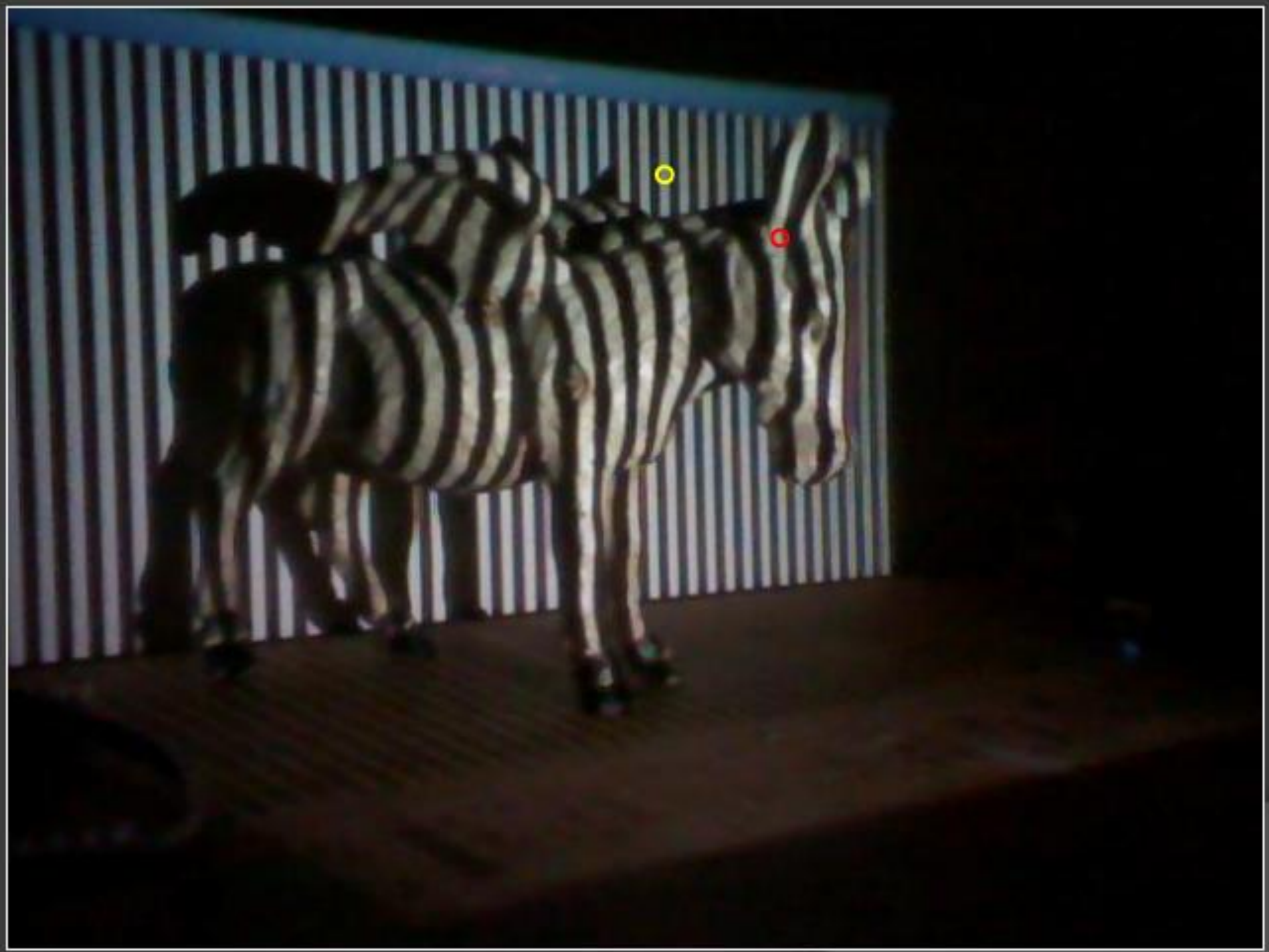


- 010000
- 110100

Example: A Tale of Two Pixels

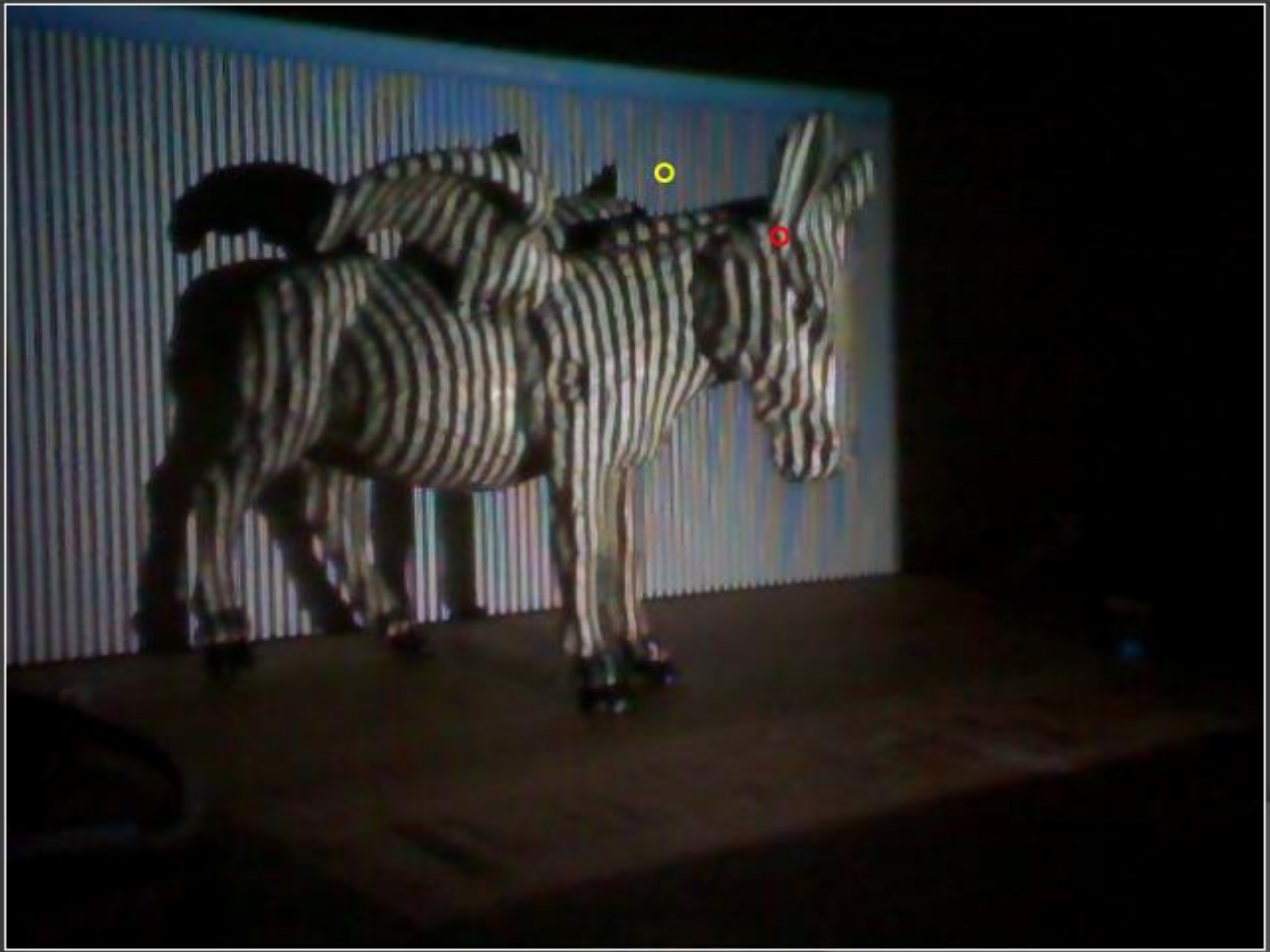
- 0100001
- 1101001

Example: A Tale of Two Pixels



- 01000011
- 11010011

Example: A Tale of Two Pixels



- 010000111
- 110100111

Decoding the Example

Yellow Pixel Decoding

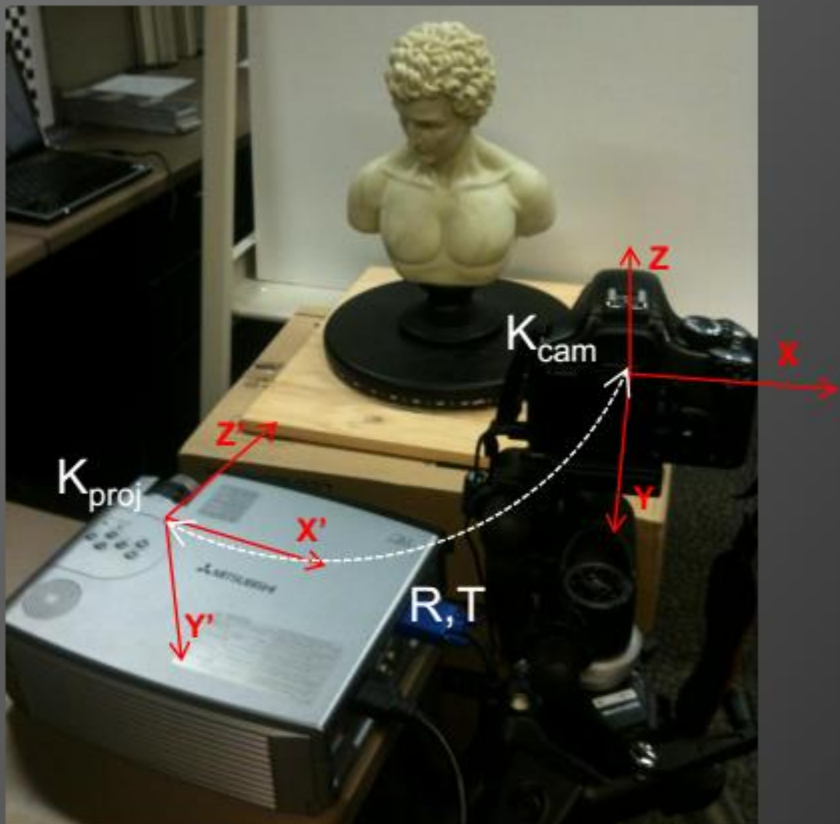
- Gray Code: 110100111
- Binary: 100111010
- Projector column: 314
- Camera column: 335
- Disparity: 335 – 314 = 21
- Unscaled results:
  - x = Camera column = 335
  - y = Camera row
  - z = $(\text{Disparity})^{-1}$ = 0.0476

Red Pixel Decoding

- Gray Code: 010000111
- Binary: 011111010
- Projector column: 250
- Camera column: 392
- Disparity = 392 – 250 = 142
- Unscaled results:
  - x = Camera column = 392
  - y = Camera row
  - z = $(\text{Disparity})^{-1}$ = 0.007042

Results from Meshlab

Overview



Geometric calibration

- Camera intrinsics: K_{cam}
- Projector intrinsics: K_{proj}
- Projector-Camera extrinsics:
  Rotation and translation:
  R,T

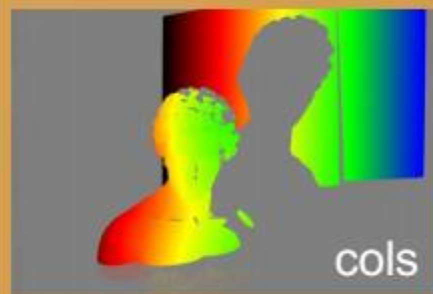
The simplest structured-light system consists of a camera and a data projector.

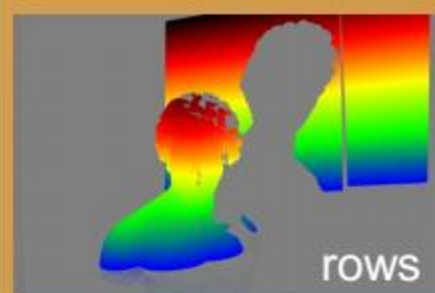
Application: 3D scanning

Projector | Camera

Data acquisition **1**

Projector-Camera correspondences



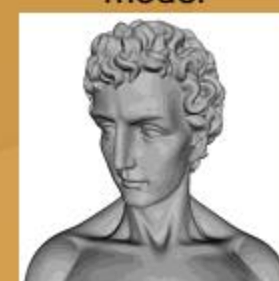


Decode **2**

Correspondences
+
Calibration
=
Pointcloud

Triangulation **3**

Pointclouds from several viewpoints can be merged into a single one and used to build a 3D model



Mesh **4**

Camera calibration: well-known problem

Pinhole model + radial distortion

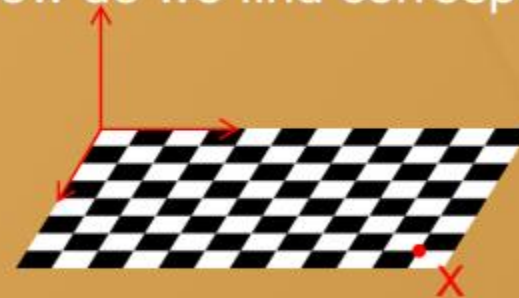
$$K = \begin{bmatrix} fx & s & cx \\ 0 & fy & cy \\ 0 & 0 & 1 \end{bmatrix}$$

$$x = K \cdot L(X; k_1, k_2, k_3, k_4)$$

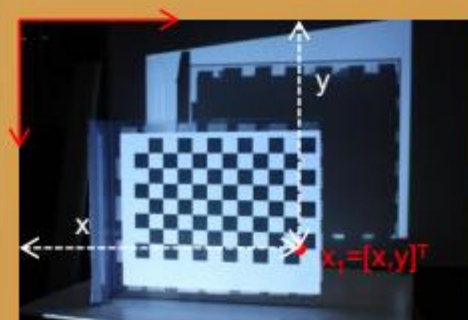
X: 3D point
$k_1,\ldots,k_4$: distortion coefficients
K: camera intrinsics
x: projection of X into the image plane

If we have enough X↔x point correspondences we can solve for all the unknowns

How do we find correspondences?



Object of known dimensions



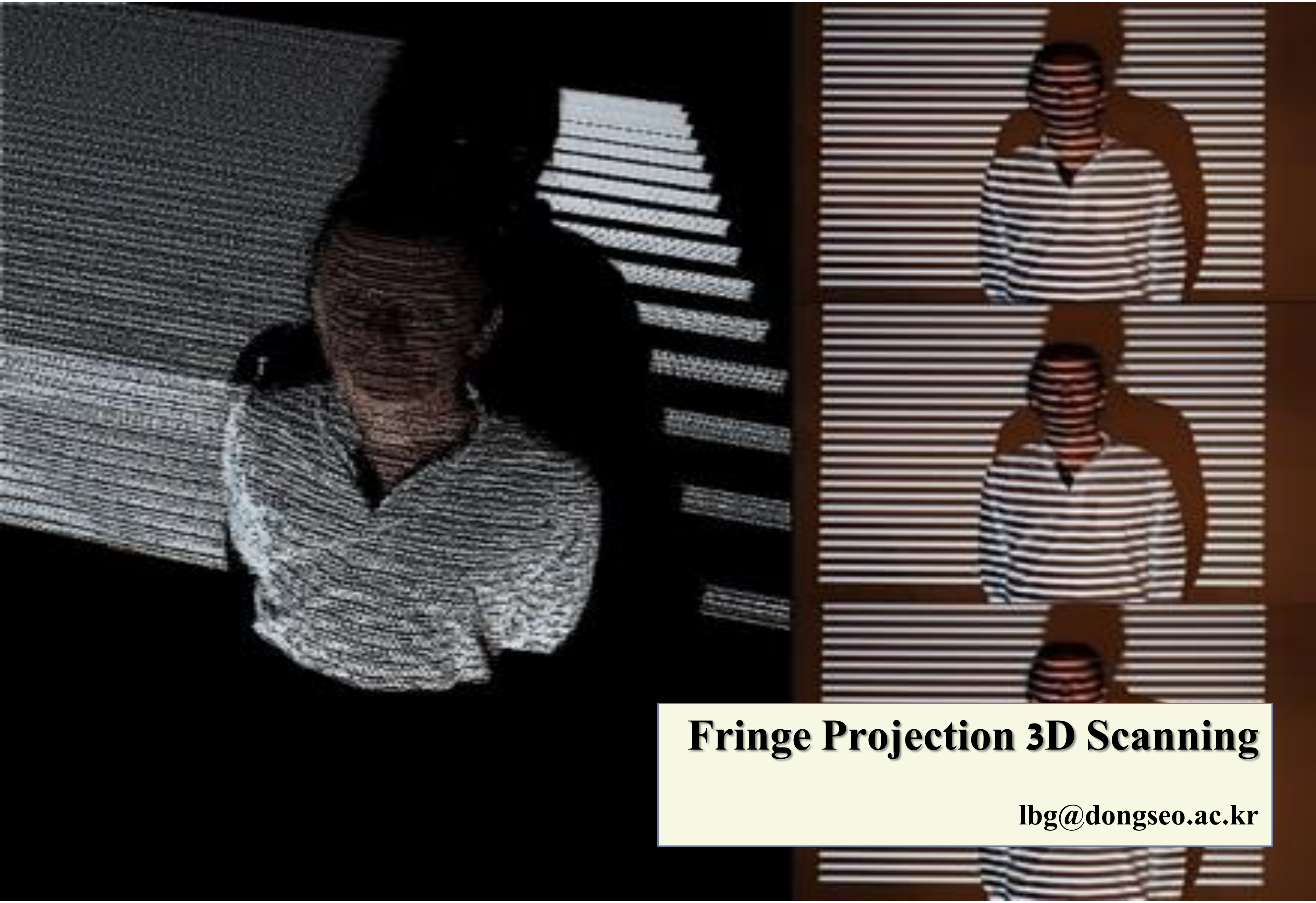
$$x_1 = K \cdot L(R_1 X + T_1; k_1, k_2, k_3, k_4)$$

$$x_2 = K \cdot L(R_2 X + T_2; k_1, k_2, k_3, k_4)$$

$$x_3 = K \cdot L(R_3 X + T_3; k_1, k_2, k_3, k_4)$$

…

Images from different viewpoints

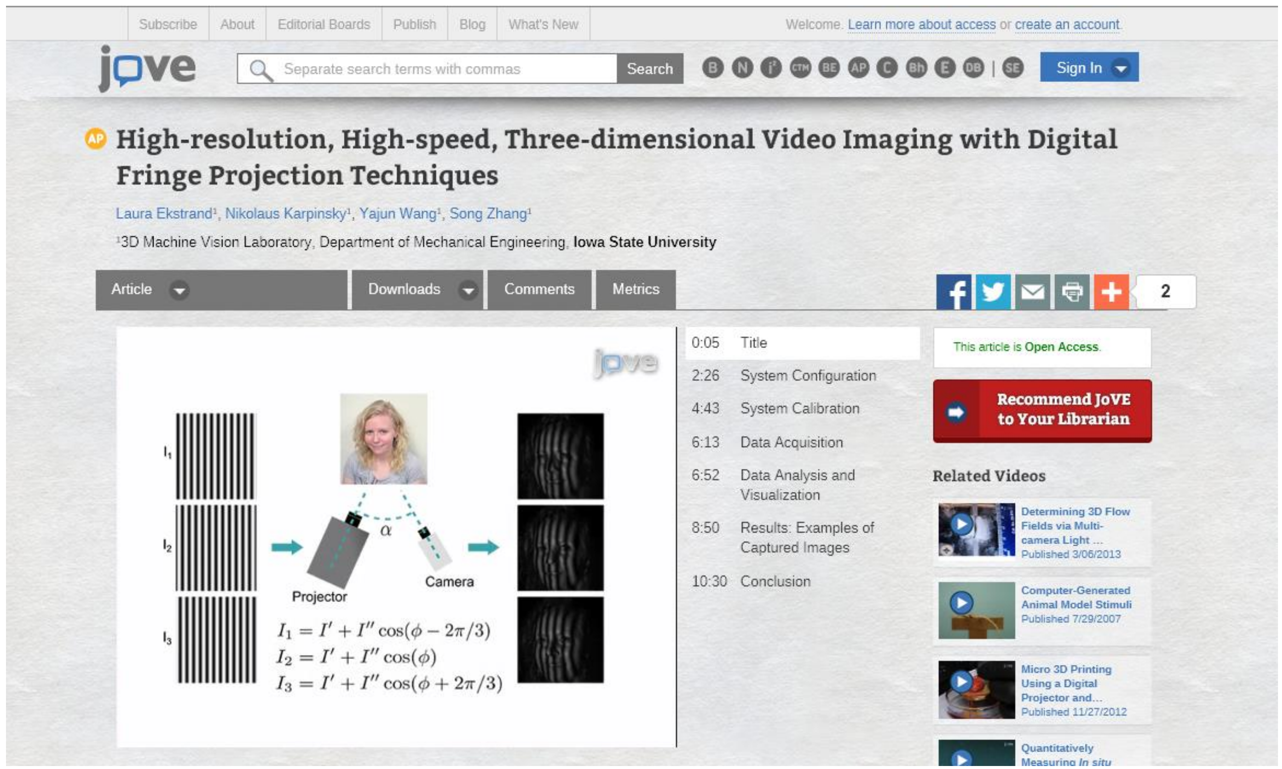


Fringe Projection 3D Scanning

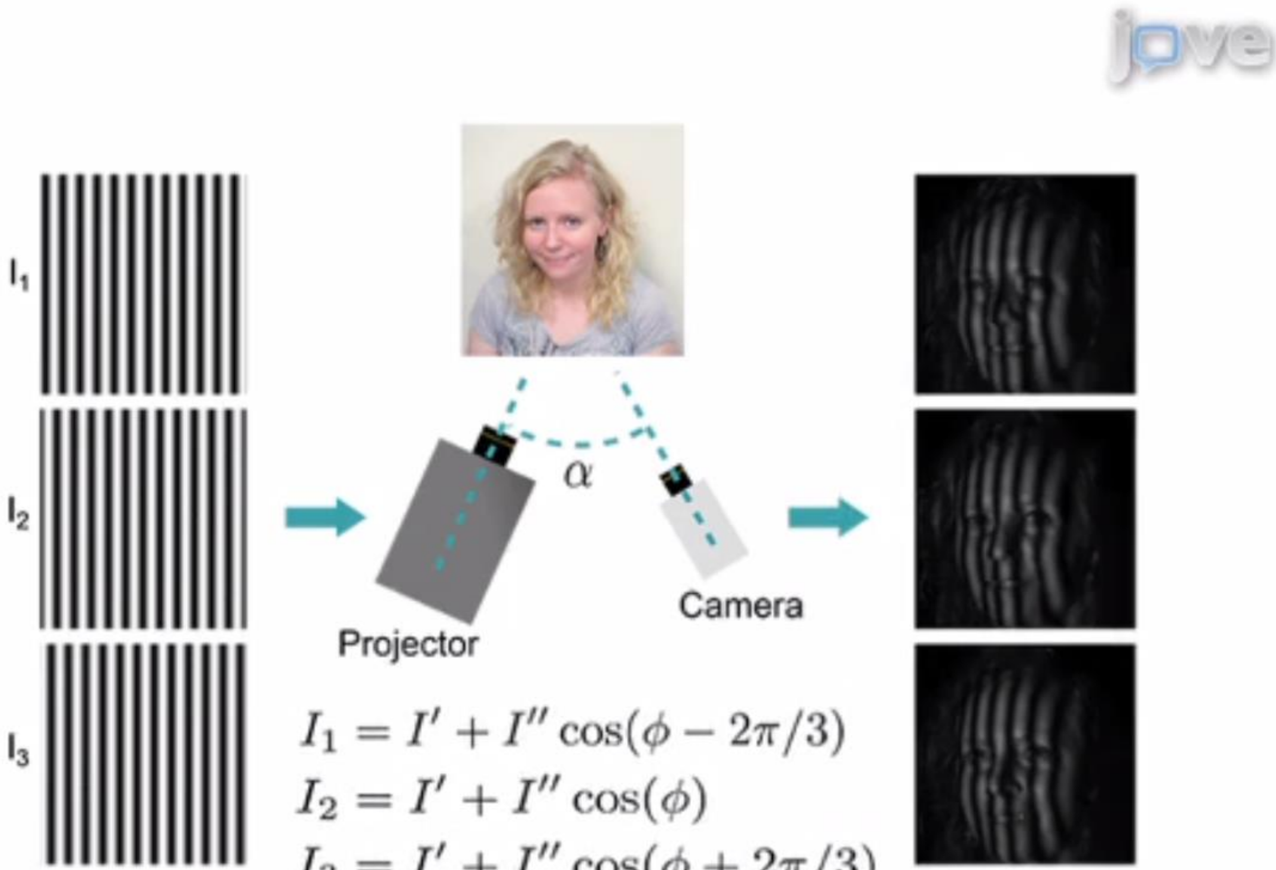
lbg@dongseo.ac.kr

Agenda

- Fringe Projection Techniques
- Three step phase shifting algorithm



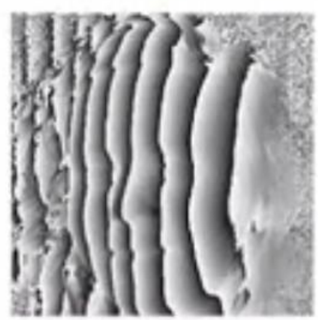
Three-step Phase-shifting algorithm



$$I_1 = I' + I'' \cos(\phi - 2\pi/3)$$
$$I_2 = I' + I'' \cos(\phi)$$
$$I_3 = I' + I'' \cos(\phi + 2\pi/3)$$

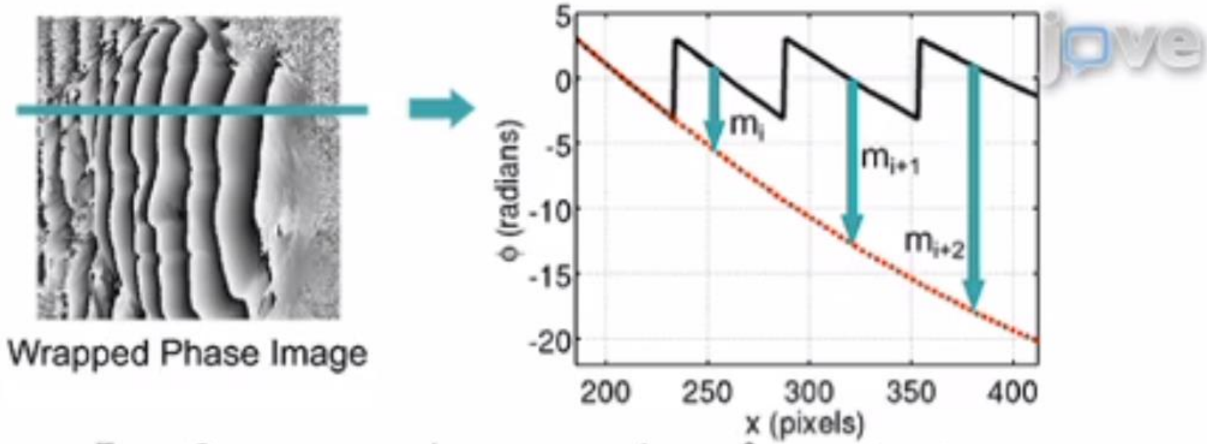
Wrapped Phase Image

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



Wrapped Phase Image

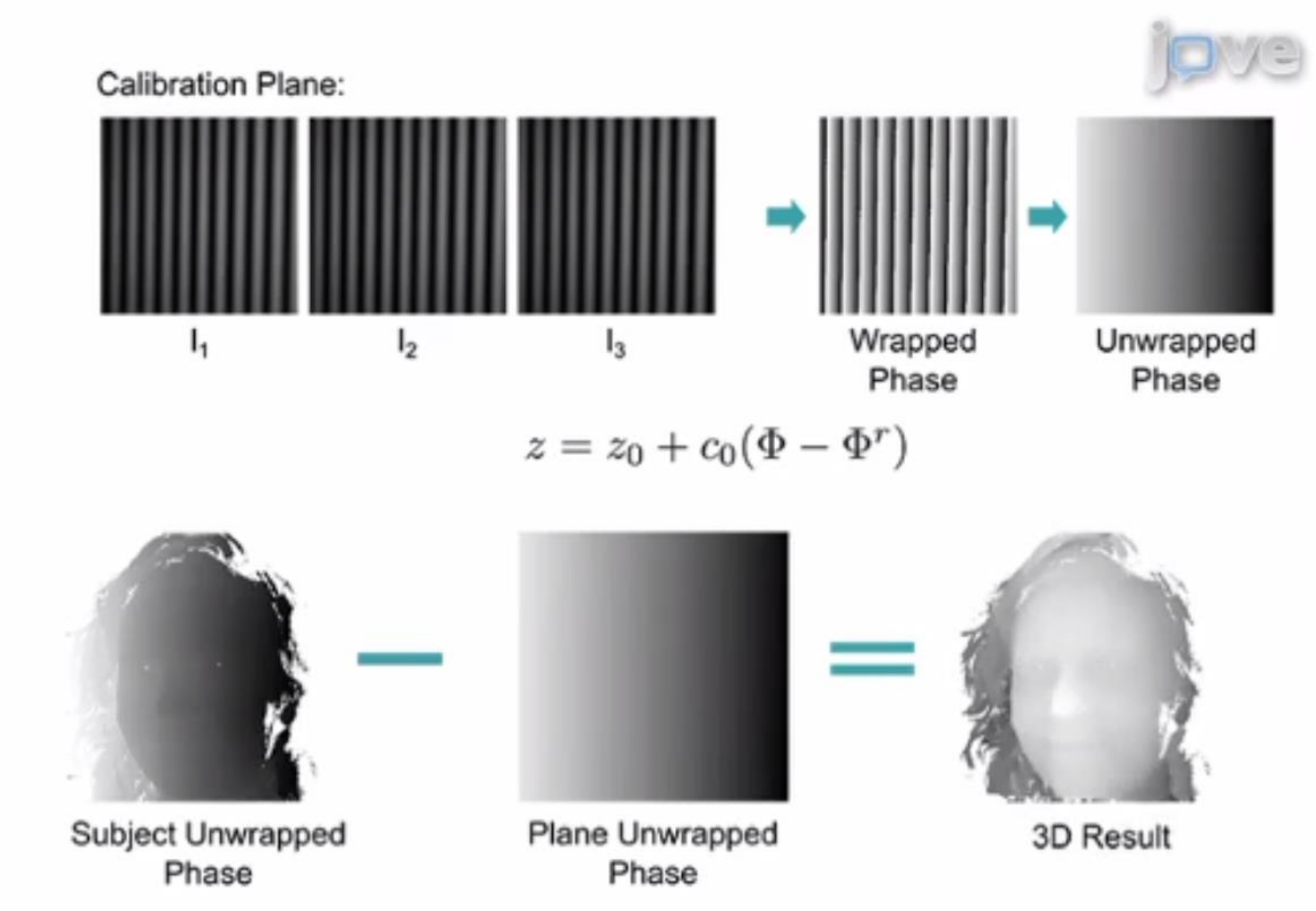
Unwrapped Phase Image



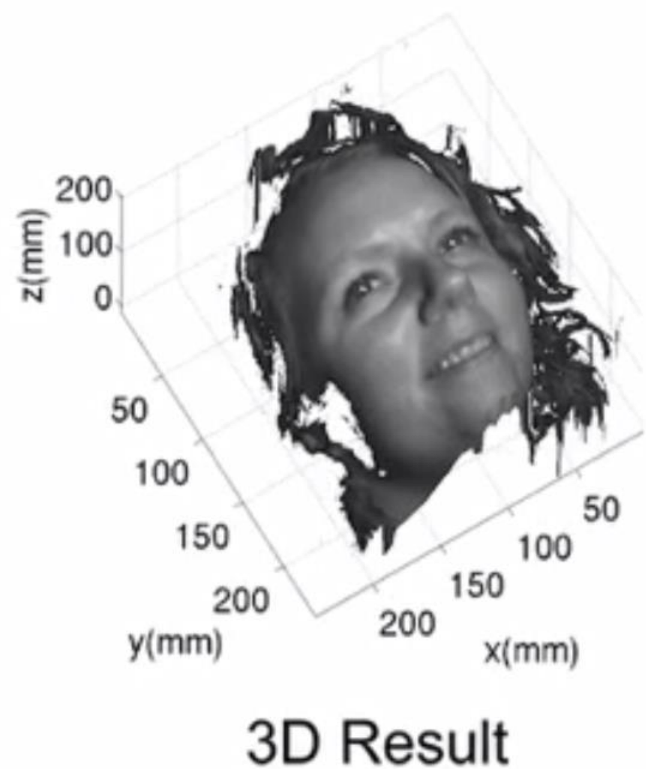
$$\Phi = 2\pi \times m + \phi, \; m \text{ a series of constants}$$

Unwrapped Phase Image
(Background Removed)

Calibration Plane



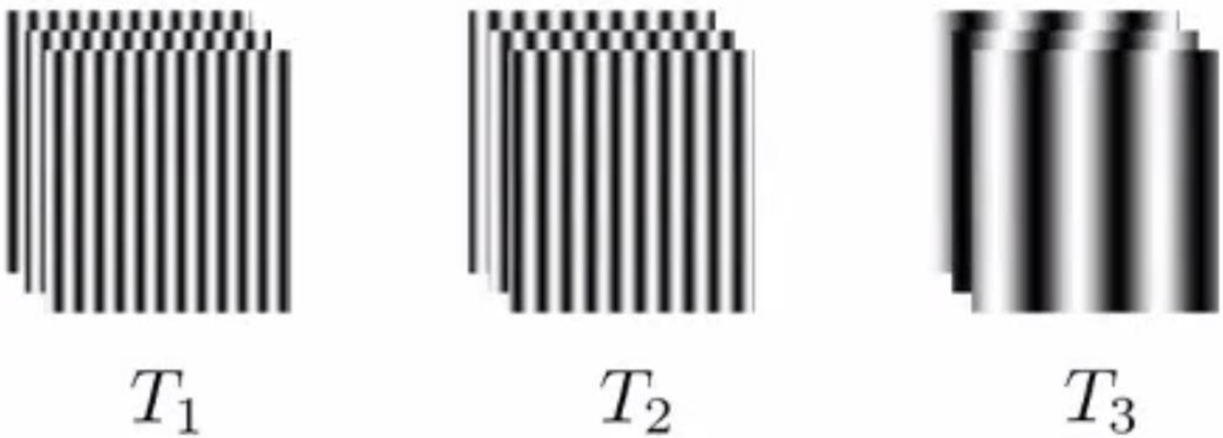
3D Result



Phase shifting patterns

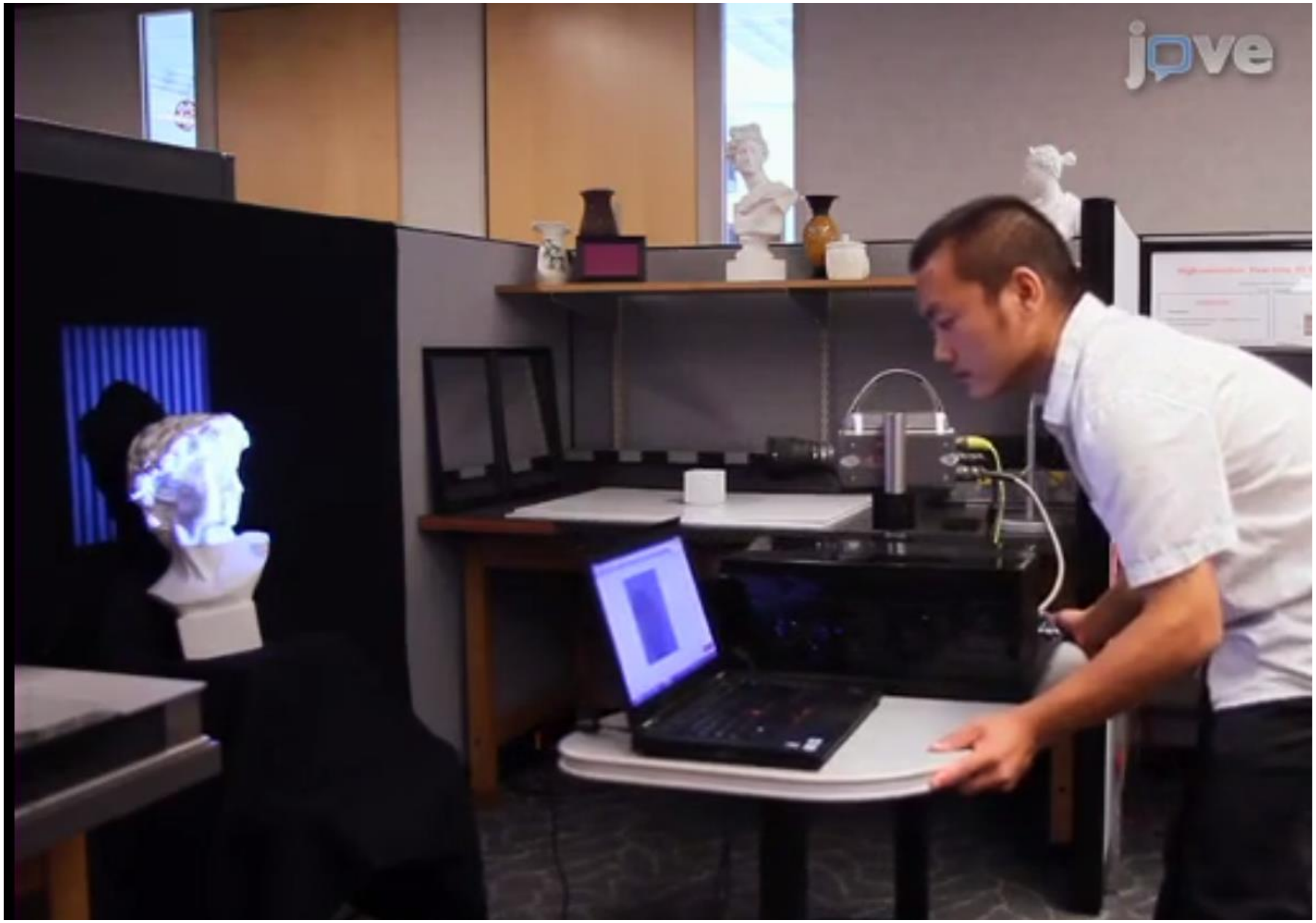
For details on three-step phase-shifting patterns see Malacara, Optical Shop Testing, in the references.

Sinusoid patterns

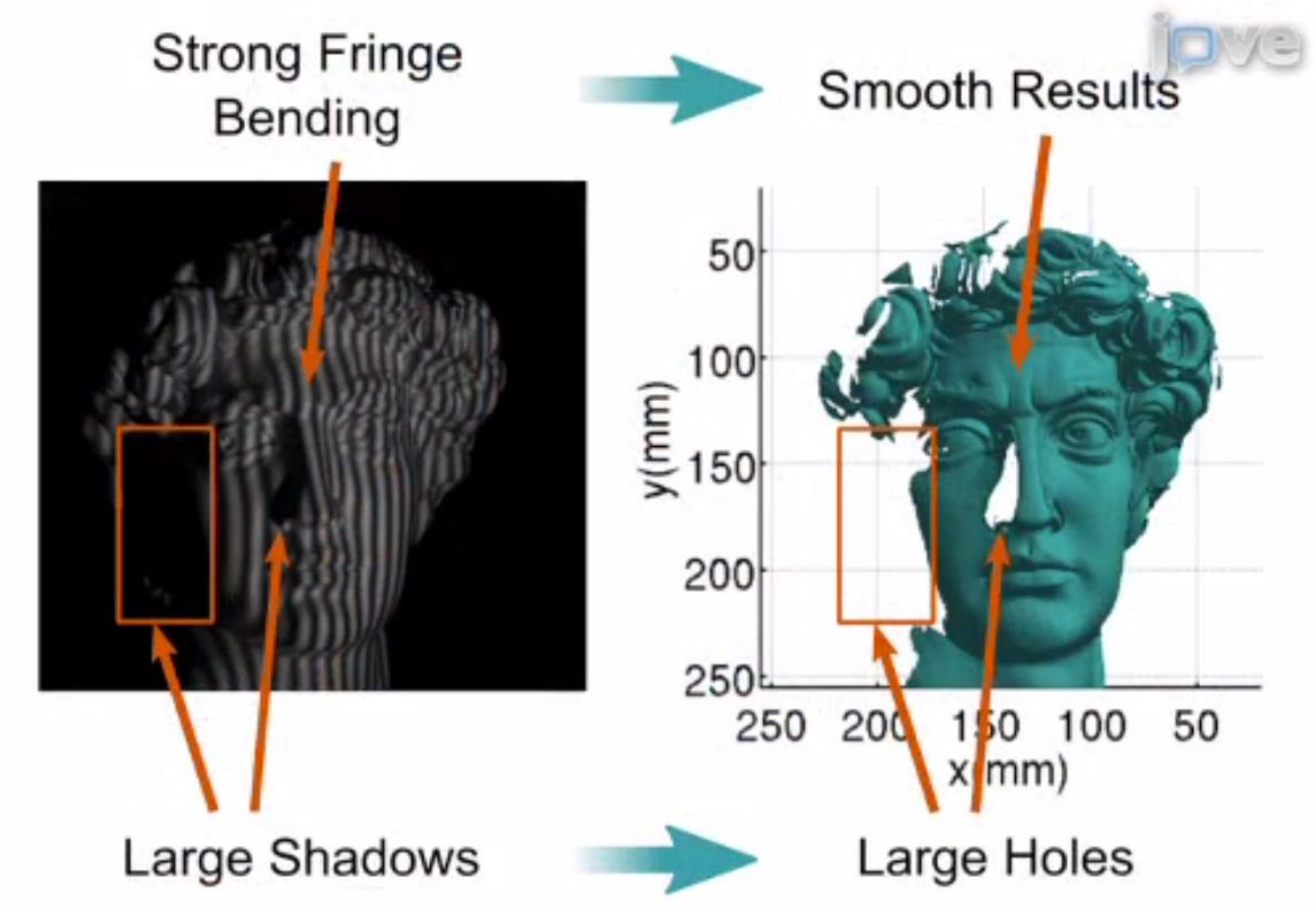


For details on generating dithered sinusoid patterns, see Wang and Zhang, Applied Optics 51(27) 2012

System Setup



Large angle setting



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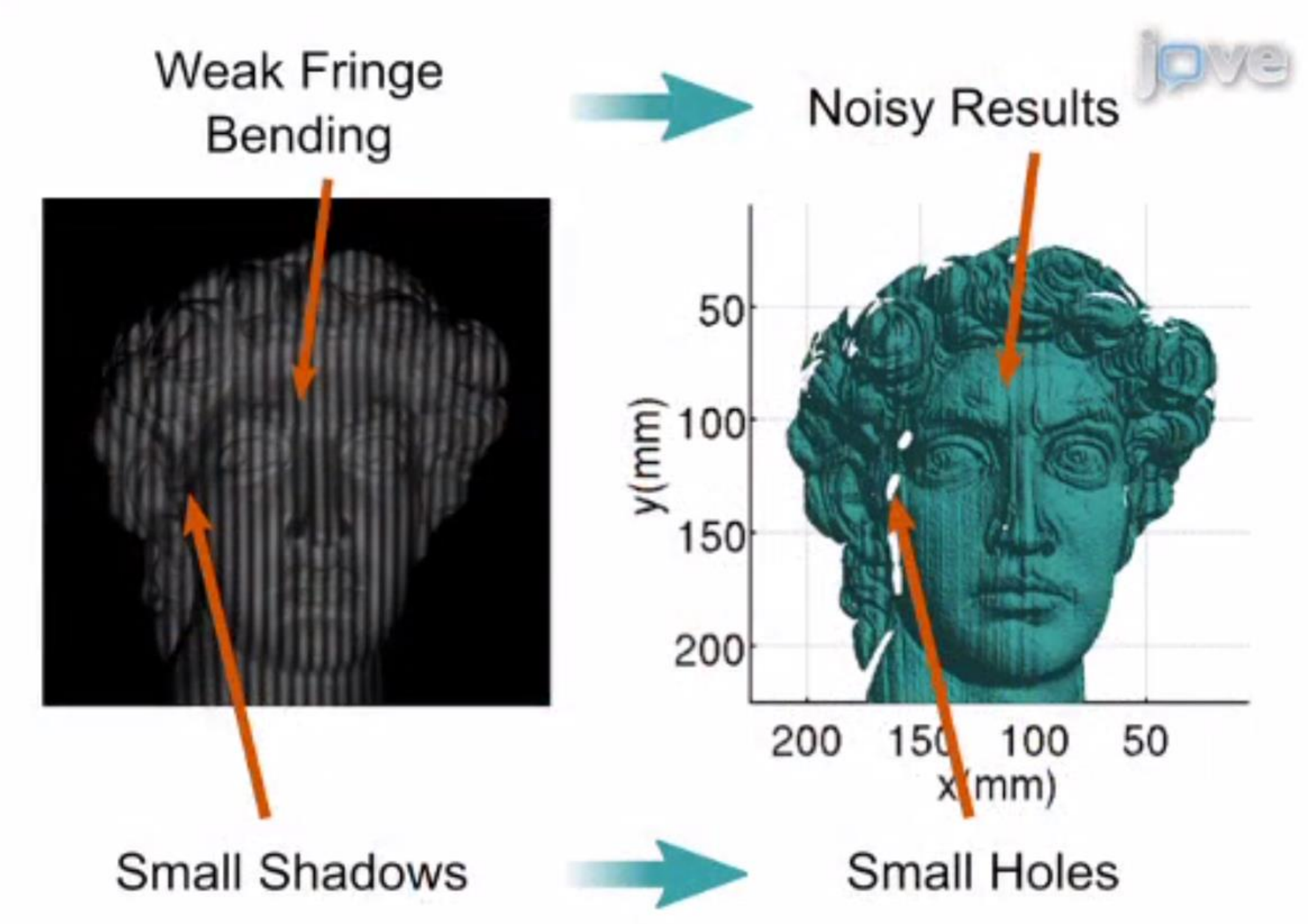
Small angle setting



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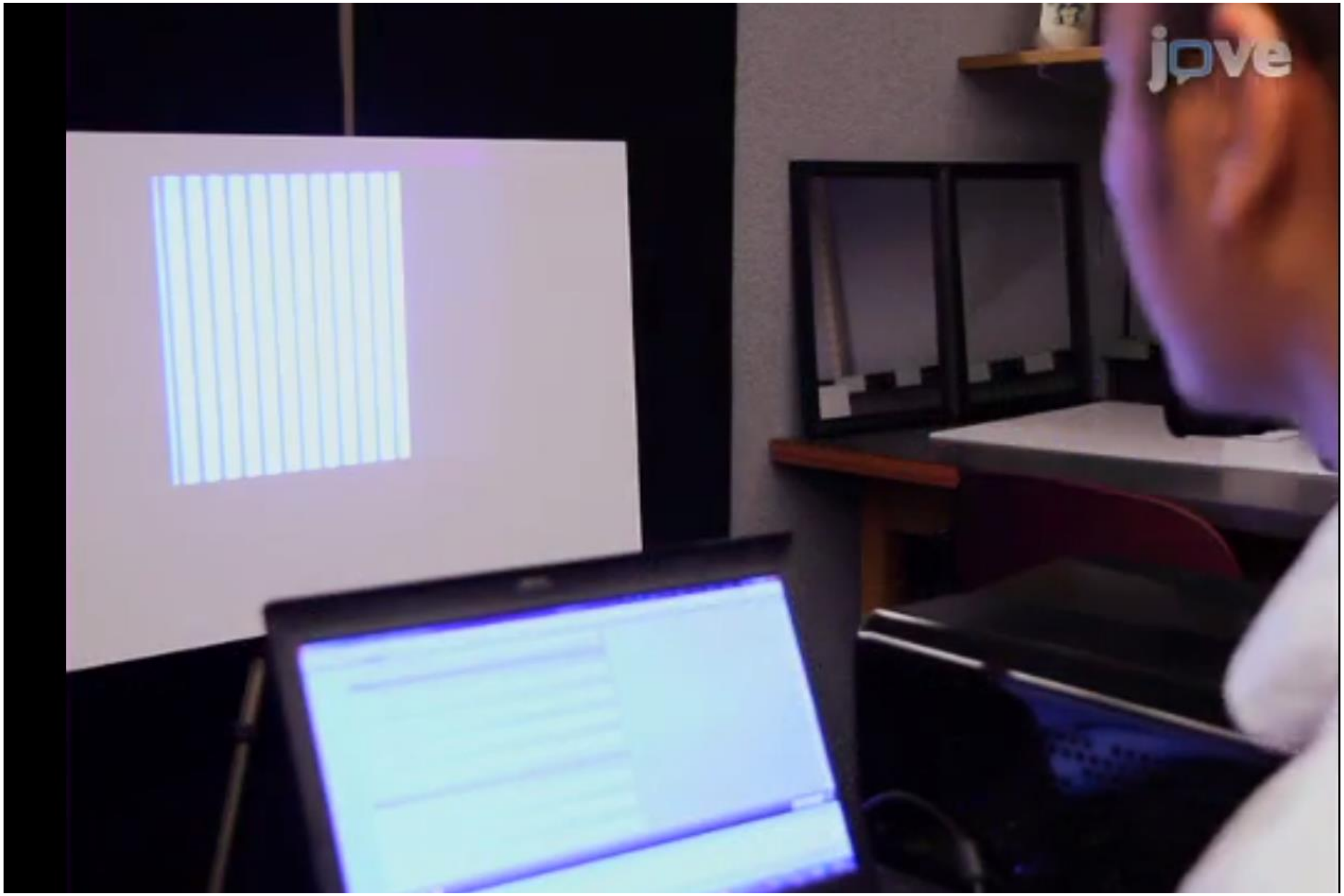
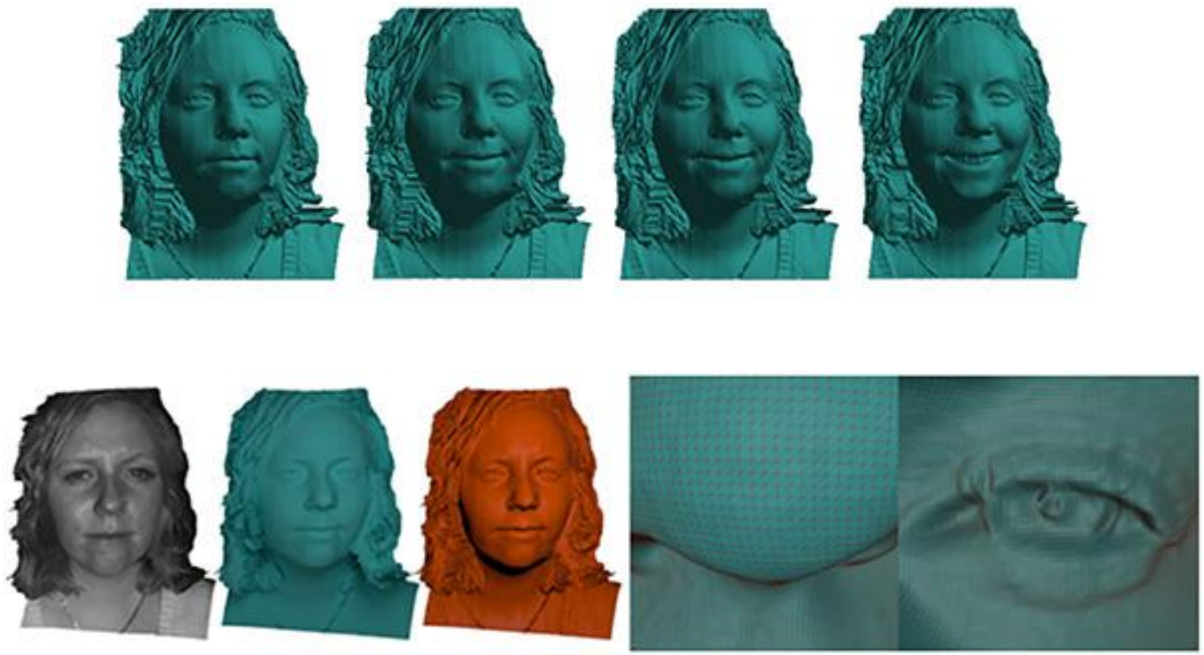
Calibration I

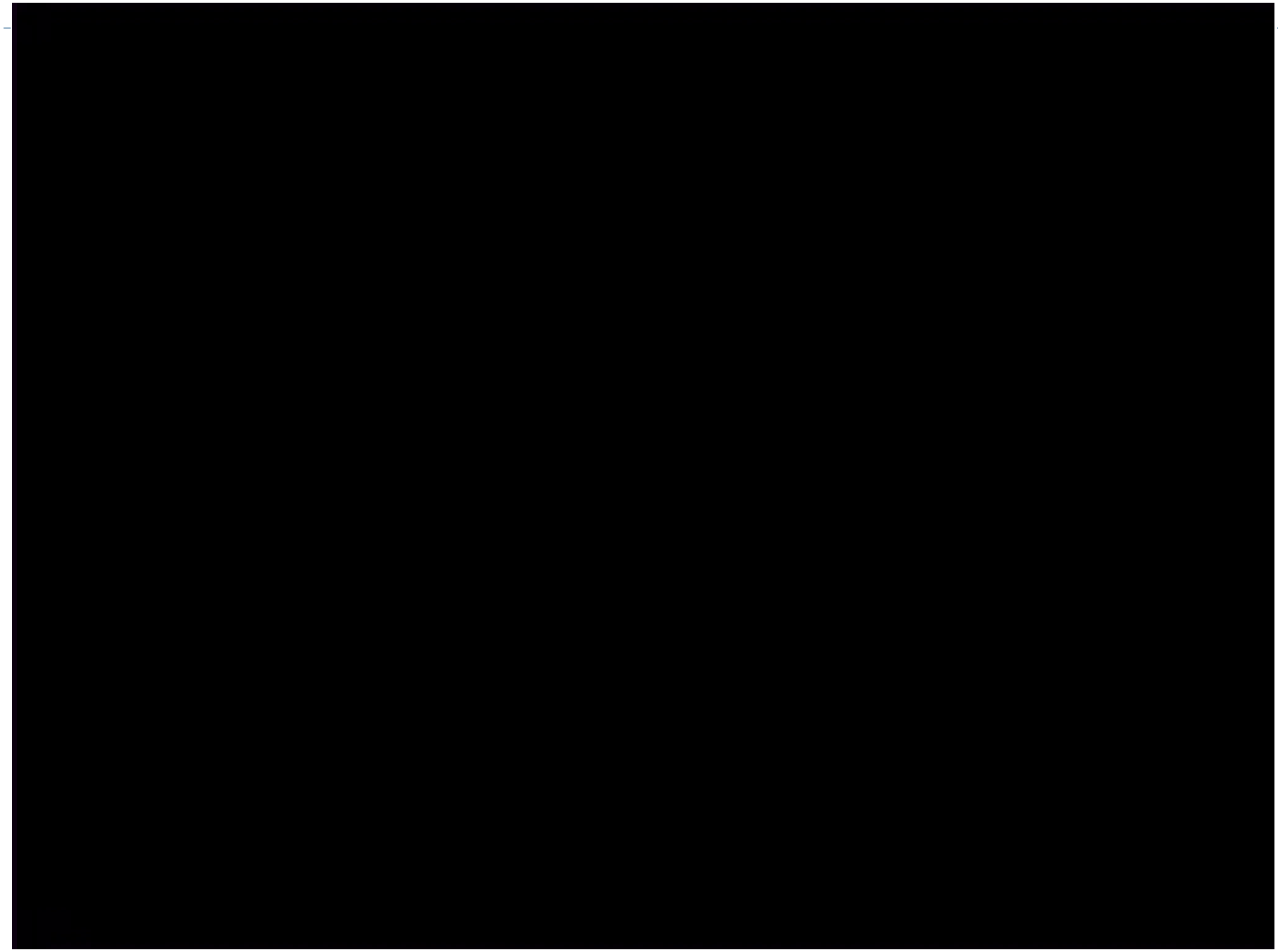


Calibration II


jove



http://www.jove.com/video/50421/high-resolution-high-speed-three-dimensional-video-imaging-with



Thanks you!!

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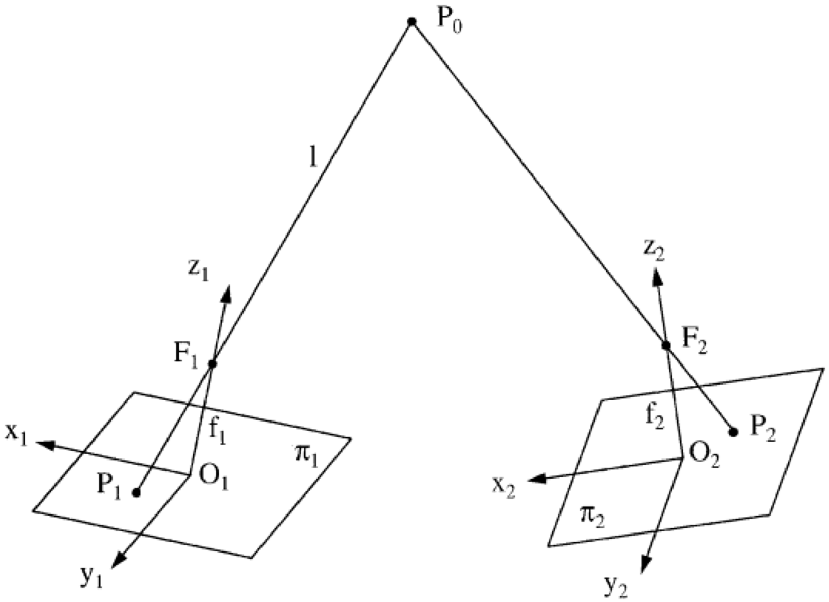
http://kowon.dongseo.ac.kr/~lbg/



Pergamon

Pattern Recognition, Vol. 31, No. 7, pp. 963–982, 1998

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PII: S0031-3203(97)00074-5

RECENT PROGRESS IN CODED STRUCTURED LIGHT AS A TECHNIQUE TO SOLVE THE CORRESPONDENCE PROBLEM: A SURVEY

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(*Received 5 December* 1996)

Abstract—We present a survey of the most significant techniques, used in the last few years, concerning the coded structured light methods employed to get 3D information. In fact, depth perception is one of the most important subjects in computer vision. Stereovision is an attractive and widely used method, but, it is rather limited to make 3D surface maps, due to the correspondence problem. The correspondence problem can be improved using a method based on structured light concept, projecting a given pattern on the measuring surfaces. However, some relations between the projected pattern and the reflected one must be solved. This relationship can be directly found codifying the projected light, so that, each imaged region of the projected pattern carries the needed information to solve the correspondence problem. © 1998 Pattern Recognition Society. Published by Elsevier Science Ltd. All rights reserved.

Pattern projection Correspondence problem Active stereo Depth perception Range data Computer vision.

General Stereoscopic System

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General Stereoscopic System

$$\begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = \mathbf{R} \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} + \mathbf{T}$$

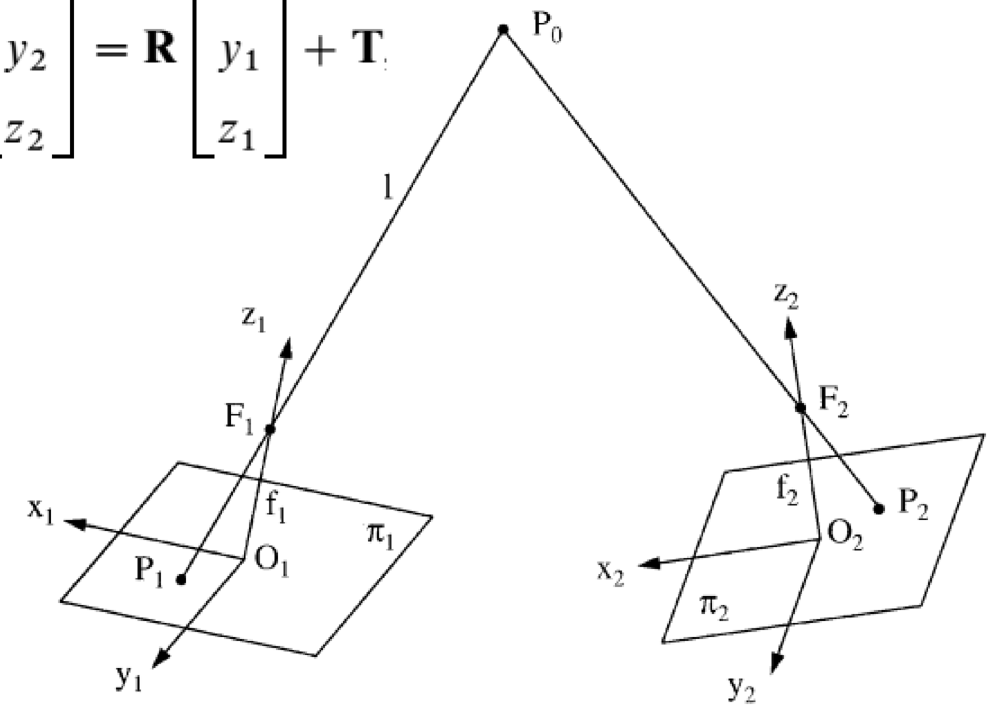


Fig. 1. A general stereoscopic system made by the relationship between two optical sensors.

$$P_1 = F_1 + \alpha(P_0 - F_1)$$

$$\begin{bmatrix} x_{p1} \\ y_{p1} \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ f_1 \end{bmatrix} + \alpha \begin{bmatrix} x_{p0} \\ y_{p0} \\ z_{p0} - f_1 \end{bmatrix}$$

$$\frac{x_{p0}}{x_{p1}} = \frac{y_{p0}}{y_{p1}} = \frac{f_1 - z_{p0}}{f_1}$$

$$\frac{x'_{p0}}{x_{p2}} = \frac{y'_{p0}}{y_{p2}} = \frac{f_2 - z'_{p0}}{f_2}.$$

Simple Stereoscopic System

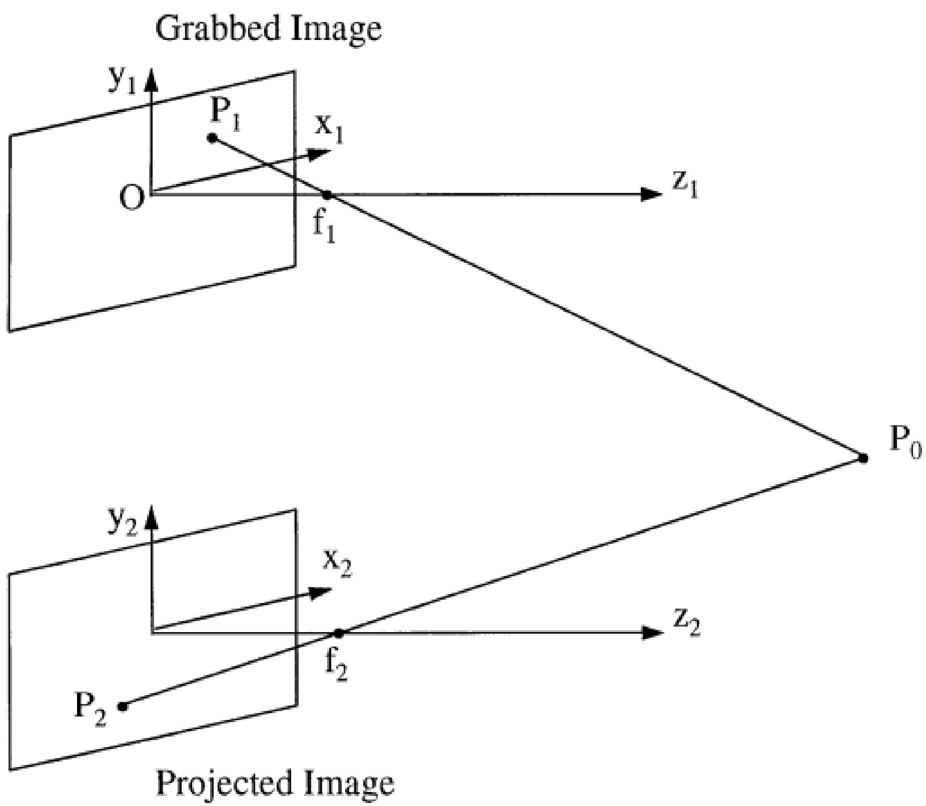


Fig. 2. Measurement system used in structured light

$$P_1 = F_1 + \alpha(P_0 - F_1)$$

$$\begin{bmatrix} x_{p1} \\ y_{p1} \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ f_1 \end{bmatrix} + \alpha \begin{bmatrix} x_{p0} \\ y_{p0} \\ z_{p0} - f_1 \end{bmatrix}.$$

$$O_2 = \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix}. \quad F_2 = \begin{bmatrix} x_2 \\ y_2 \\ z_2 + f_2 \end{bmatrix}.$$

$$P_2 = \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} + \begin{bmatrix} x_{p2} \\ y_{p2} \\ 0 \end{bmatrix} = \begin{bmatrix} x_2 + x_{p2} \\ y_2 + y_{p2} \\ z_2 \end{bmatrix}.$$

Simple Stereoscopic System

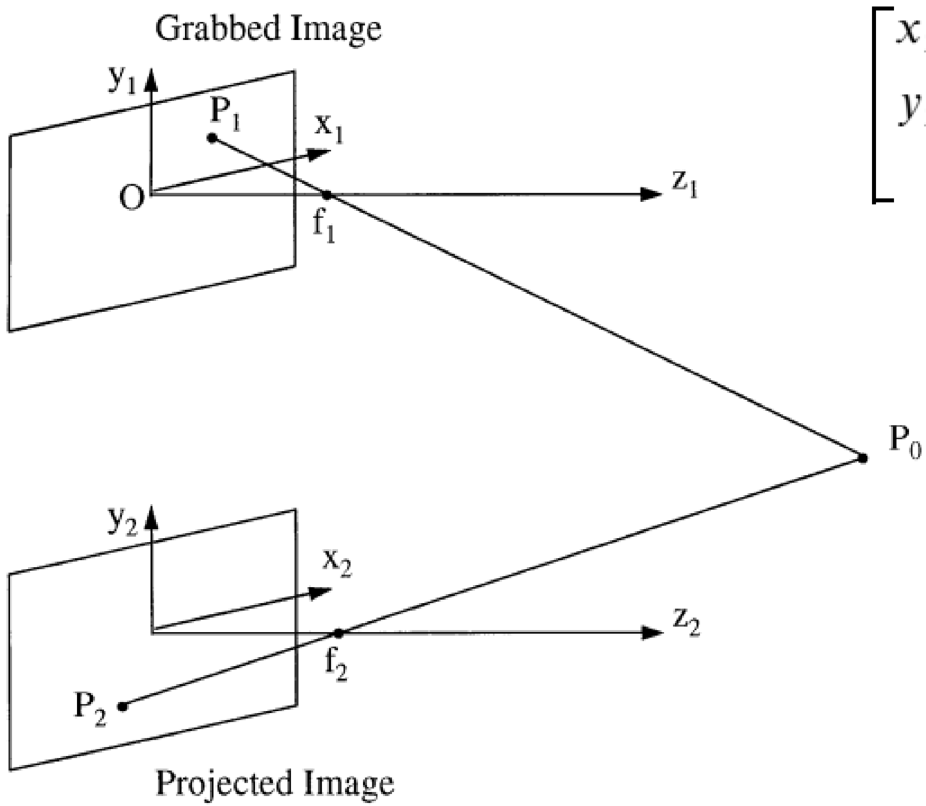


Fig. 2. Measurement system used in structured light

$$P_2 = F_2 + \beta(P_0 - F_2)$$

$$\begin{bmatrix} x_2 + x_{p2} \\ y_2 + y_{p2} \\ z_2 \end{bmatrix} = \begin{bmatrix} x_2 \\ y_2 \\ z_2 + f_2 \end{bmatrix} + \beta \begin{bmatrix} x_{p0} - x_2 \\ y_{p0} - y_2 \\ z_{p0} - z_2 - f_2 \end{bmatrix}$$

$$x_{p0} = \frac{f_1 - z_{p0}}{f_1} x_{p1},$$

$$y_{p0} = \frac{f_1 - z_{p0}}{f_1} y_{p1},$$

$$x_{p0} = x_2 + \frac{f_2 + z_2 - z_{p0}}{f_2} x_{p2},$$

$$y_{p0} = y_2 + \frac{f_2 + z_2 - z_{p0}}{f_2} y_{p2}.$$

Simple Stereoscopic System

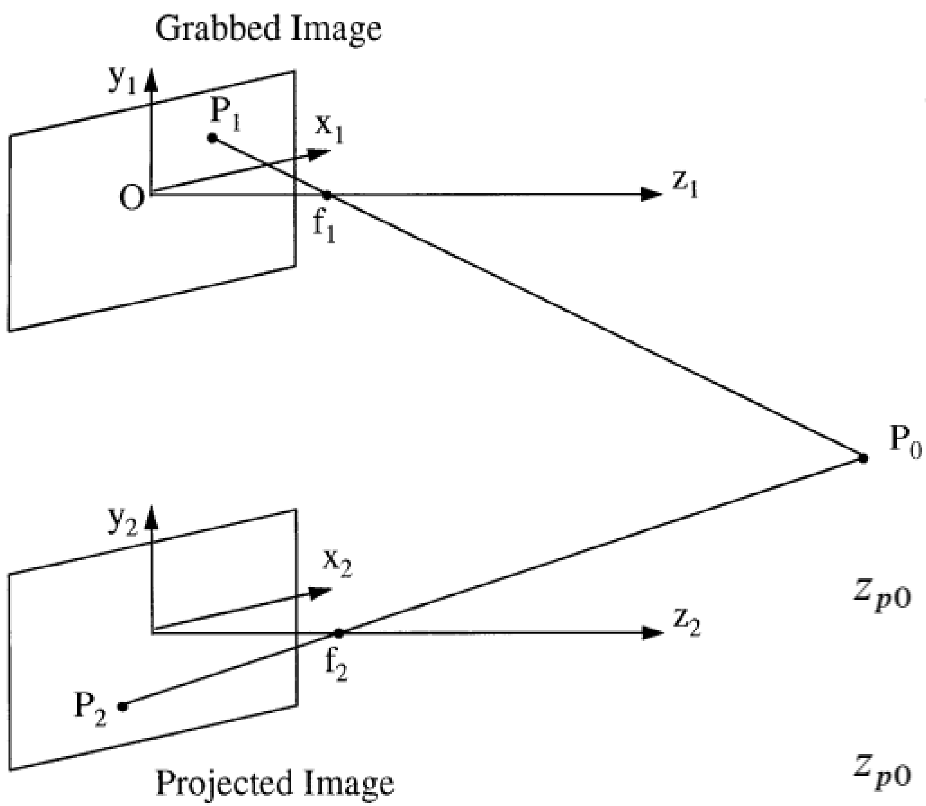


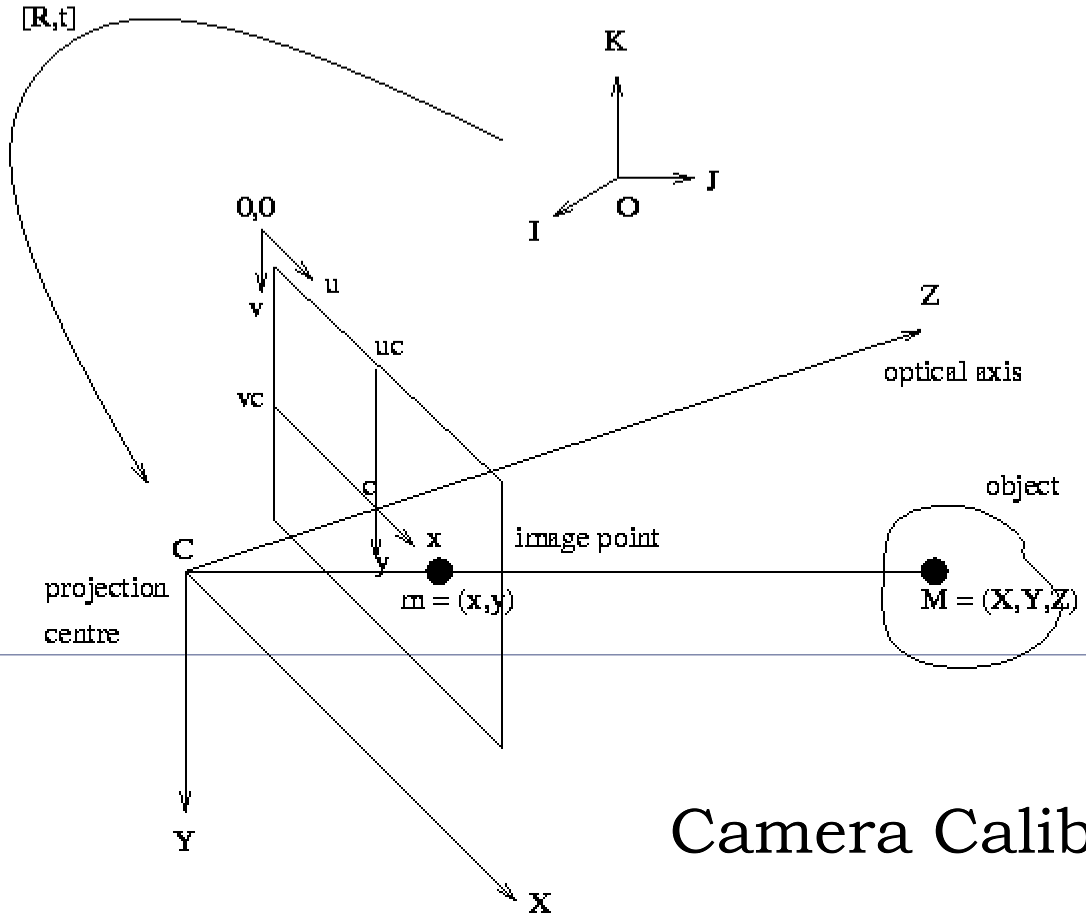
Fig. 2. Measurement system used in structured light

$$\frac{f_1 - z_{p0}}{f_1} x_{p1} = x_2 + \frac{f_2 + z_2 - z_{p0}}{f_2} x_{p2},$$

$$\frac{f_1 - z_{p0}}{f_1} y_{p1} = y_2 + \frac{f_2 + z_2 - z_{p0}}{f_2} y_{p2}.$$

$$z_{p0} = \frac{f_1 f_2}{f_1 x_{p2} - f_2 x_{p1}} \left(x_2 + x_{p2} - x_{p1} + \frac{z_2 x_{p2}}{f_2} \right).$$

$$z_{p0} = \frac{f_1 f_2}{f_1 y_{p2} - f_2 y_{p1}} \left(y_2 + y_{p2} - y_{p1} + \frac{z_2 y_{p2}}{f_2} \right).$$



Camera Calibration

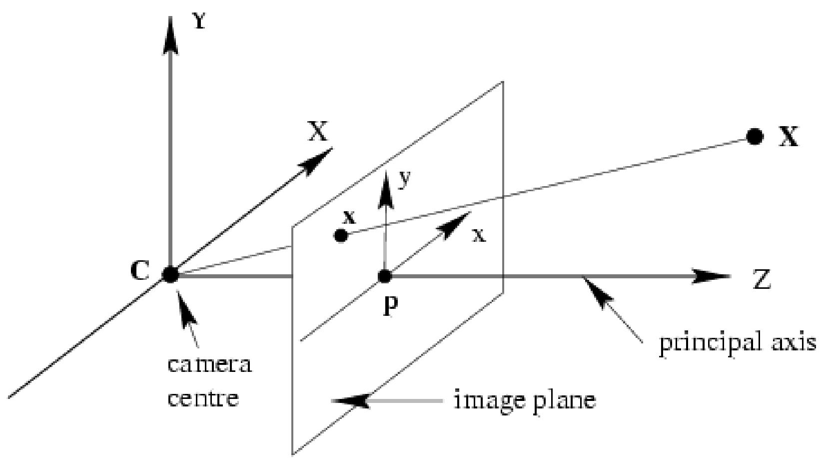
lbg@dongseo.ac.kr

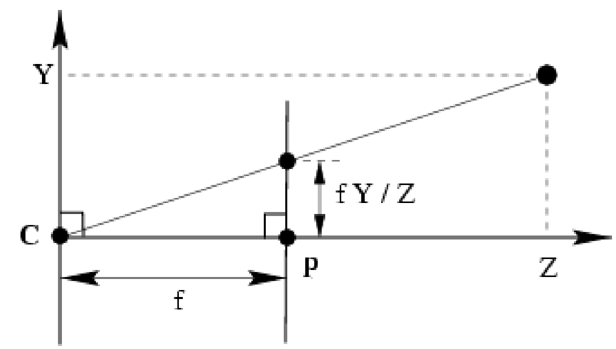
Pinhole Camera Model

$$(X,Y,Z)^T \mapsto (fX/Z, fY/Z)^T$$

$$\begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix} \mapsto \begin{pmatrix} fX \\ fY \\ Z \end{pmatrix} = \begin{bmatrix} f & & & 0 \\ & f & & 0 \\ & & 1 & 0 \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$

$$\begin{pmatrix} fX \\ fY \\ Z \end{pmatrix} = \begin{bmatrix} f & & \\ & f & \\ & & 1 \end{bmatrix} \begin{bmatrix} 1 & & & 0 \\ & 1 & & 0 \\ & & 1 & 0 \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$



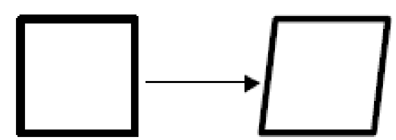


Internal Camera Parameters

$$\begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = \begin{bmatrix} \alpha_x & s & x_0 & 0 \\ 0 & \alpha_y & y_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_s \\ y_s \\ z_s \\ 1 \end{bmatrix} \quad \text{with} \quad \begin{array}{l} \alpha_x = f\, k_x \\ \alpha_y = -f\, k_y \end{array} \qquad \begin{array}{l} x_{pix} = u'/w' \\ y_{pix} = v'/w' \end{array}$$

$$\begin{bmatrix} \alpha_x & s & x_0 & 0 \\ 0 & \alpha_y & y_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} = \begin{bmatrix} \alpha_x & s & x_0 \\ 0 & \alpha_y & y_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} = \mathbf{K}\left[\mathbf{I}_3 \quad | \quad \mathbf{0}_3\right]$$

- α_x and α_y "focal lengths" in pixels
- x_0 and y_0 coordinates of image center in pixels
- Added parameter s is skew parameter



- **K** is called *calibration matrix*. **Five degrees of freedom.**
  - **K** is a 3x3 upper triangular matrix

Camera rotation and translation

$$\tilde{X}_{cam} = R(\tilde{X} - \tilde{C})$$

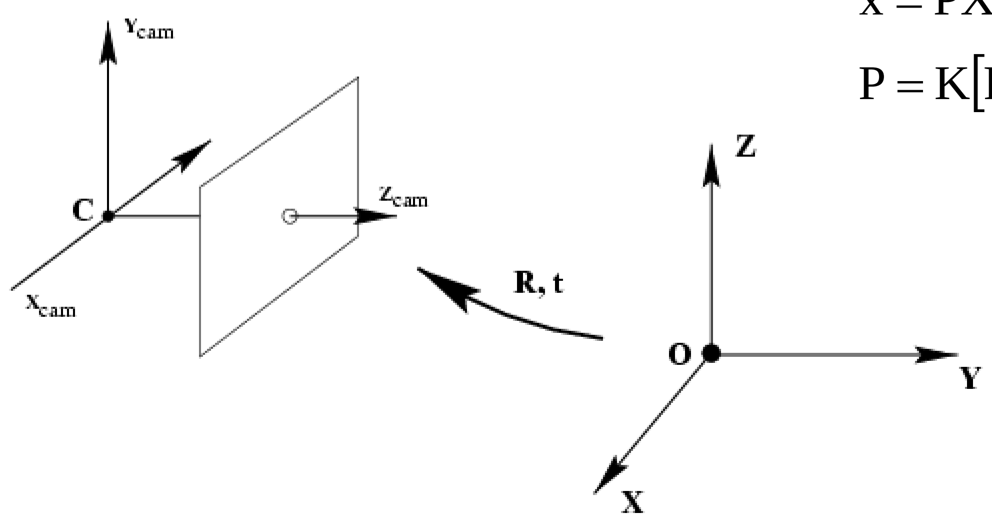
$$X_{cam} = \begin{bmatrix} R & -R\tilde{C} \\ 0 & 1 \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix} = \begin{bmatrix} R & -RC \\ 0 & 1 \end{bmatrix} X$$

$$x = K[I \mid 0] X_{cam}$$

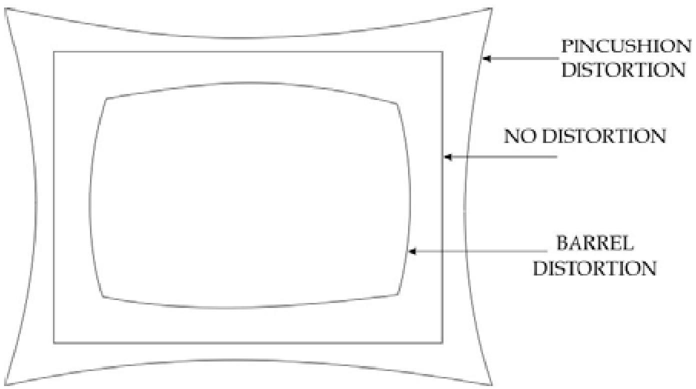
$$x = KR[I \mid -\tilde{C}] X$$

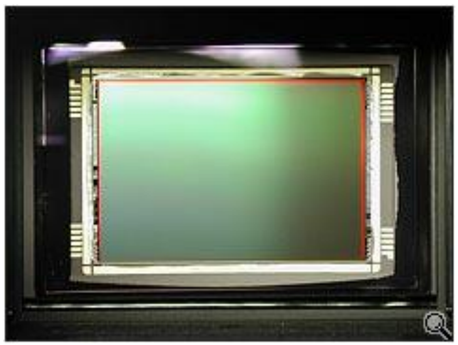
$$x = PX$$

$$P = K[R \mid t] \quad t = -R\tilde{C}$$

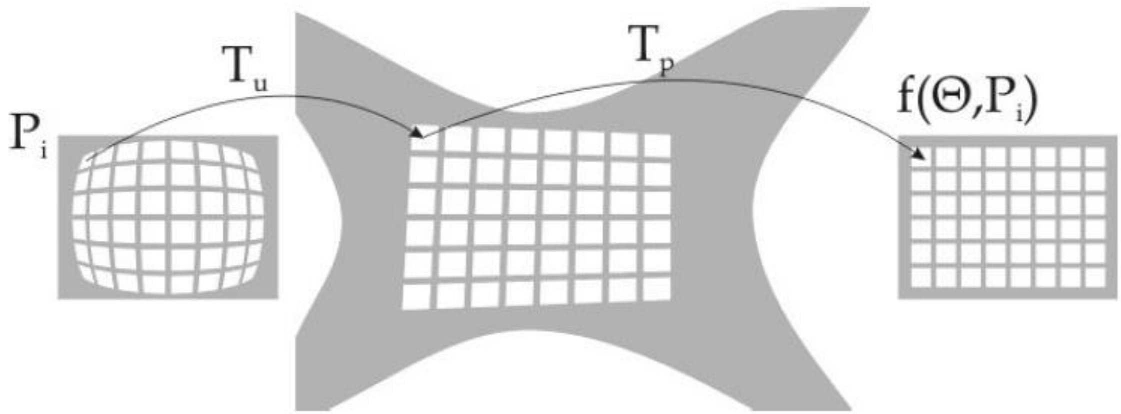


Camera Distortion





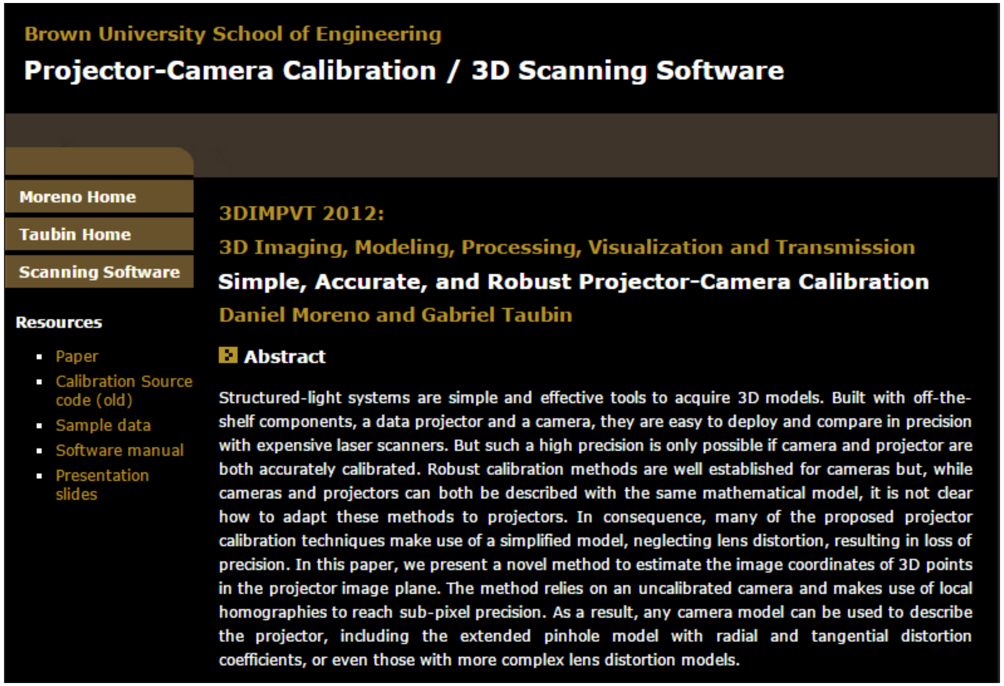
Correcting Radial Distortion of Cameras



$$
\begin{aligned}
x_u &= c_x + (x_d - c_x)\, f_2(r_d^2) \\
&= c_x + (x_d - c_x)(1 + k_1 r_d^2 + k_2 r_d^4 + k_3 r_d^6) \\
y_u &= c_y + (y_d - c_y)\, f_2(r_d^2) \\
&= c_y + (y_d - c_y)(1 + k_1 r_d^2 + k_2 r_d^4 + k_3 r_d^6) \\
r_d^2 &= (x_d - c_x)^2 + (y_d - c_y)^2
\end{aligned}
$$

$$
x_p = \frac{m_0 x_u + m_1 y_u + m_2}{m_6 x_u + m_7 y_u + 1}
$$

$$
y_p = \frac{m_3 x_u + m_4 y_u + m_5}{m_6 x_u + m_7 y_u + 1}
$$


Brown University School of Engineering

Projector-Camera Calibration / 3D Scanning Software

- Moreno Home
- Taubin Home
- Scanning Software

Resources

- Paper
- Calibration Source code (old)
- Sample data
- Software manual
- Presentation slides

3DIMPVT 2012:

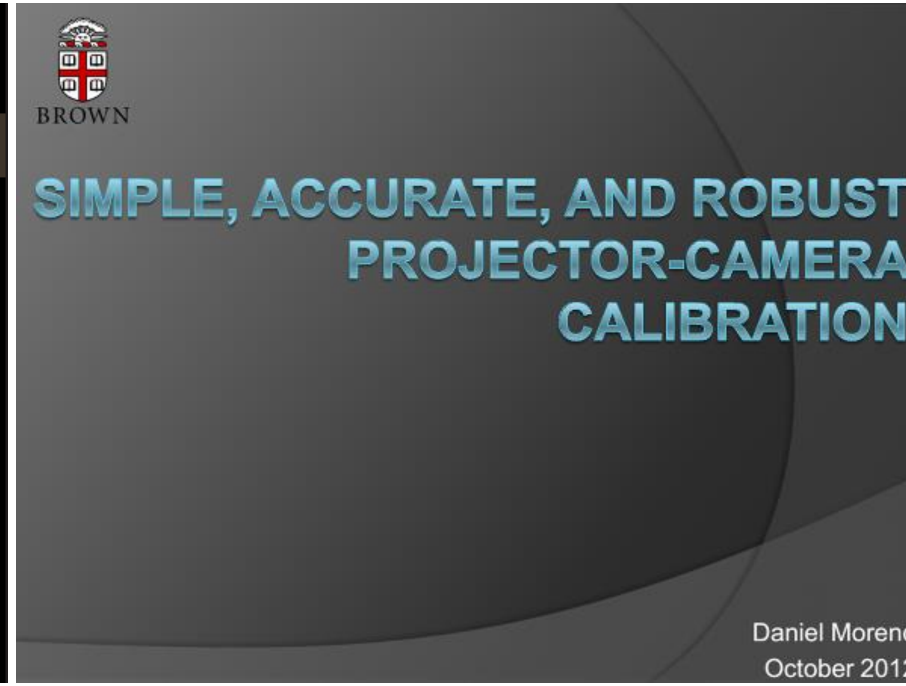
3D Imaging, Modeling, Processing, Visualization and Transmission

Simple, Accurate, and Robust Projector-Camera Calibration

Daniel Moreno and Gabriel Taubin

Abstract

Structured-light systems are simple and effective tools to acquire 3D models. Built with off-the-shelf components, a data projector and a camera, they are easy to deploy and compare in precision with expensive laser scanners. But such a high precision is only possible if camera and projector are both accurately calibrated. Robust calibration methods are well established for cameras but, while cameras and projectors can both be described with the same mathematical model, it is not clear how to adapt these methods to projectors. In consequence, many of the proposed projector calibration techniques make use of a simplified model, neglecting lens distortion, resulting in loss of precision. In this paper, we present a novel method to estimate the image coordinates of 3D points in the projector image plane. The method relies on an uncalibrated camera and makes use of local homographies to reach sub-pixel precision. As a result, any camera model can be used to describe the projector, including the extended pinhole model with radial and tangential distortion coefficients, or even those with more complex lens distortion models.



Daniel Moreno and Gabriel Taubin
Brown University School of Engineering
Projector-Camera Calibration / 3D Scanning Software
http://mesh.brown.edu/calibration/

Projector Calibration

lbg@dongseo.ac.kr

Projector calibration: ?

Use the pinhole model to describe the projector:

- Projectors work as an inverse camera

$$K_{proj} = \begin{bmatrix} fx & s & cx \\ 0 & fy & cy \\ 0 & 0 & 1 \end{bmatrix}$$

$$x = K_{proj} \cdot L(X; k_1, k_2, k_3, k_4)$$

If we model the projector the same as our camera, we would like to calibrate the projector just as we do for the camera:

- We need correspondences between 3D world points and projector image plane points: $X \leftrightarrow x$
- The projector cannot capture images

Challenge: How do we find point correspondences?

Related works

There have been proposed several projector calibration methods*, they can be divided in three groups:

1. Rely on camera calibration
   - First the camera is calibrated, then, camera calibration is used to find the 3D world coordinates of the projected pattern
   - Inaccuracies in the camera calibration translates into errors in the projector calibration
2. Find projector correspondences using homographies between planes
   - Cannot model projector lens distortion because of the linearity of the transformation
3. Too difficult to perform
   - Required special equipments or calibration artifacts
   - Required color calibration
   - …

(*) See the paper for references

Existing methods were not accurate enough or not practical

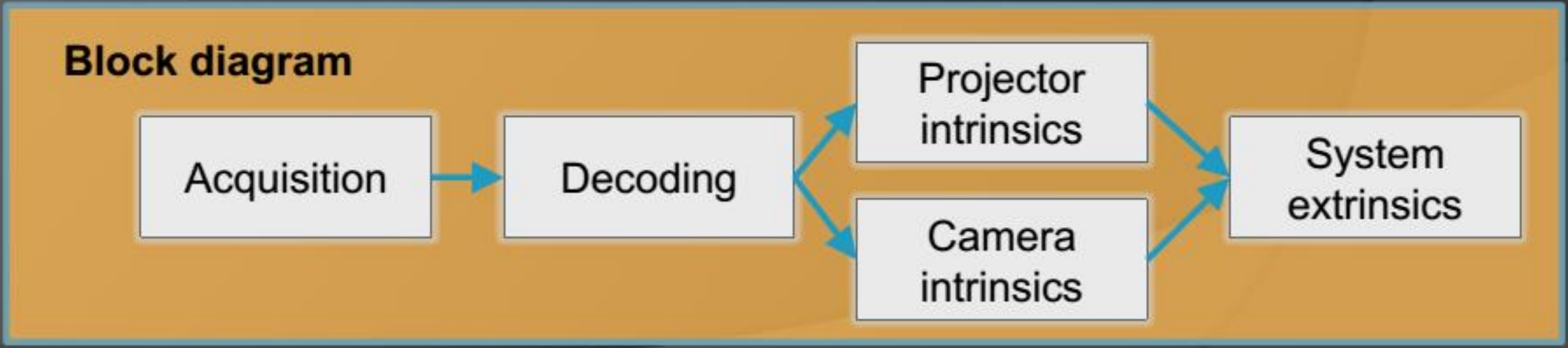
Proposed method: overview

Features:

Simple to perform:
- no special equipment required
- reuse existing components

Accurate:
- there are no constrains for the mathematical model used to describe the projector
- we use the full pinhole model with radial distortion (as for cameras)

Robust:
- can handle small decoding errors



Proposed method: acquisition

Traditional camera calibration

- requires a planar checkerboard (easy to make with a printer)
- capture pictures of the checkerboard from several viewpoints

Structured-light system calibration

- use a planar checkerboard
- capture structured-light sequences of the checkerboard from several viewpoints

Proposed method: decoding

Decoding depends on the projected pattern

- The method does not rely on any specific pattern

Our implementation uses complementary gray code patterns

- Robust to light conditions and different object colors (notice that we used the standard B&W checkerboard)
- Does not required photometric calibration (as phase-shifting does)
- We prioritize calibration accuracy over acquisition speed
- Reasonable fast to project and capture: if the system is synchronized at 30fps, the 42 images used for each pose are acquired in 1.4 seconds

Our implementation decodes the pattern using "robust pixel classification"(*)

- High-frequency patterns are used to separate direct and global light components for each pixel
- Once direct and global components are known each pixel is classified as ON, OFF, or UNCERTAIN using a simple set of rules

(*) Y. Xu and D. G. Aliaga, "Robust pixel classification for 3D modeling with structured light"

Conclusions

- It works ☺
- No special setup or materials required
- Very similar to standard stereo camera calibration
- Reuse existing software components
  - Camera calibration software
  - Structured-light projection, capture, and decoding software
- Local homographies effectively handle projector lens distortion
- Adding projector distortion model improves calibration accuracy
- Well-calibrated structured-light systems have a precision comparable to some laser scanners

엠비언트 인텔리전스 연구소
Institute of Ambient Intelligence

Thanks you!!

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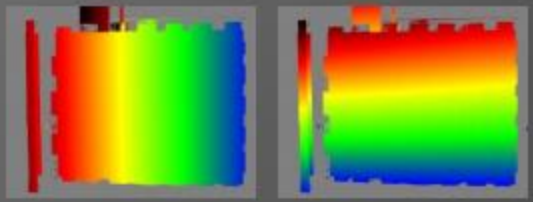
Dongseo University
동서대학교

Proposed method: projector calibration

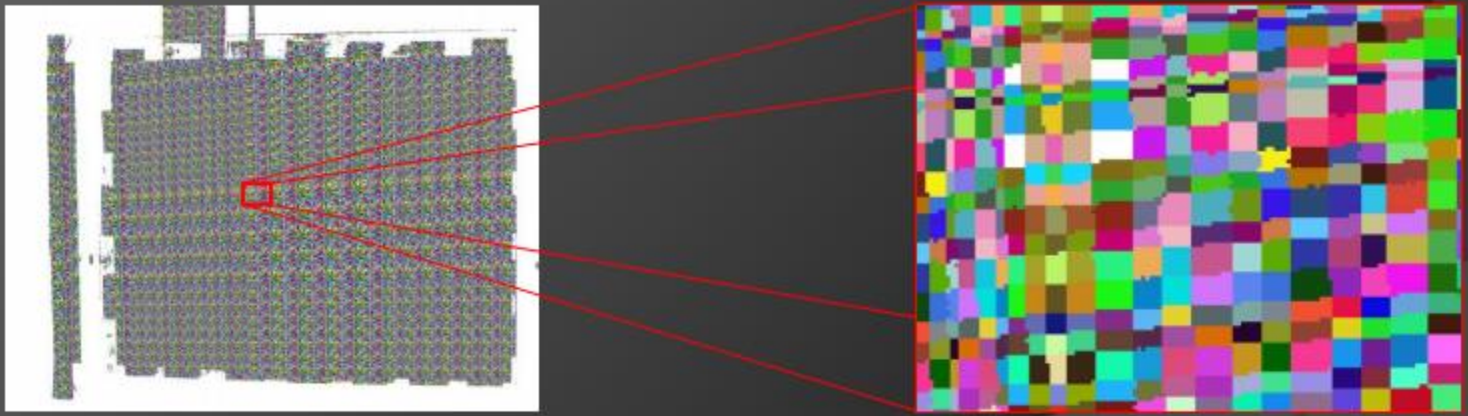
Once the structured-light pattern is decoded we have a mapping between projector and camera pixels:

1) Each camera pixel is associated to a projector row and column, or set to UNCERTAIN



For each (x, y): Map(x, y) = (row, col) or UNCERTAIN

2) The map is not bijective: many camera pixels corresponds to the same projector pixel

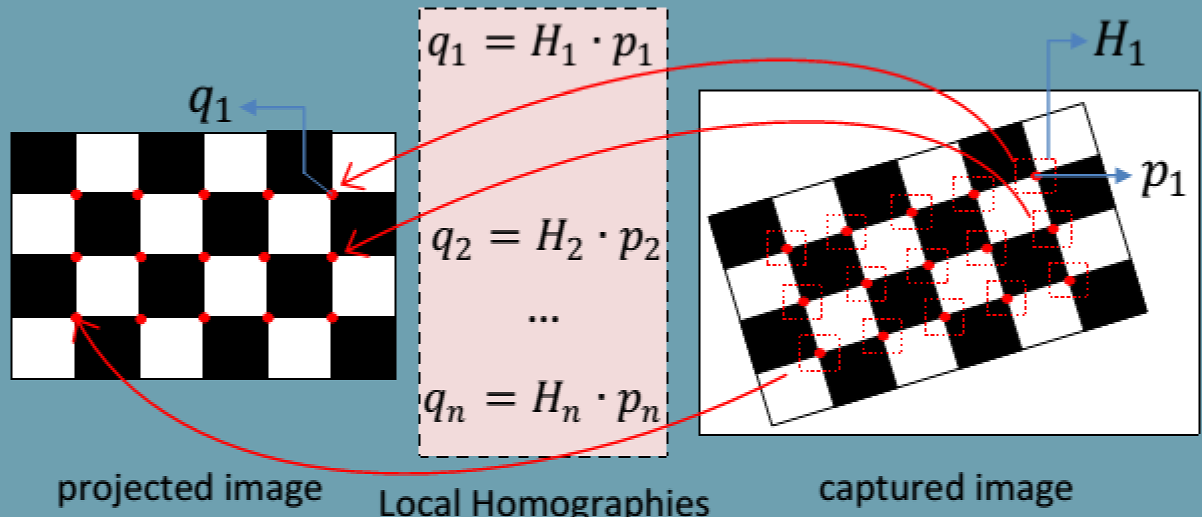


3) Checkerboard corners are not located at integer pixel locations

Proposed method: projector calibration

Solution: local homographies

1. Surface is locally planar: actually the complete checkerboard is a plane
2. Radial distortion is negligible in a small neighborhood
3. Radial distortion is significant in the complete image:
    - a single global homography is not enough



For each checkerboard corner solve:

$$\hat{H} = \underset{H}{argmin} \sum_{\forall p} \|q - Hp\|^2, \qquad \bar{q} = \hat{H} \cdot p$$

$$\hat{H} \in \mathbb{R}^{3\times3},\ p = [x, y, 1]^T,\ q = [col, row, 1]^T$$

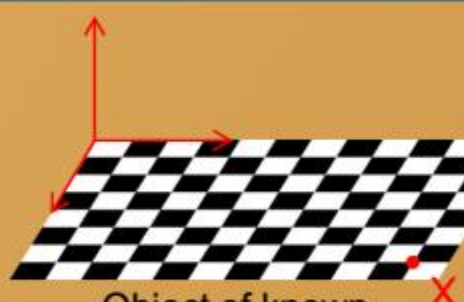
Proposed method: projector calibration

Summary:

1. Decode the structured-light pattern: camera ↔ projector map
2. Find checkerboard corner locations in camera image coordinates
3. Compute a local homography H for each corner
4. Translate each corner from image coordinates x to projector coordinates x' applying the corresponding local homography H

$$x' = H \cdot x$$

5. Using the correspondences between the projector corner coordinates and 3D world corner locations, $X \leftrightarrow x'$, find projector intrinsic parameters



Object of known dimensions

$$x'_1 = K_{proj} \cdot L(R_1 X + T_1; k_1, k_2, k_3, k_4)$$

$$x'_2 = K_{proj} \cdot L(R_2 X + T_2; k_1, k_2, k_3, k_4)$$

$$x'_3 = K_{proj} \cdot L(R_3 X + T_3; k_1, k_2, k_3, k_4)$$

...

No difference with camera calibration!!

Camera calibration and system extrinsics

Camera intrinsics

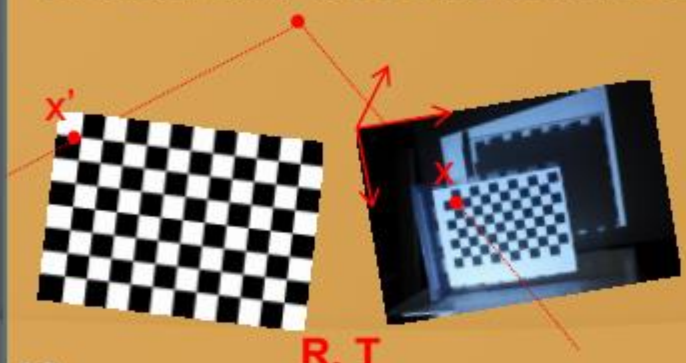
Using the corner locations in image coordinates and their 3D world coordinates, we calibrate the camera as usual

- Note that no extra images are required

System extrinsics

Once projector and camera intrinsics are known we calibrate the extrinsics (R and T) parameters as is done for camera-camera systems

Using the previous correspondences, $x \leftrightarrow x'$, we fix the coordinate system at the camera and we solve for R and T:



$$\tilde{x}_1 = L^{-1}(K_{cam}^{-1} \cdot x_1; k_1, k_2, k_3, k_4) \qquad x'_1 = K_{proj} \cdot L(R \cdot \tilde{x}_1 + T; k'_1, k'_2, k'_3, k'_4)$$

$$\tilde{x}_2 = L^{-1}(K_{cam}^{-1} \cdot x_2; k_1, k_2, k_3, k_4) \qquad x'_2 = K_{proj} \cdot L(R \cdot \tilde{x}_2 + T; k'_1, k'_2, k'_3, k'_4)$$

$$\tilde{x}_3 = L^{-1}(K_{cam}^{-1} \cdot x_3; k_1, k_2, k_3, k_4) \qquad x'_3 = K_{proj} \cdot L(R \cdot \tilde{x}_3 + T; k'_1, k'_2, k'_3, k'_4)$$

... ...

Calibration software

Software

The proposed calibration method can be implemented fully automatic:

- The user provides a folder with all the images
- Press "calibrate" and the software automatically extracts the checkerboard corners, decode the structured-light pattern, and calibrates the system

Algorithm

1. Detect checkerboard corner locations for each plane orientation
2. Estimate global and direct light components
3. Decode structured-light patterns
4. Compute a local homography for each checkerboard corner
5. Translate corner locations into projector coordinates using local homographies
6. Calibrate camera intrinsics using image corner locations
7. Calibrate projector intrinsics using projector corner locations
8. Fix projector and camera intrinsics and calibrate system extrinsic parameters
9. Optionally, all the parameters, intrinsic and extrinsic, can be optimized together

Results

Comparison with existing software:

procamcalib
- Projector-Camera Calibration Toolbox
- http://code.google.com/p/procamcalib/

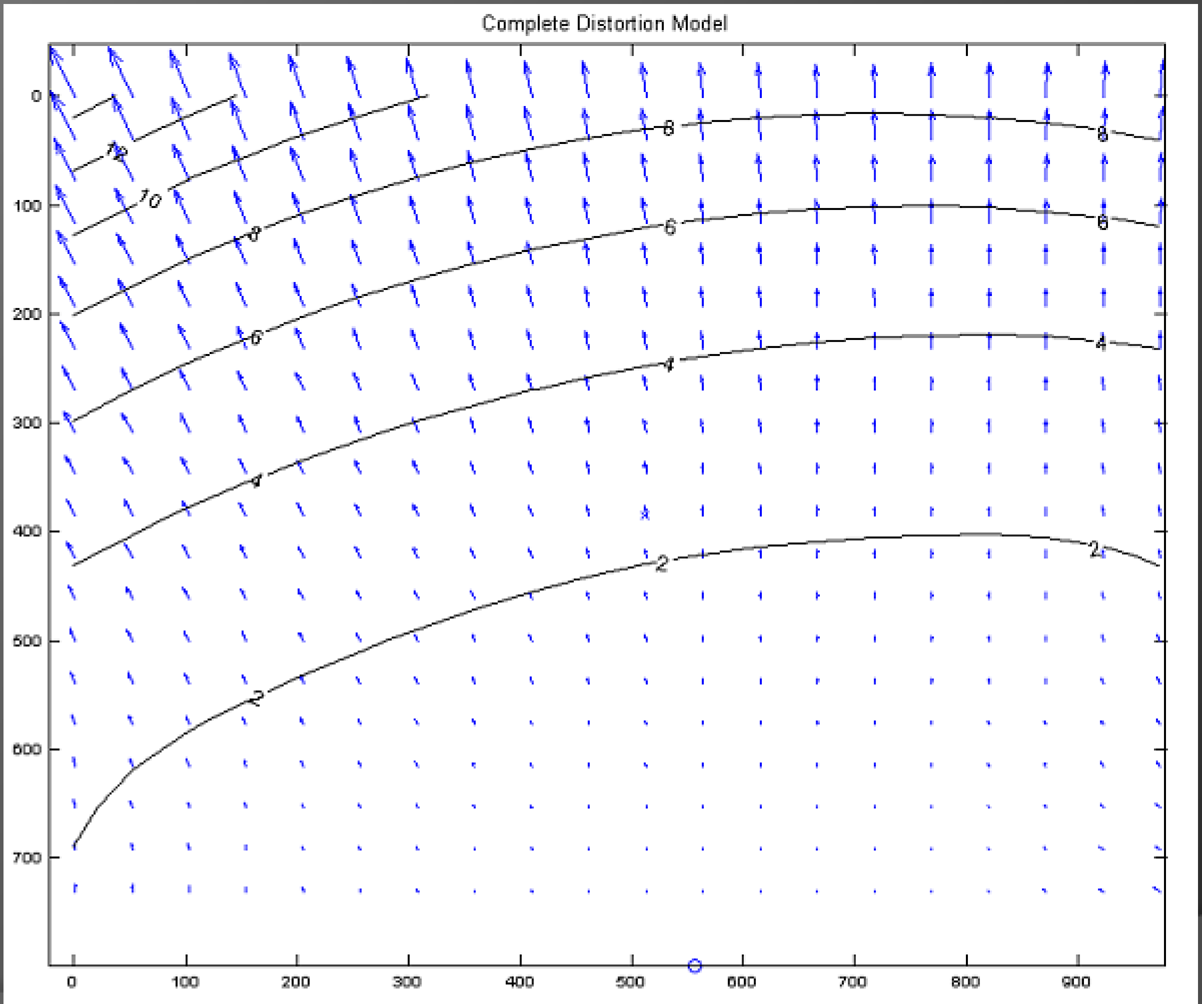
Reprojection error comparison

Method	Camera	Projector
Proposed	0.3288	0.1447
With global homography		0.2176
Procamcalib		0.8671

- Only projector calibration is compared
- Same camera intrinsics is used for all methods
- Global homography means that a single homography is used to translate all corners

Results

Example of projector lens distortion



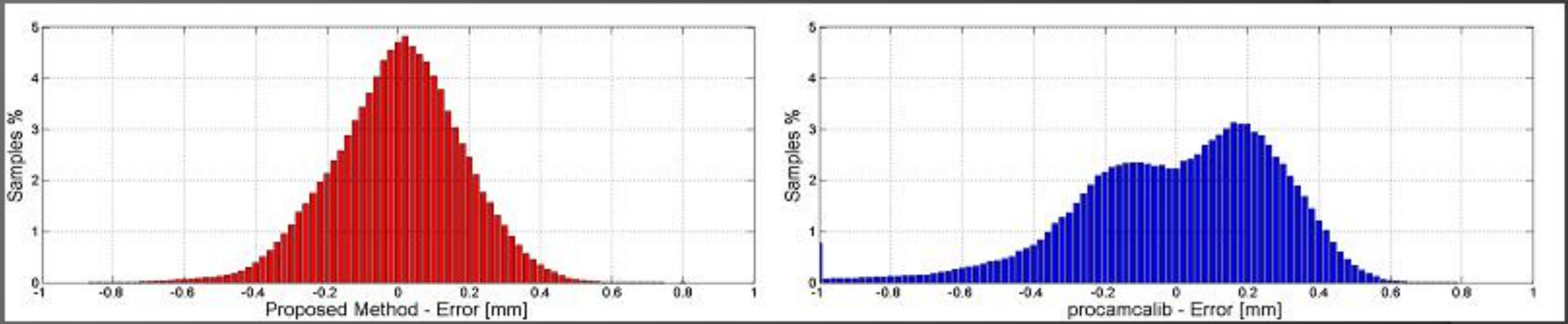
Distortion coefficients

k_1	k_2	k_3	k_4
-0.0888	0.3365	-0.0126	-0.0023

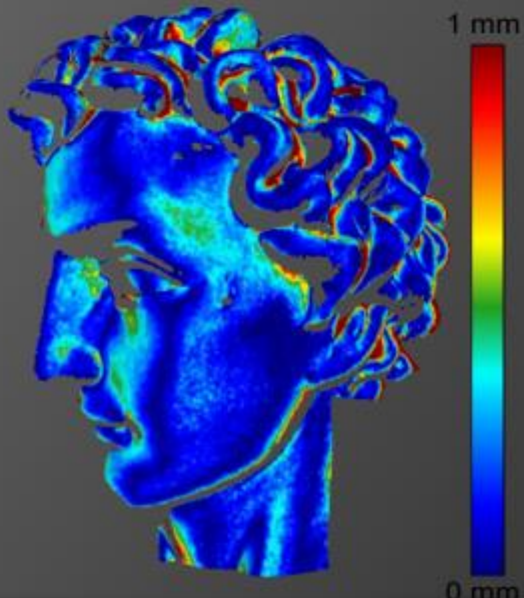
Non trivial distortion!

Results

Error distribution on a scanned 3D plane model:

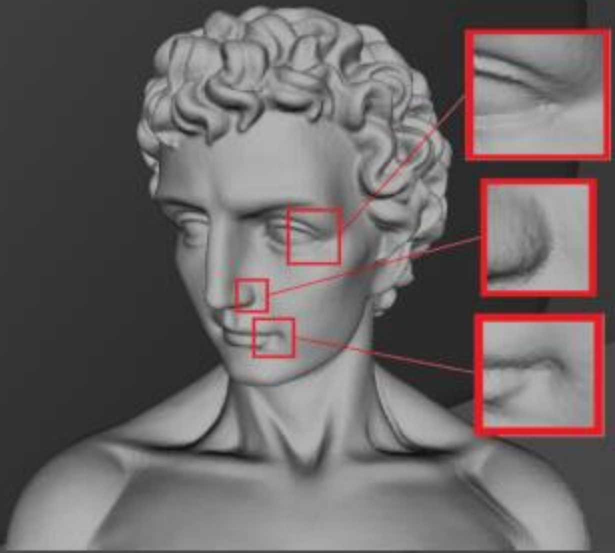


Laser scanner comparison



Hausdorff distance

3D Model



Model with small details reconstructed using SSD

ADDITIONAL

Direct/Global light components

$$L^{+} = L_d + \alpha L_g + b(1-\alpha)L_g \qquad L^{-} = bL_d + (1-\alpha)L_g + \alpha b L_g$$

$$L_d = \frac{L^{+} - L^{-}}{1-b} \qquad L_g = 2\frac{L^{-} - bL^{+}}{1-b^2} \qquad \hat{L}^{+} = \max_{0<i<K} I_i \qquad \hat{L}^{-} = \min_{0<i<K} I_i$$

Robust pixel classification

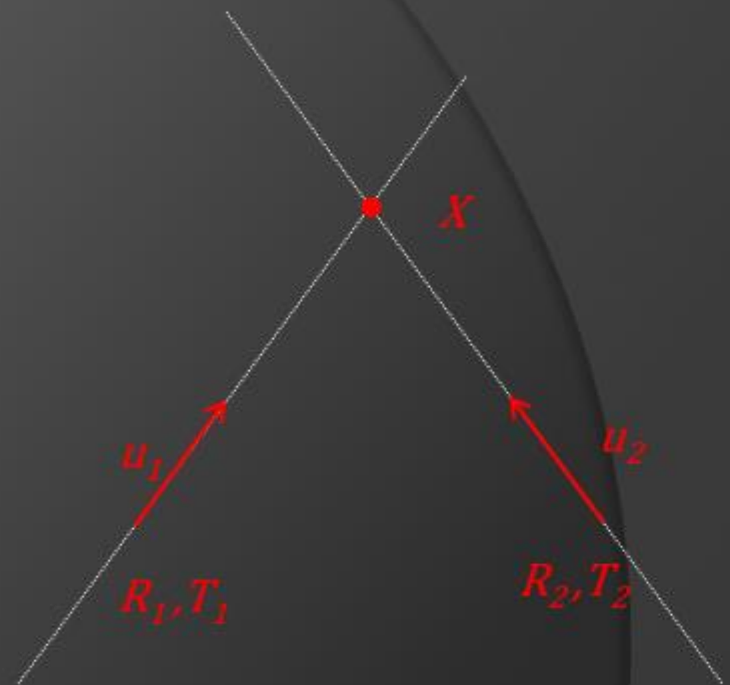
$$\begin{cases} L_d < m \rightarrow \text{UNCERTAIN} \\ L_d > L_g \wedge p > \overline{p} \rightarrow \text{ON} \\ L_d > L_g \wedge p < \overline{p} \rightarrow \text{OFF} \\ p < L_d \wedge \overline{p} > L_g \rightarrow \text{OFF} \\ p > L_g \wedge \overline{p} < L_d \rightarrow \text{ON} \\ otherwise \rightarrow \text{UNCERTAIN} \end{cases}$$

ADDITIONAL

Triangulation

$$\lambda_1 u_1 = R_1 X + T_1$$
$$\lambda_2 u_2 = R_2 X + T_2$$

$$\hat{u}_1 \lambda_1 u_1 = \hat{u}_1 R_1 X + \hat{u}_1 T_1 = 0$$
$$\hat{u}_2 \lambda_2 u_2 = \hat{u}_2 R_2 X + \hat{u}_2 T_2 = 0$$



In homogeneous coordinates:

$$\begin{bmatrix} \hat{u}_1 R_1 & \hat{u}_1 T_1 \\ \hat{u}_2 R_2 & \hat{u}_2 T_2 \end{bmatrix} X = 0$$

Calibration – Perspective Transformation

$$\begin{bmatrix} wx_{p1} \\ wy_{p1} \\ w \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \end{bmatrix} \begin{bmatrix} x_{p0} \\ y_{p0} \\ z_{p0} \\ 1 \end{bmatrix}.$$

$$A_{11}x_{p0} - A_{31}x_{p1}x_{p0} + A_{12}y_{p0} - A_{32}x_{p1}y_{p0}$$
$$+ A_{13}z_{p0} - A_{33}x_{p1}z_{p0} + A_{14} - A_{34}x_{p1} = 0,$$
$$A_{21}x_{p0} - A_{31}y_{p1}x_{p0} + A_{22}y_{p0} - A_{32}y_{p1}y_{p0}$$
$$+ A_{23}z_{p0} - A_{33}y_{p1}z_{p0} + A_{24} - A_{34}y_{p1} = 0.$$

$$QA = B,$$

$$A = [A_{11}A_{12}A_{13}A_{14}A_{21}A_{22}A_{23}A_{24}A_{31}A_{32}A_{33}]^t$$

$$q_x = \begin{bmatrix} x_{p0} \\ y_{p0} \\ z_{p0} \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ -x_{p1}x_{p0} \\ -x_{p1}y_{p0} \\ -x_{p1}z_{p0} \end{bmatrix}^t, \quad q_y = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ x_{p0} \\ y_{p0} \\ z_{p0} \\ 1 \\ -y_{p1}x_{p0} \\ -y_{p1}y_{p0} \\ -y_{p1}z_{p0} \end{bmatrix}^t, \quad \begin{aligned} b_x &= [x_{p1}] \\ b_y &= [y_{p1}]. \end{aligned} \quad \begin{bmatrix} q_{x1} \\ q_{y1} \\ q_{x2} \\ q_{y2} \\ \cdots \\ q_{x6} \\ q_{y6} \end{bmatrix} A = \begin{bmatrix} b_{x1} \\ b_{y1} \\ b_{x2} \\ b_{y2} \\ \cdots \\ b_{x6} \\ b_{y6} \end{bmatrix}.$$

$$
\begin{bmatrix} w_1 x_{p1} \\ w_1 y_{p1} \\ w_1 \end{bmatrix} = \begin{bmatrix} A_{111} & A_{112} & A_{113} & A_{114} \\ A_{121} & A_{122} & A_{123} & A_{124} \\ A_{131} & A_{132} & A_{133} & A_{134} \end{bmatrix} \begin{bmatrix} x_{p0} \\ y_{p0} \\ z_{p0} \\ 1 \end{bmatrix}
$$

$$
\begin{aligned}
&(A_{111} - A_{131}x_{p1})x_{p0} + (A_{112} - A_{132}x_{p1})y_{p0} \\
&\quad + (A_{113} - A_{133}x_{p1})z_{p0} = A_{134}x_{p1} - A_{114}, \\
&(A_{121} - A_{131}y_{p1})x_{p0} + (A_{122} - A_{132}y_{p1})y_{p0} \\
&\quad + (A_{123} - A_{133}y_{p1})z_{p0} = A_{134}y_{p1} - A_{124},
\end{aligned}
$$

$$
\begin{bmatrix} w_2 x_{p2} \\ w_2 y_{p2} \\ w_2 \end{bmatrix} = \begin{bmatrix} A_{211} & A_{212} & A_{213} & A_{214} \\ A_{221} & A_{222} & A_{223} & A_{224} \\ A_{231} & A_{232} & A_{233} & A_{234} \end{bmatrix} \begin{bmatrix} x_{p0} \\ y_{p0} \\ z_{p0} \\ 1 \end{bmatrix}
$$

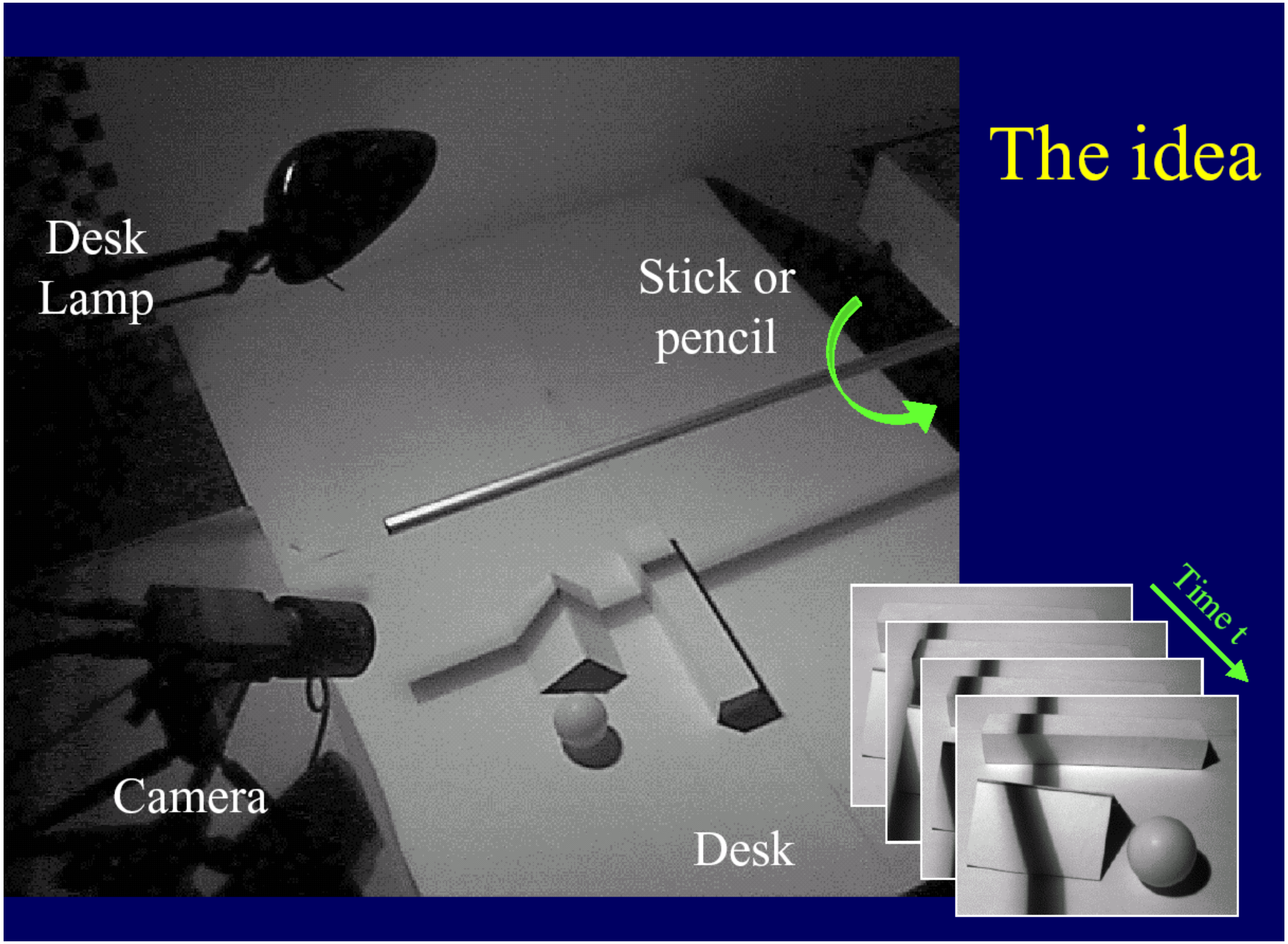
$$
\begin{aligned}
&(A_{211} - A_{231}x_{p2})x_{p0} + (A_{212} - A_{232}x_{p2})y_{p0} \\
&\quad + (A_{213} - A_{233}x_{p2})z_{p0} = A_{234}x_{p2} - A_{214}, \\
&(A_{221} - A_{231}y_{p2})x_{p0} + (A_{222} - A_{232}y_{p2})y_{p0} \\
&\quad + (A_{223} - A_{233}y_{p2})z_{p0} = A_{234}y_{p2} - A_{224}.
\end{aligned}
$$

$$PV = F, \qquad V = (P^{t}P)^{-1}P^{t}F.$$

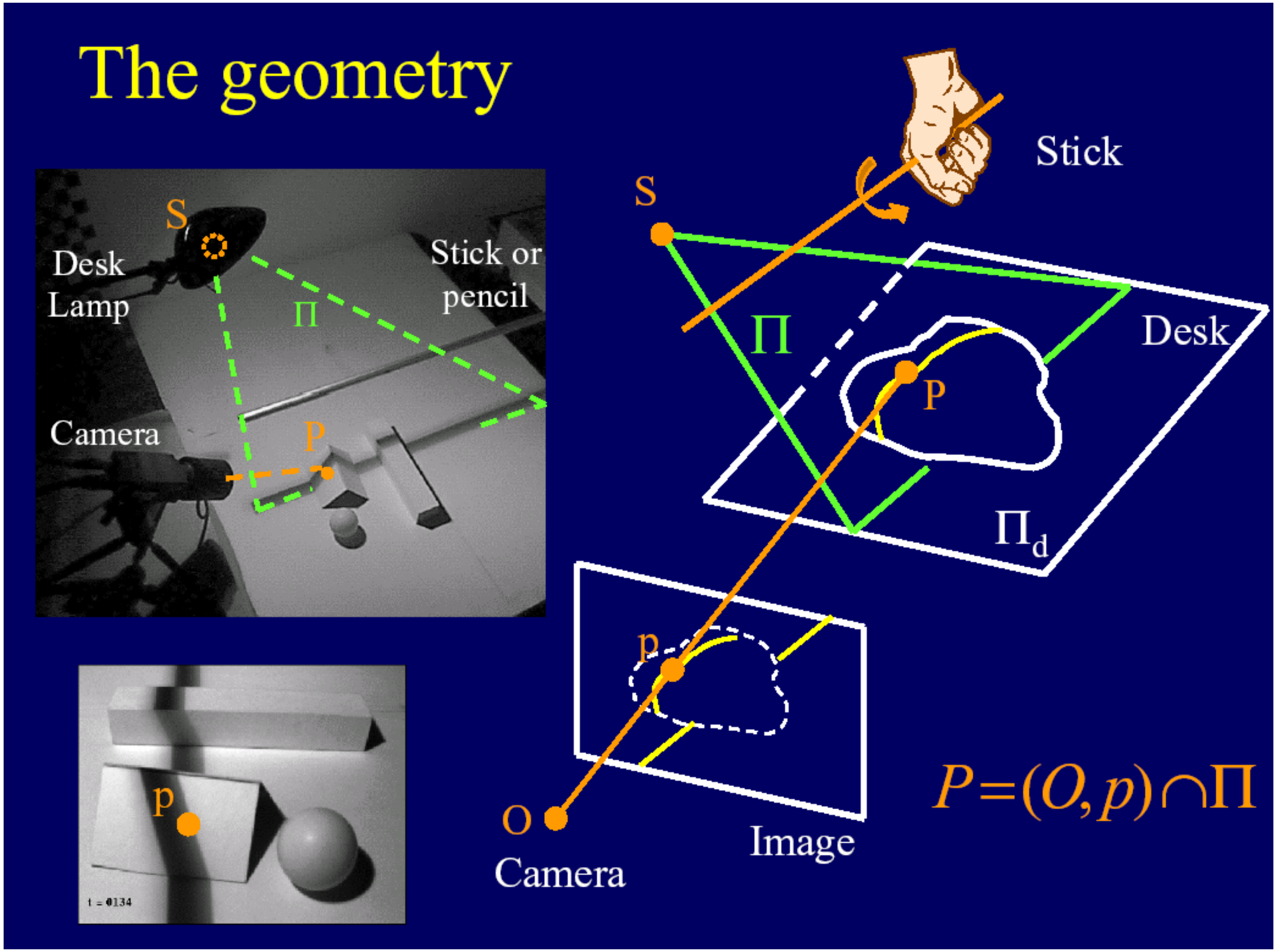
$$P =$$

$$\begin{bmatrix} A_{111} - A_{131}x_{p1} & A_{112} - A_{132}x_{p1} & A_{113} - A_{133}x_{p1} \\ A_{121} - A_{131}y_{p1} & A_{122} - A_{132}y_{p1} & A_{123} - A_{133}y_{p1} \\ A_{211} - A_{231}x_{p2} & A_{212} - A_{232}x_{p2} & A_{213} - A_{233}x_{p2} \\ A_{221} - A_{231}y_{p2} & A_{222} - A_{232}y_{p2} & A_{223} - A_{233}y_{p2} \end{bmatrix}, \; V = \begin{bmatrix} x_{p0} \\ y_{p0} \\ z_{p0} \end{bmatrix}, \; F = \begin{bmatrix} A_{134}x_{p1} - A_{114} \\ A_{134}y_{p1} - A_{124} \\ A_{234}x_{p2} - A_{214} \\ A_{234}y_{p2} - A_{224} \end{bmatrix}.$$

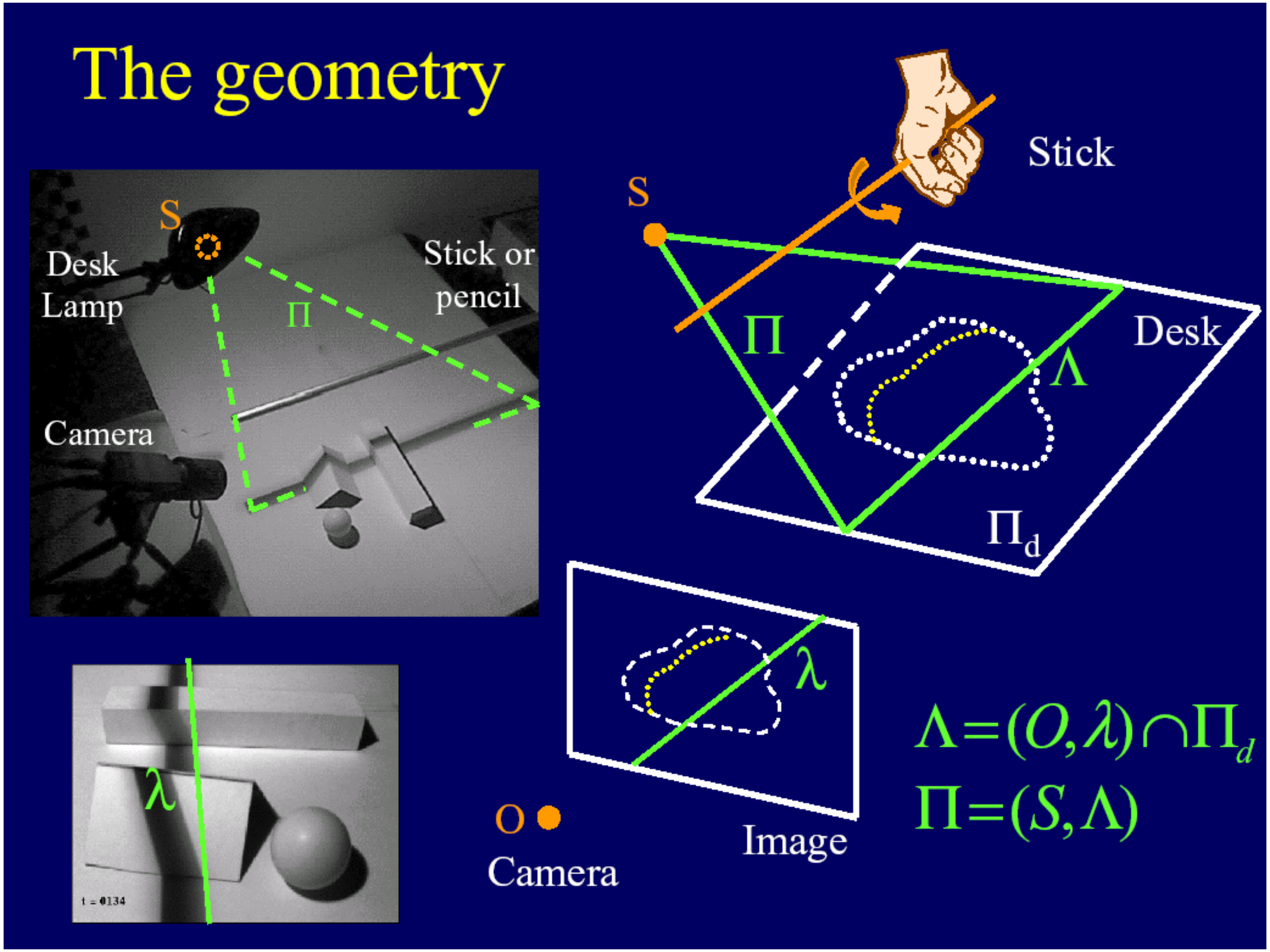
3D Acquisition from Shadows



3D Acquisition from Shadows

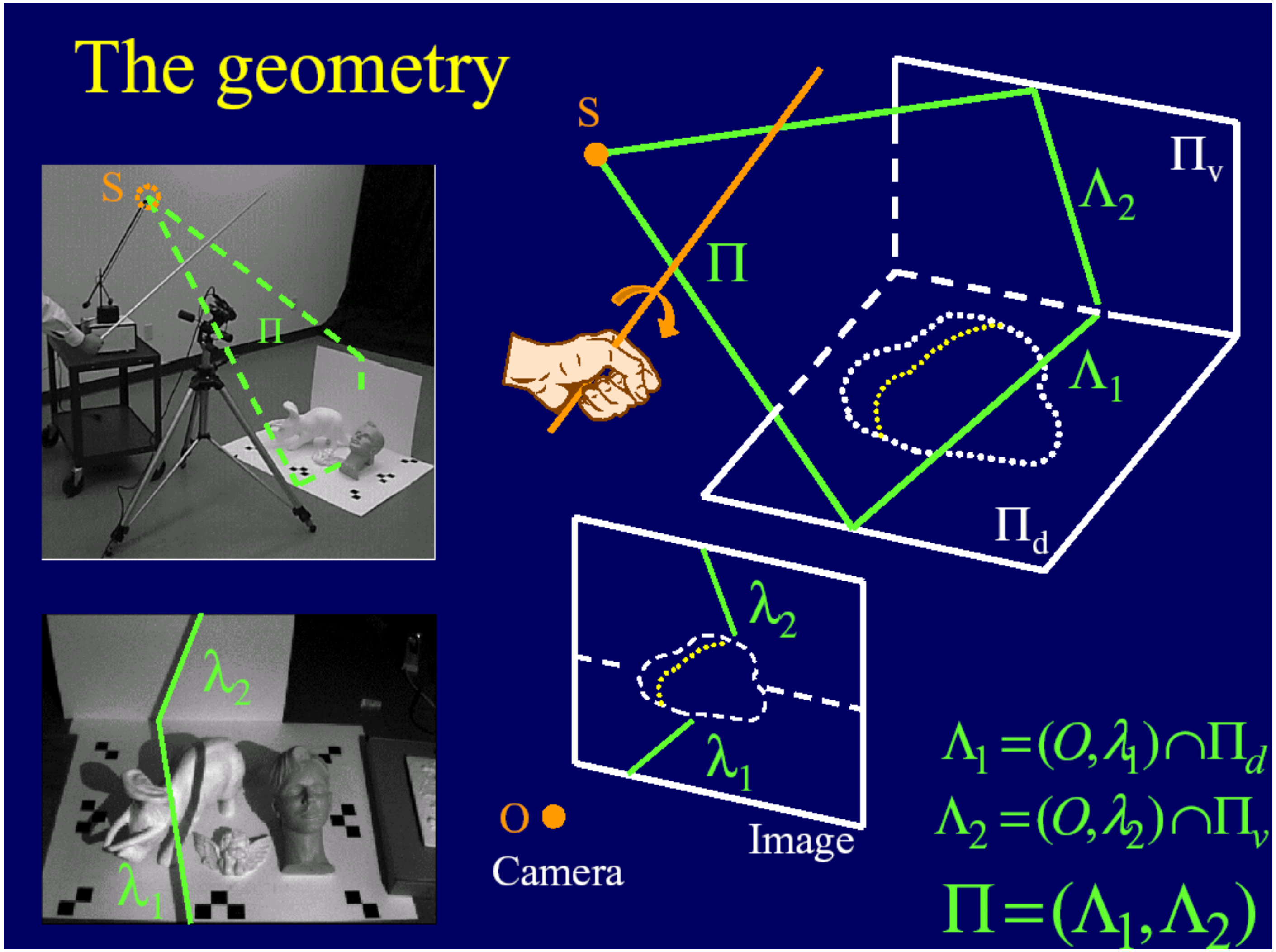


3D Acquisition from Shadows

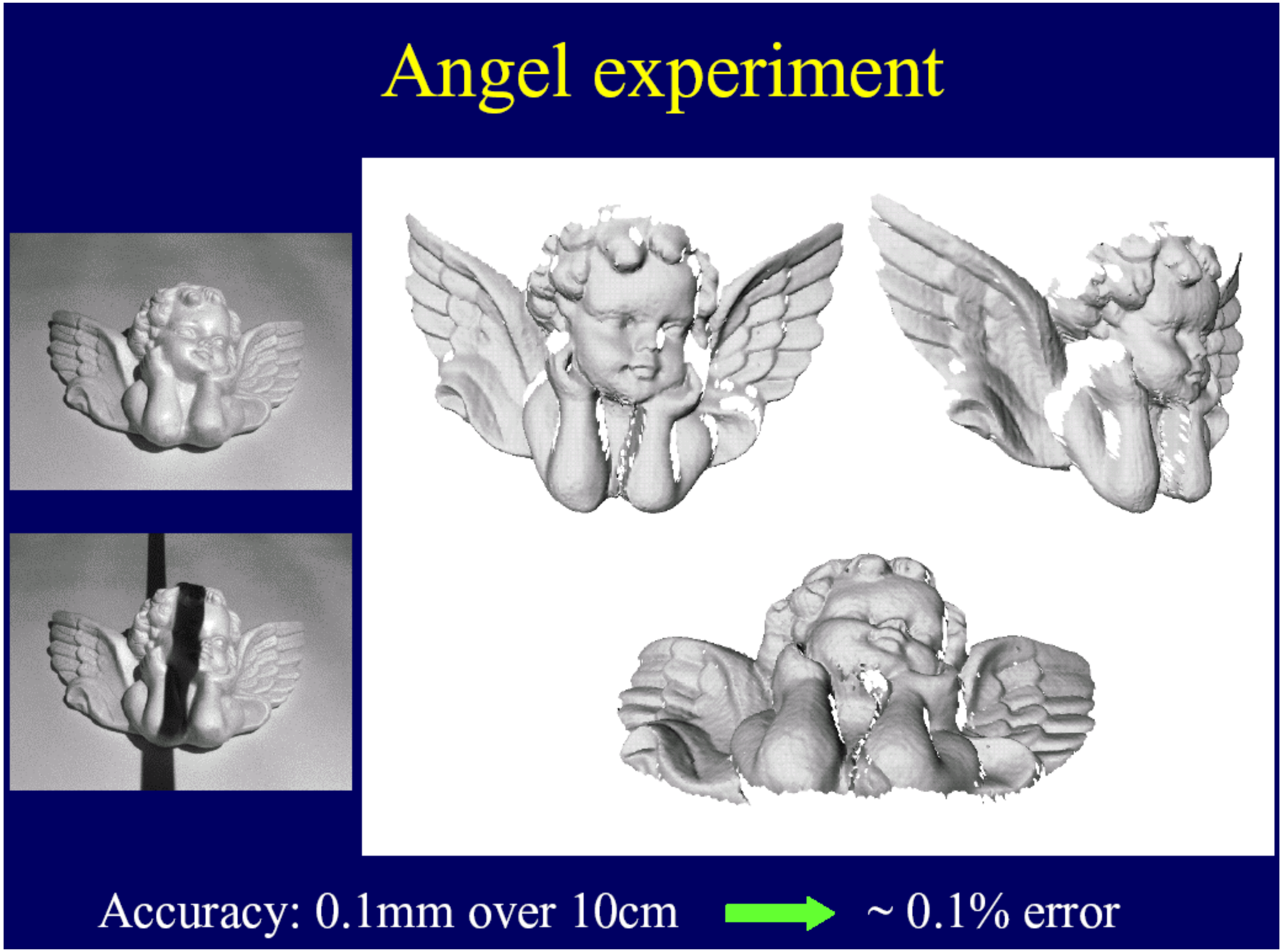


lbg@dongseo.ac.kr

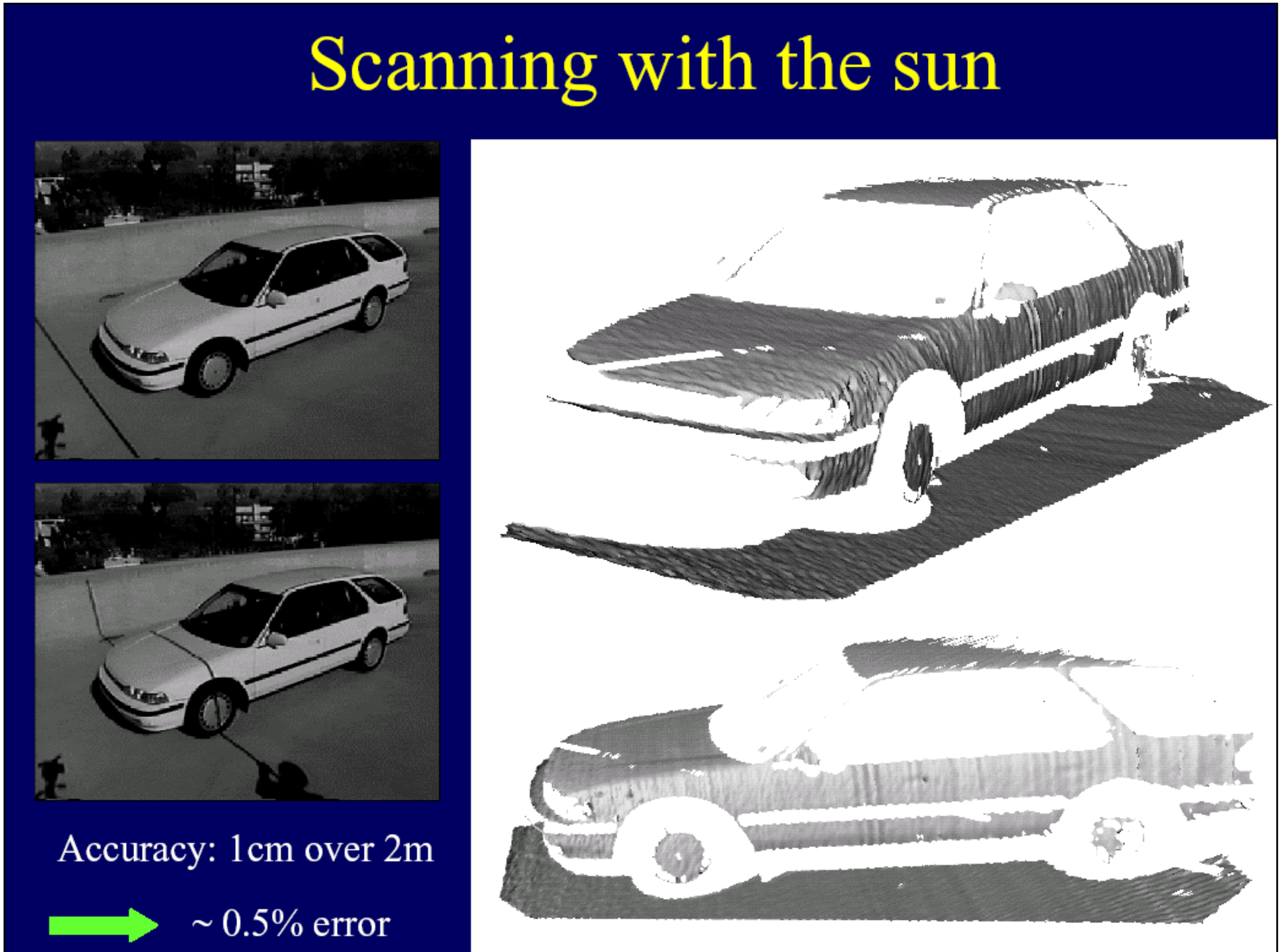
3D Acquisition from Shadows



3D Acquisition from Shadows

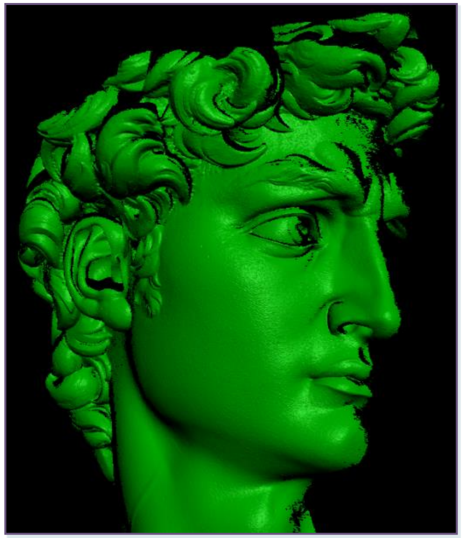


3D Acquisition from Shadows

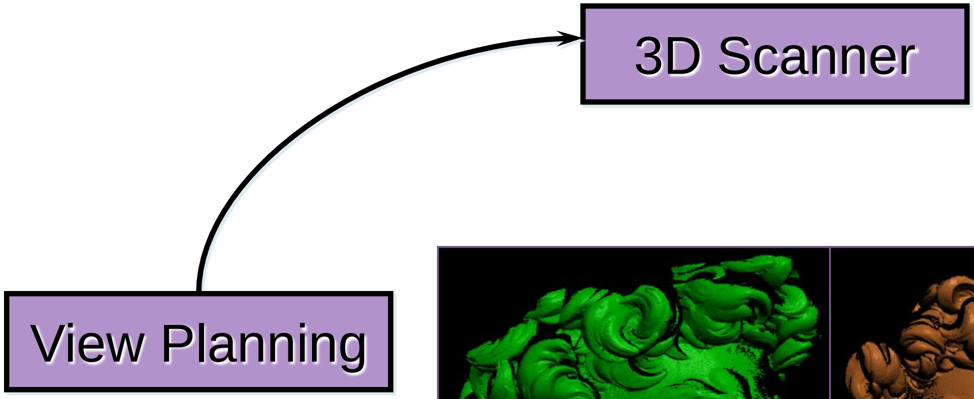


3D Model Acquisition Pipeline

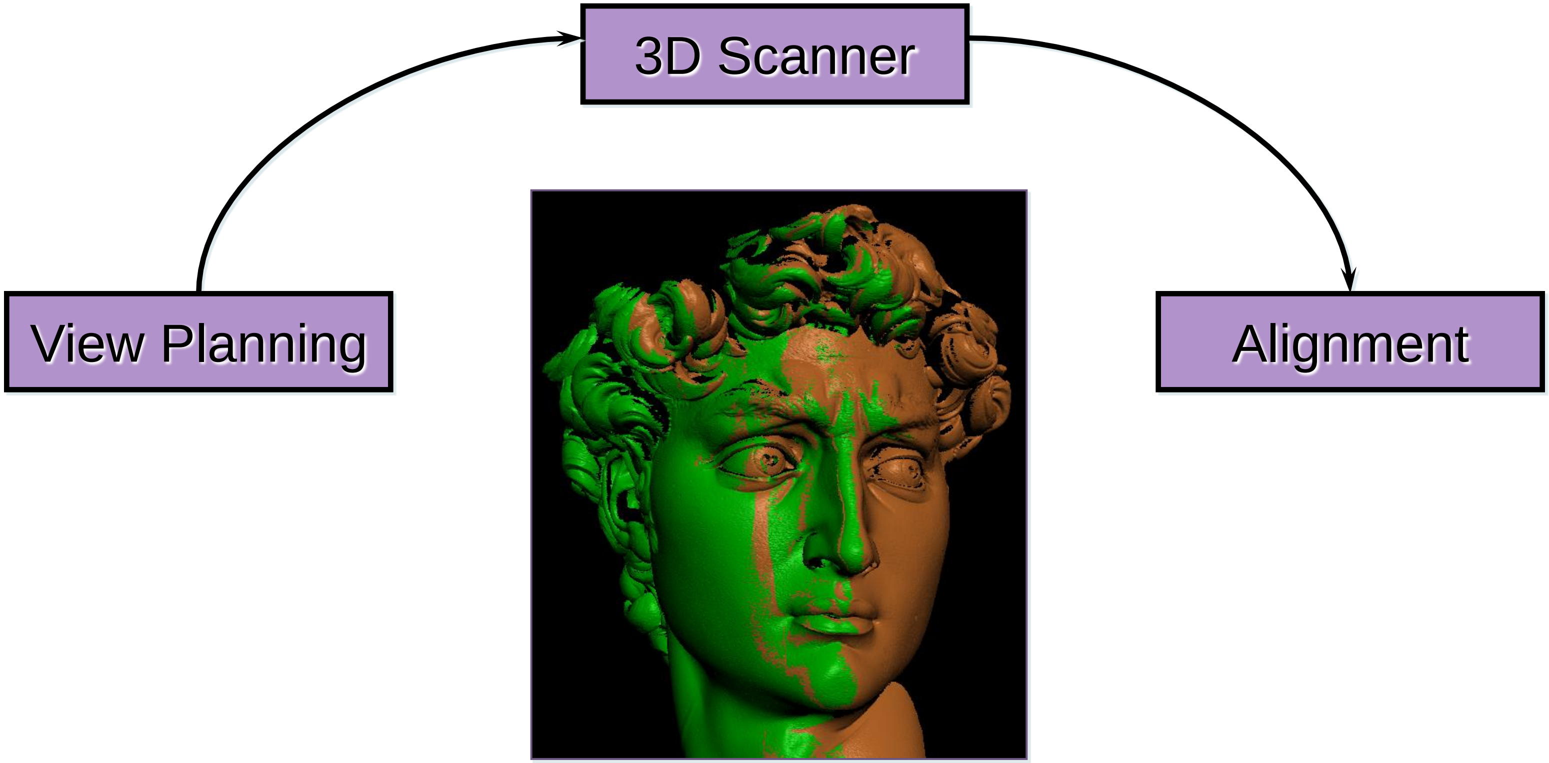
3D Scanner



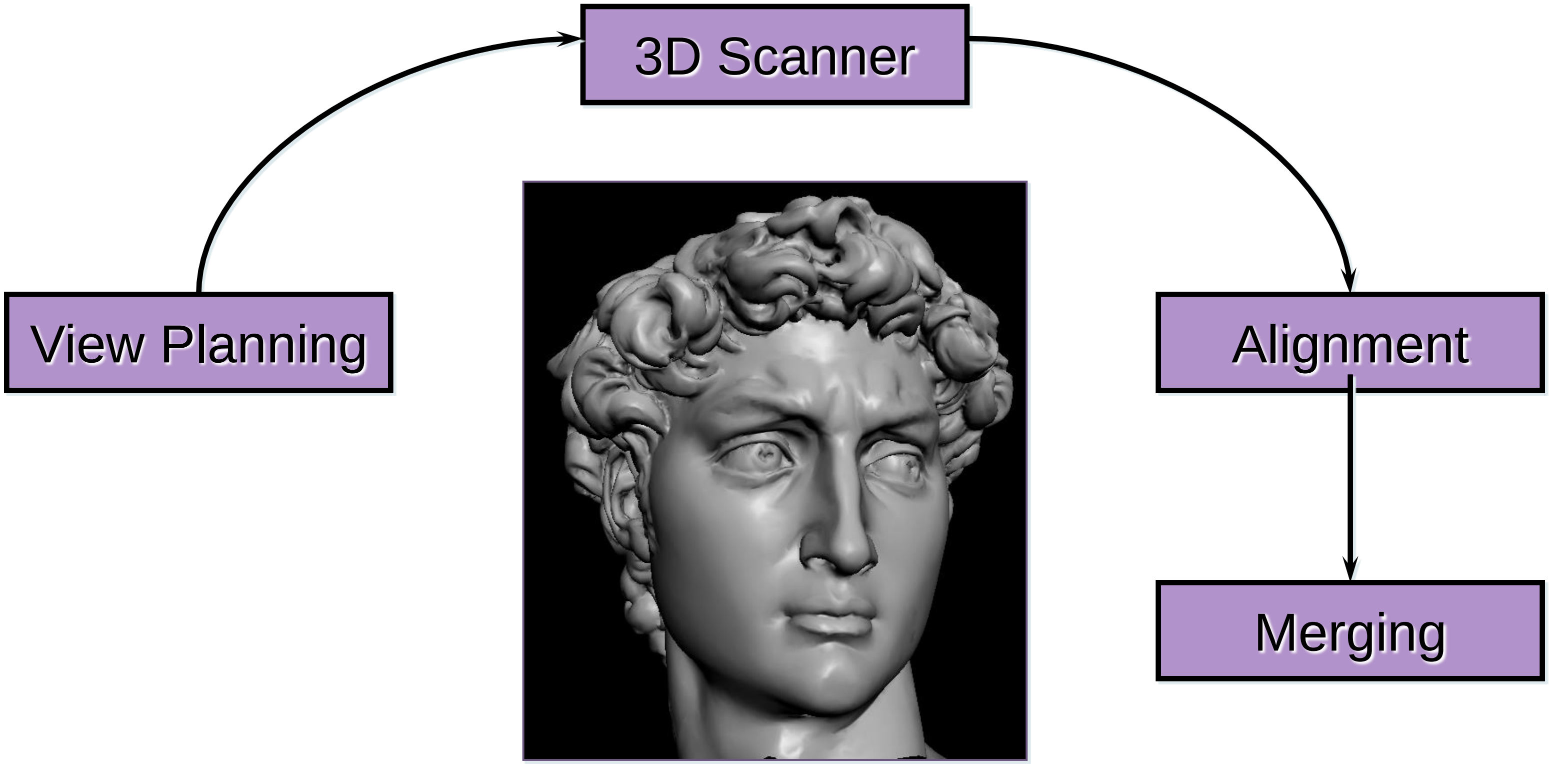
3D Model Acquisition Pipeline



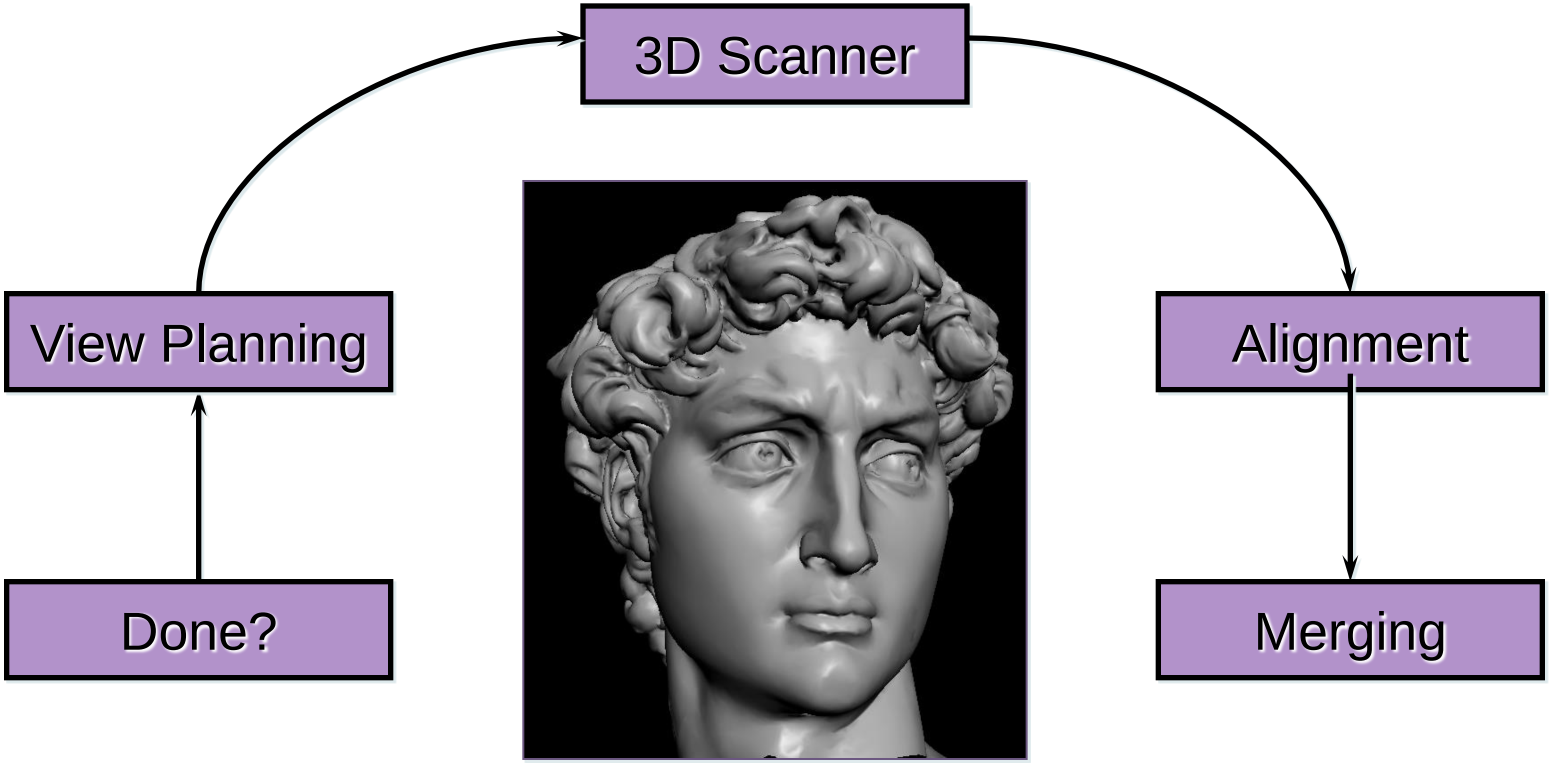
3D Model Acquisition Pipeline



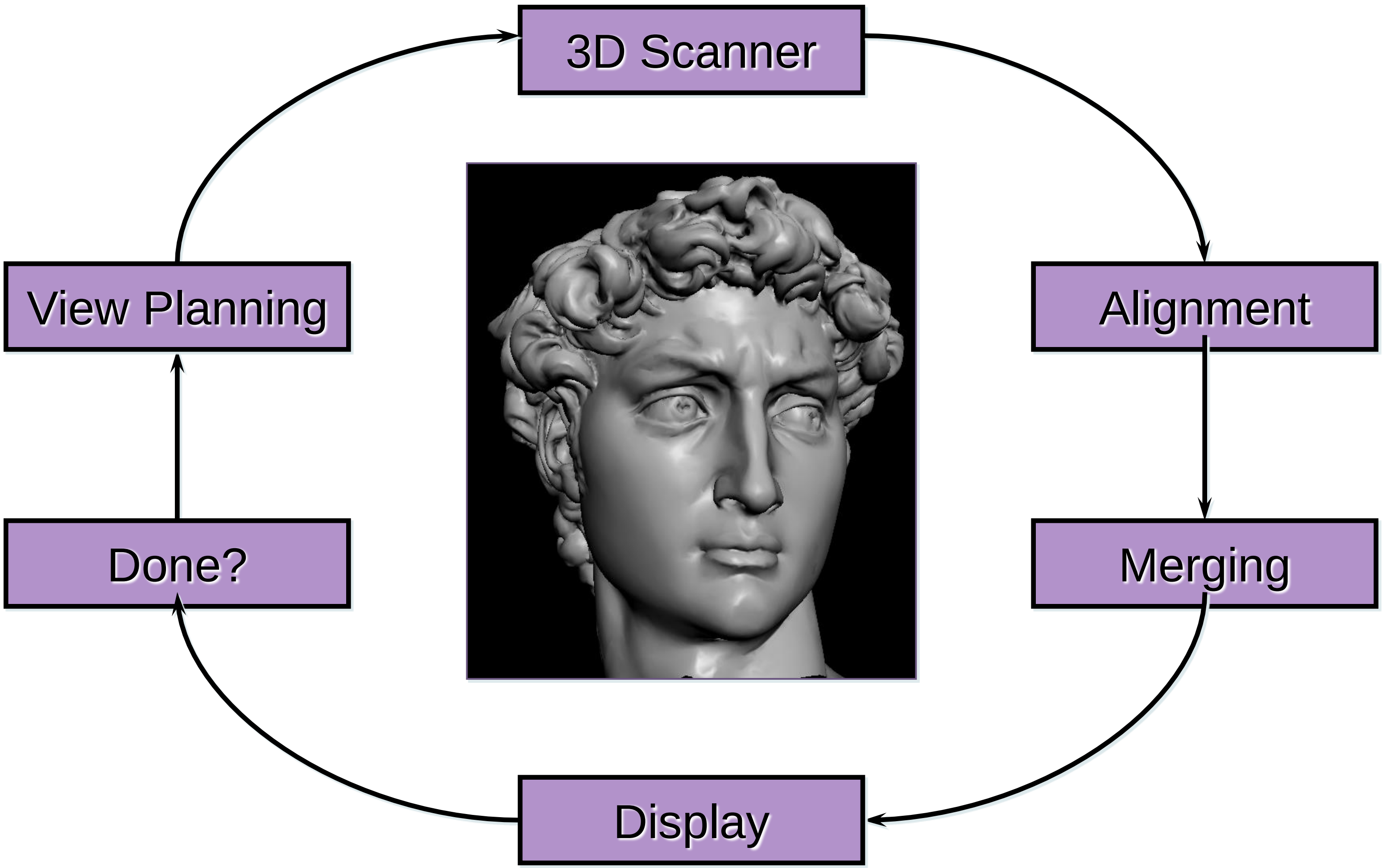
3D Model Acquisition Pipeline



3D Model Acquisition Pipeline



3D Model Acquisition Pipeline



Light Field Camera

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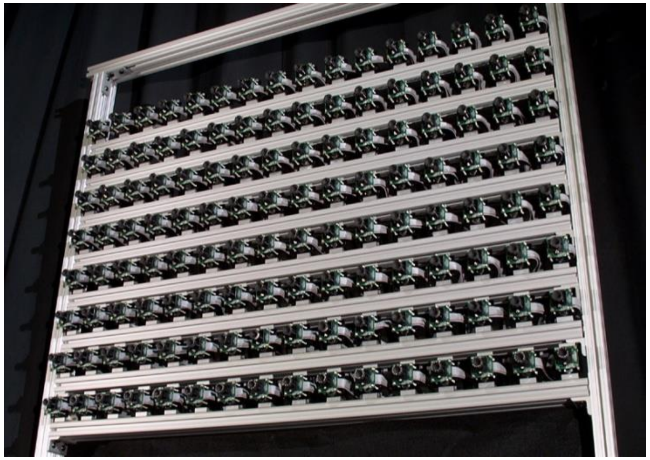
Stanford Multi-Camera Array



- 640 × 480 pixels × 30 fps × 128 cameras
- synchronized timing
- continuous streaming
- flexible arrangement

http://lightfield.stanford.edu/lfs.html

Stanford Light Field Archive

The (New) Stanford Light Field Archive

Computer Graphics Laboratory, Stanford University

Home | Light Fields | Calibration | Acquisition | Software | Publications

Listed below are the light fields in our archive. For each light field, there is a link to the imagery - sometimes in several forms, and sometimes accompanied by calibration information. Following this is a link that allows you to view the light field in your browser using our Flash-based light field viewer.

Notes about the light field viewer

In most cases you shouldn't need to download any software to use our viewer; just click on the indicated links below. Be warned though, this involves loading the entire light field (usually at slightly reduced spatial resolution) into memory. For the largest light fields, this involves downloading about 30MB of data, and will cause your browser to use up to a gigabyte of RAM. Firefox 3 uses notably less RAM than Firefox 2 when viewing these light fields, as does Internet Explorer 7. Safari and Opera should also work, with the appropriate flash player plugin.

You're free to take the viewer and use it for your own light fields. The source code and instructions for the using or modifying viewer are available.

Light Fields from the Lego Gantry

The light fields in this section were acquired by Andrew Adams.

Chess

289 views on a 17x17 grid, image resolution 1400x800
Original camera images, Rectified and cropped images

A chess board with pieces. Chess boards are great for demonstrating refocusing.

View light field online

Lego Bulldozer

289 views on a 17x17 grid, image resolution 1536x1152
Original camera images, Rectified and cropped images

A Lego Technic bulldozer. Very complex geometry.

View light field online

Lego Truck

289 views on a 17x17 grid, image resolution 1280x960
Original camera images, Rectified and cropped images

A Lego Technic truck. Very complex geometry.

View light field online

Eucalyptus Flowers

289 views on a 17x17 grid, image resolution 1280x1536
Original camera images, Rectified and cropped images

Some traditional Australian flowers. Lots of fine geometry.

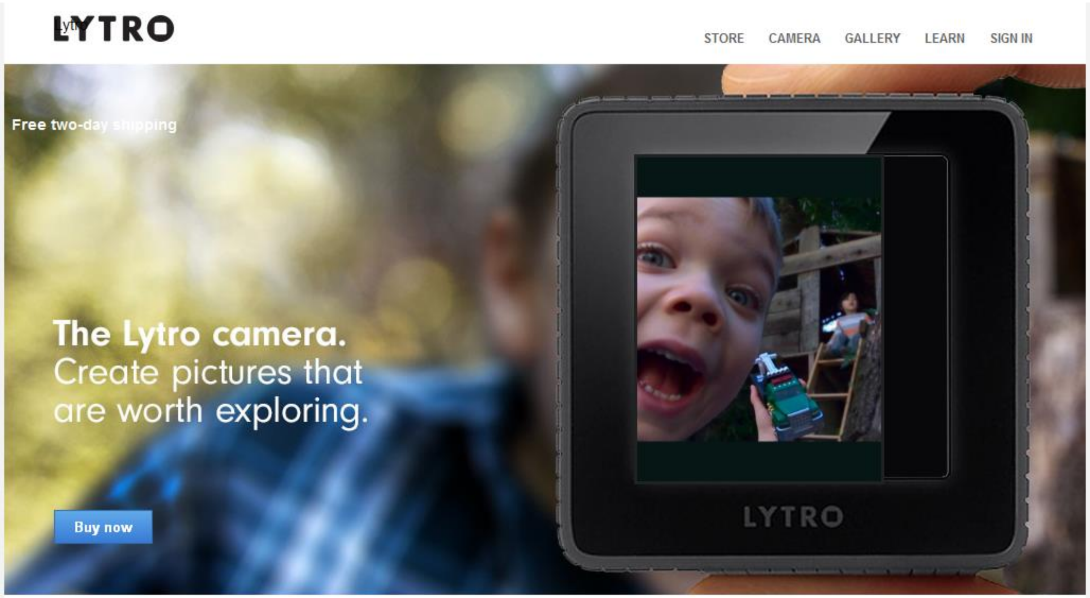
View light field online

http://lightfield.stanford.edu/lfs.html

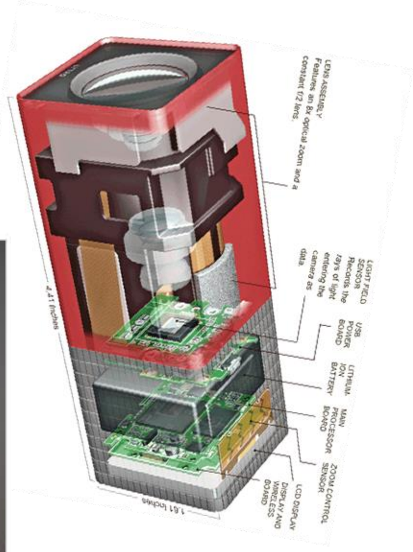
Stanford Light Field Archive

https://www.lytro.com/

Lytro Camera

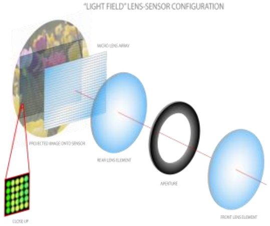


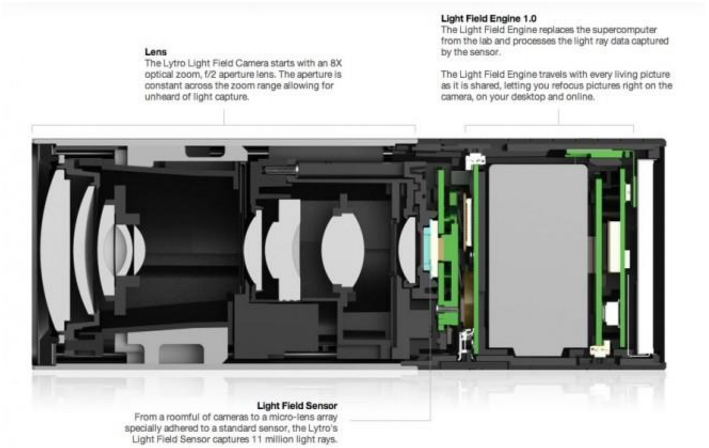
Fred R. Conrad/The New York Times
Ren Ng, chief executive of Lytro, a start-up company in Silicon Valley.



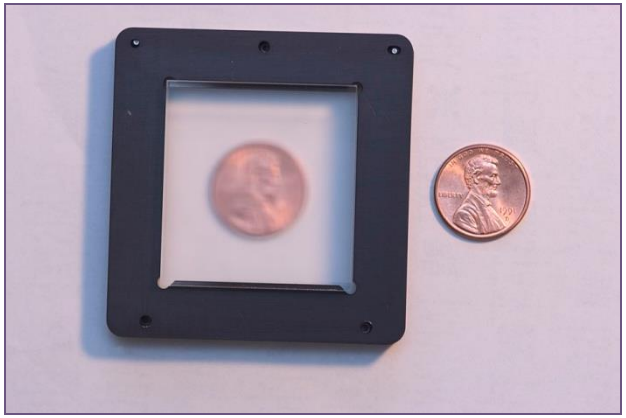
Red Hot
16GB
750 Pictures
$499.00

Electric Blue
8GB
350 Pictures
$399.00

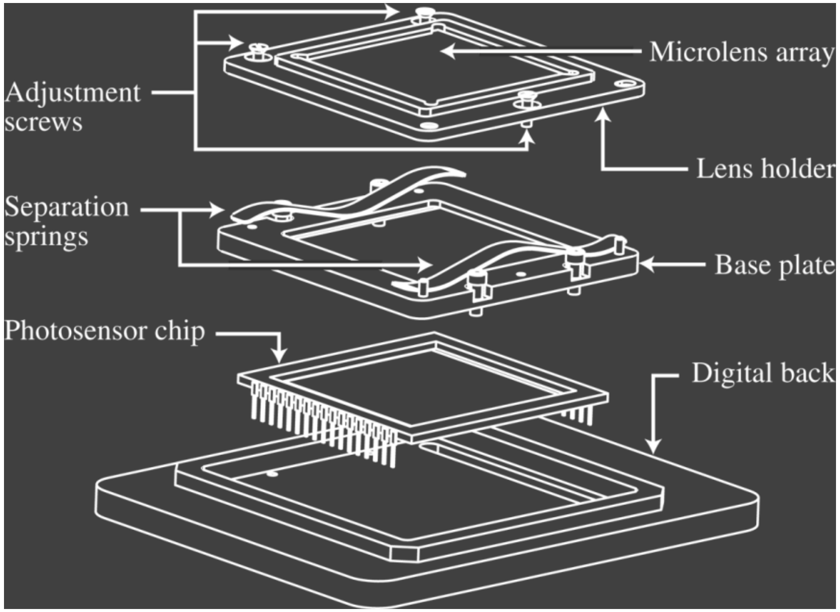


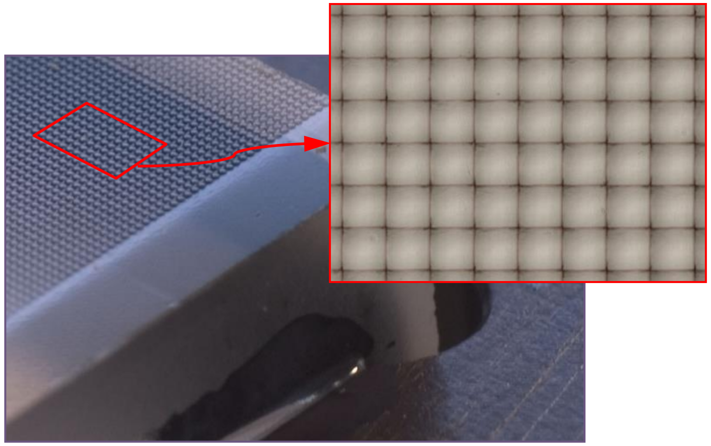


Adaptive Optics Microlens Array



Adaptive Optics microlens array





125μ square-sided microlenses

4000 × 4000 pixels ÷ 292 × 292 lenses = 14 × 14 pixels per lens

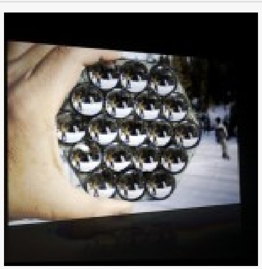
Adobe LightField Camera

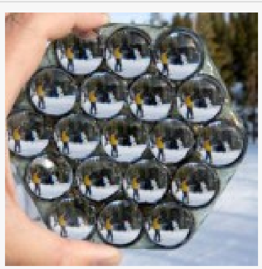
Adobe LightField Camera Protypes

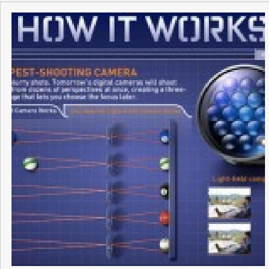
Adobe Systems, the leading specialist of image manipulation, multimedia and creativity software products, has long been investigating the possibilities of LightField photography and computational imaging. Known prototypes date back to 2004, and have evolved from compound lenses with only a few sub-images to microlense arrays.
Here's an overview of Adobe's (publicly shown) LightField camera prototypes.

1. Generation Prototype: Magic Lens

Adobe's first LightField camera prototype was tested and developed in 2004-2006, and publicly demoed in 2006/2007. It consisted of a 100 megapixel camera with a special compound lens (dubbed "Magic Lens") made of 19 sub-lenses in a hexagonal array. Each of these is facing an individually configured prism set at a unique angle, resulting in 19 different focal points.
This setup created 19 subpictures of the entire scene, with a resolution of 5.2 megapixels per subpicture.







Thanks you!!

lbg@dongseo.ac.kr
http://kowon.dongseo.ac.kr/~lbg/

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동서대학교