# 3D Sensors

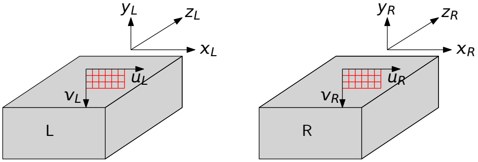
(Source: https://www.google.com/selfdrivingcar/)

Slide credit to Radu Horaud, http://perception.inrialpes.fr

# Structured Light Imaging

## Pinhole camera model & binocular stereo

To understand the principles of structured light imaging, we introduce a minimal stereo system (calibrated and rectified) first.



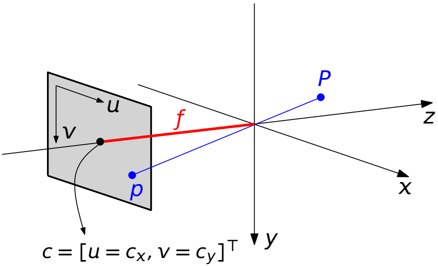

We adhere to the following convention:

- Left camera (L): reference camera
- Right camera (R): target camera

# Structured Light Imaging

## Pinhole camera model & binocular stereo

### Pinhole camera model




We see that

$$u - c_x = f\frac{x}{z}$$
$$v - c_y = f\frac{y}{z}$$

and thus

$$z[u, v, 1]^\top = \mathbf{K}[x, y, z]^\top$$

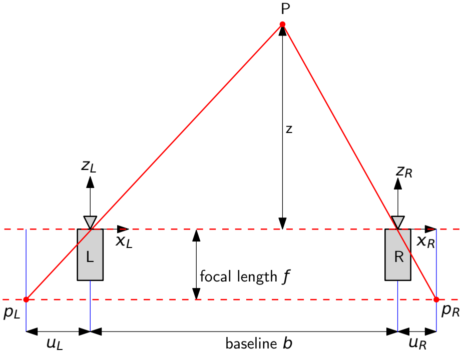
with $\mathbf{K}$ defined as

$$\mathbf{K} = \begin{bmatrix} f & 0 & c_x \\ 0 & f & c_x \\ 0 & 0 & 1 \end{bmatrix}$$

# Structured Light Imaging

## Pinhole camera model & binocular stereo – Disparity vs. depth

Lets consider a point $P = [x, y, z]^\top$




The point is projected to $p_L$ and $p_R$ with $p_L$ $p_R$. We denote $d = u_L + u_R$ as the disparity.

# Structured Light Imaging

## Pinhole camera model & binocular stereo – Disparity vs. depth

The relationship between disparity $d$, the $z$-coordinate of $P$ (depth) and the focal length $f$ is (via comparing similar triangles)

$$z = \frac{b|f|}{d}$$

Once we have a couple of conjugate pixel $p_L$ and $p_R$ and depth $z$, we can compute $[x, y, z]$ via the inverse of $\mathbf{K}_L^{-1}$ with $\mathbf{K}_L$ being the intrinsic parameter matrix of a camera (here: for camera $L$).

# Structured Light Imaging

## From cameras to projectors

Detecting the conjugate pixel pairs is known as the correspondence problem in stereo vision (which is typically the tricky part).

How do we get $p_L$ and $p_R$?

- From light being reflected off $P$ towards the cameras $L$ and $R$
- But is this really the relevant point?

# Structured Light Imaging

## From cameras to projectors

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- But is this really the relevant point?

In fact, important is only the triangle geometry! In projective geometry, points are equivalent to rays exiting a center of projection.

# Structured Light Imaging

## Light coding system

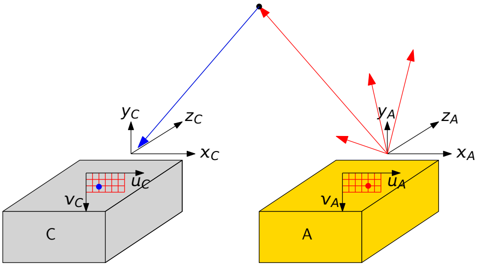
**Definition (Light coding system)**

A stereo system, in which one of the two cameras is replaced by a projector is called a *light coding system*.

# Structured Light Imaging

## From cameras to projectors

Camera $R$ is replaced by the projector $A$




If $P$ is not occluded, it projects the light, emitted by A, to pixel $p_C$ of camera $C$.

As before, $p_A$ (point to be projected) and $p_C$ are conjugate points.

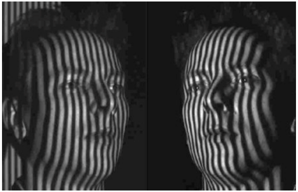
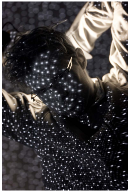
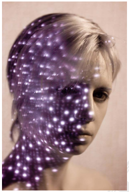
# Structured Light Imaging

## From cameras to projectors

Example: Consider a straight wall with uniform color

- Projector A "colors", with its radiant power, the scene point $P$
- Its "easy" to identify $p_C$ from its neighbors, due to color of $P$

In general, a suitable light pattern needs to be adopted!

(Pictures from Wikipedia and artist Audrey Penven)

# Structured Light Imaging

## Microsoft's Kinect™

- Light-coded range camera
- 30 frames per second (FPS) with VGA $640 \times 480$ resolution
- Equipped with color video camera and microphones
- Based on the Primesensor™chip (also used by Asus X-tion)
- Uses Infrared (IR) light-coded patterns

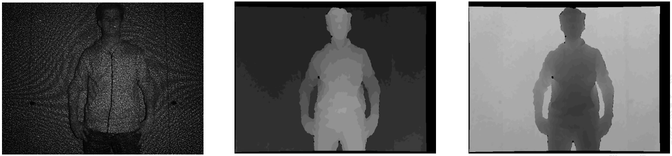
Image source: http://www.futurepicture.org

# Structured Light Imaging

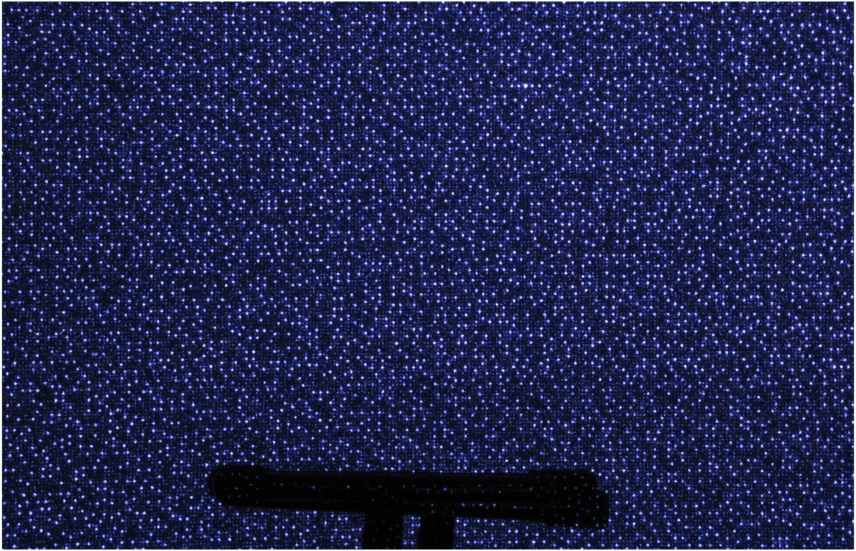
## Microsoft's Kinect™– Available data (at 30 [FPS])

- IR Image $I_K$: defined on lattice $\Lambda_K$; values in $[0, 1]$
- Disparity map $D_K$: defined on lattice $\Lambda_K$; values in $[d_{min}, d_{max}]$
- Depth map $Z_K$: defined on lattice $\Lambda_K$; values in $[z_{min}, z_{max}]$ with

$$z_{min} = \frac{bf}{d_{max}} \quad \text{and} \quad z_{max} = \frac{bf}{d_{min}}$$



From *left* to *right*: $I_K$, $D_K$ and $Z_K$.



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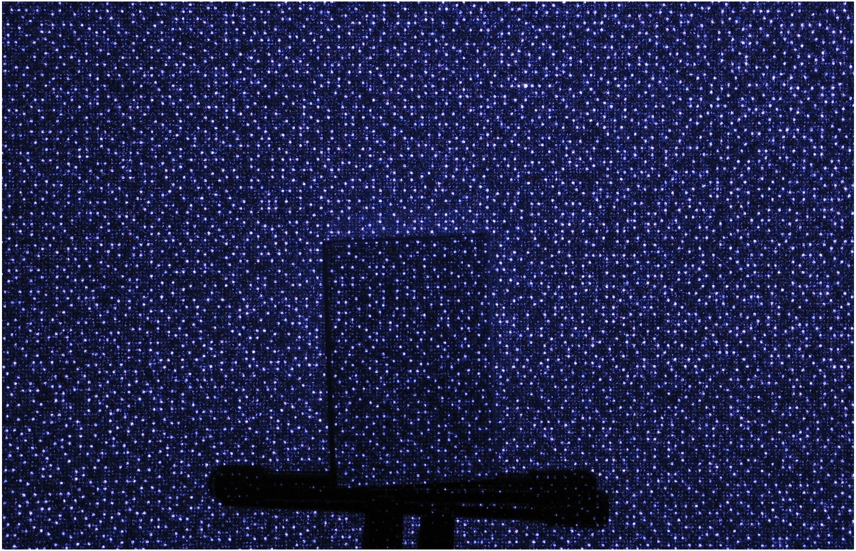

Image source: http://www.futurepicture.org

# Structured Light Imaging

## Microsoft's Kinect™

Some more Kintect™ internals:

- Baseline $b$: 75 [mm]
- Focal length $f$: $\sim$ 585.6 [px]

Hence, we get (in pixel): $(d_{min}, d_{max}) = (2, 88)$

# Structured Light Imaging

## Light coding principles – What is the goal?

Goal of pattern design: decodable in the presence of non-idealities

- Assume that the projected pattern has $N_R \times N_C$ pixel $p_A^i$
- Active triangulation requires one codeword per pixel
- The more codewords are different $\rightarrow$ better robustness

# Structured Light Imaging

## Light coding principles – What is the goal?

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In a calibrated + rectified setup ...

- conjugated points lie on horizontal lines
- $\rightarrow$ coding problem independent for each row
- we can use a small number of codewords

# Structured Light Imaging

## Light coding principles

In one row, there are $N := N_C^A$ pixel $p_A^1, \dots, p_A^N$ to be encoded with codewords $w_1, \dots, w_N$.

# Structured Light Imaging

## Light coding principles

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### How is this implemented?

- Projector with $n_P$ different illumination patterns

# Structured Light Imaging

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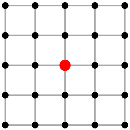

we have $n_P^{n_W}$ possible configurations

# Structured Light Imaging

## Light coding principles

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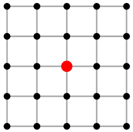

  we have $n_P^{n_W}$ possible configurations
- $N$ of them need to be chosen to encode the pixel!

# Structured Light Imaging

## Light coding principles

Remember,

$$\underbrace{p_A = [u_A, v_A]^\top}_{\text{to be projected}} \rightarrow \underbrace{P = [x, y, z]^\top}_{\text{scene point}} \rightarrow \underbrace{p_C = [u_A + d, v_A]^\top}_{\text{camera point}}$$

where $\rightarrow$ denotes "projected to"

# Structured Light Imaging

## Light coding principles

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where $\rightarrow$ denotes “projected to”

Projection introduces a horizontal shift $d$, inverse proportional to the estimated depth $z$, i.e.,

$$d = \frac{b|f|}{z}$$

# Structured Light Imaging

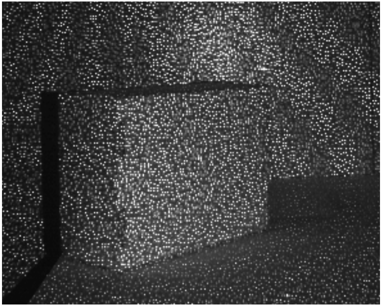
## Light coding principles – Artificats

- Perspective distortion
- Color/Gray-level distortion
- Projector/Camera non-idealities
- Projector/Camera noise
- External illumination
- Occlusions

# Structured Light Imaging

## Light coding techniques – Artifacts

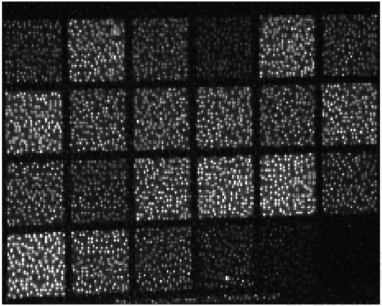
Projected pattern + depth map of slanted surface



# Structured Light Imaging

## Light coding techniques – Artifacts

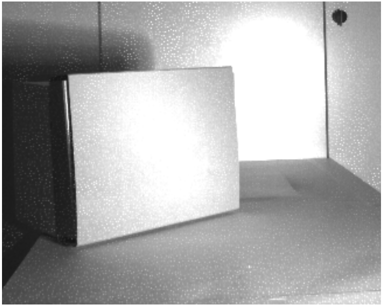
Projected pattern of color checkerboard (on left)

# Structured Light Imaging

## Light coding techniques – Artifacts

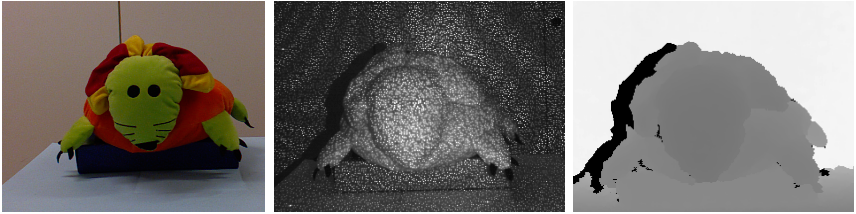
Effect on a strong external light source. The IR image saturates (relative to the strongest reflections) $\rightarrow$ no depth values (black regions in right image)



# Structured Light Imaging

## Light coding techniques – Artifacts

Occlusion (look at the left ear)



# Structured Light Imaging

## Light coding principles – Coding schemes

Two fundamental design considerations:

1. What codeword to assign to pixel $p_A$?

   The codeword corresponds to a pattern to be projected on a window centered at $p_A$.

# Structured Light Imaging

## Light coding principles – Coding schemes

Two fundamental design considerations:

1. What codeword to assign to pixel $p_A$?

   The codeword corresponds to a pattern to be projected on a window centered at $p_A$.

2. What codeword to assign to pixel $p_C$?

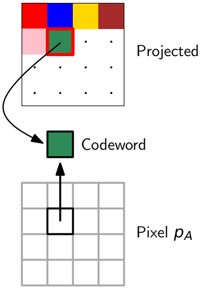
   How do we identify the codeword most similar to the local pattern distribution around $p_C$ to establish correspondences?

# Structured Light Imaging

## Light coding techniques – Coding schemes

### What codeword should we assign to a pixel $p_A$?

1. Direct coding



# Structured Light Imaging

## Light coding techniques – Coding schemes

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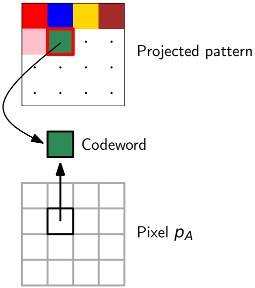
### 1. Direct coding

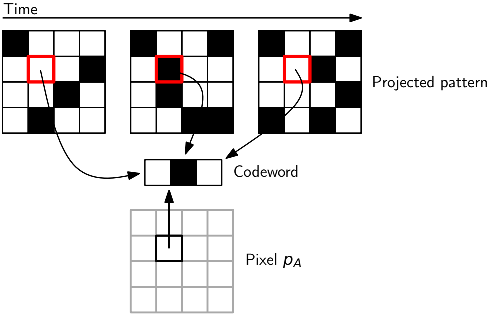



The codeword at $p_A$ is the pattern value at that pixel $\rightarrow$ up to $n_P$ codewords, since $n_W = 1$ (i.e., the "window" is just 1 pixel)

# Structured Light Imaging

## Light coding techniques – Coding schemes

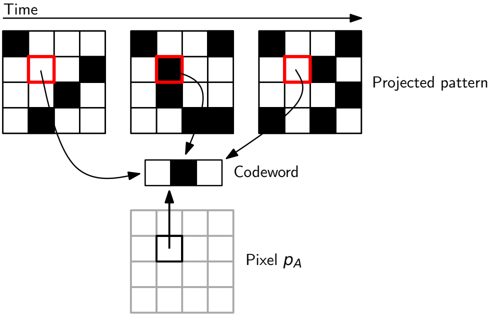
### 2. Time-multiplexed coding



# Structured Light Imaging

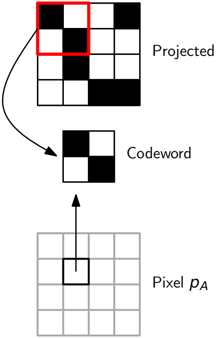
## Light coding techniques – Coding schemes

### 2. Time-multiplexed coding




The codeword at pixel $p_A$ is the sequence of projected patterns at that pixel $\rightarrow$ up to $n_P^T$ codewords (pattern is projected $T$ times).

## 3. Spatial-multiplexed coding

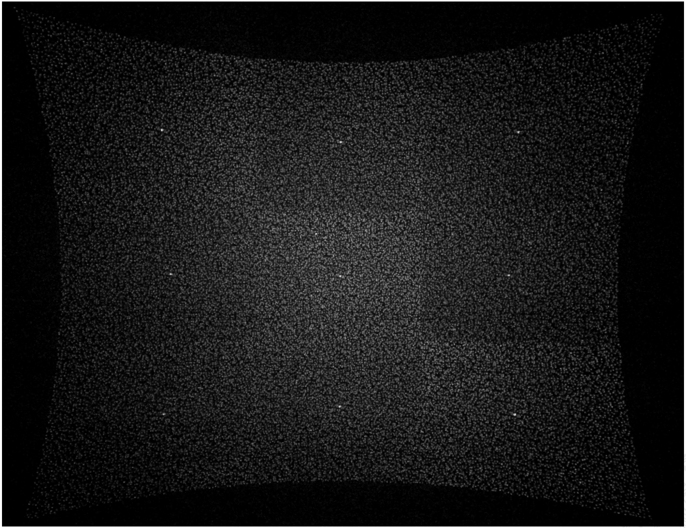



The codeword at pixel $p_A$ is the spatial pattern distribution in a window with $n_W$ pixel centered at $p_A$ $\rightarrow$ up to $n_P^{n_W}$ codewords.

# Structured Light Imaging

## Light coding principles – Pixel matching on the example of Microsoft's Kinect™

- Spatial-multiplexed coding (ideal for dynamic scenes)
- $A$ and $C$ might have different spatial resolutions (undisclosed)
- The projected pattern is uncorrelated across each row
- Reverse engineering suggests a window of either $7 \times 7$ or $9 \times 9$



Pattern projected by the Kinect™ (on flat surface)

# Structured Light Imaging

## Light coding principles – Pixel matching on the example of Microsoft's Kinect™

### What does "uncorrelated across each row" mean ?

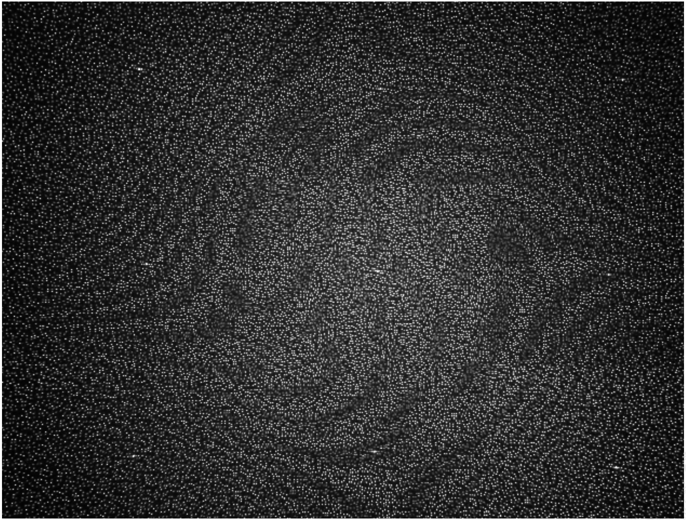
Let $s(u,v)$ be the projected pattern and $W(u_A, v_A)$ the support of the spatial multiplexing window, centered at $p_A$. Then

$$\underbrace{C(u^i, u^j, v_i)}_{\textit{horizontal covariance between supports centered at } p_A^i \textit{ and } p_A^j}$$

$$= \sum_{(u,v)\in W(u_A,v_A)} [s(u-u_A^i, v-v_A^i) - \bar{s}(u_A^i, v_A^i)][s(u-u_A^j, v-v_A^j) - \bar{s}(u_A^j, v_A^j)]$$

is 1 if $i = j$ and 0 otherwise (in the ideal case), where

$$\bar{s}(u_A, v_A) = \sum_{(u,v)\in W(u_A,v_A)} s(u-u_A, v-v_A) \quad .$$



Pattern acquired by the Kinect™ IR camera

# Structured Light Imaging

## Light coding principles – Pixel matching on the example of Microsoft's Kinect™

Pixel matching: Ideally, for each pixel $p_C^j$ of $I_K$ and each pixel $p_A^i$ in the same row, we obtain a unique covariance peak for an actual couple of conjugate points (there will be noise in real life :)

# Slide credits / Literature

Most of the material presented in this lecture is either taken from the textbook of Dal Mutto et al., online at

http://freia.dei.unipd.it/nuovo/Papers/ToF-Kinect-book.pdf

and the PhD thesis of O. Elkhalili here.