Computer Vision

18AI742

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BRIDGE TO THE FUTURE

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Stereopsis

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Stereopsis

Contents

1) Binocular camera geometry and the epipolar constraints
2) Binocular reconstruction
3) Human stereopsis
4) Local methods for binocular fusion
5) Global methods for binocular fusion
6) Using more cameras
7) Application: robot navigation
8) Conclusion
9) Q&A

$$\nabla \cdot \mathbf{E} = \rho / \varepsilon_0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \boldsymbol{j}_c$$

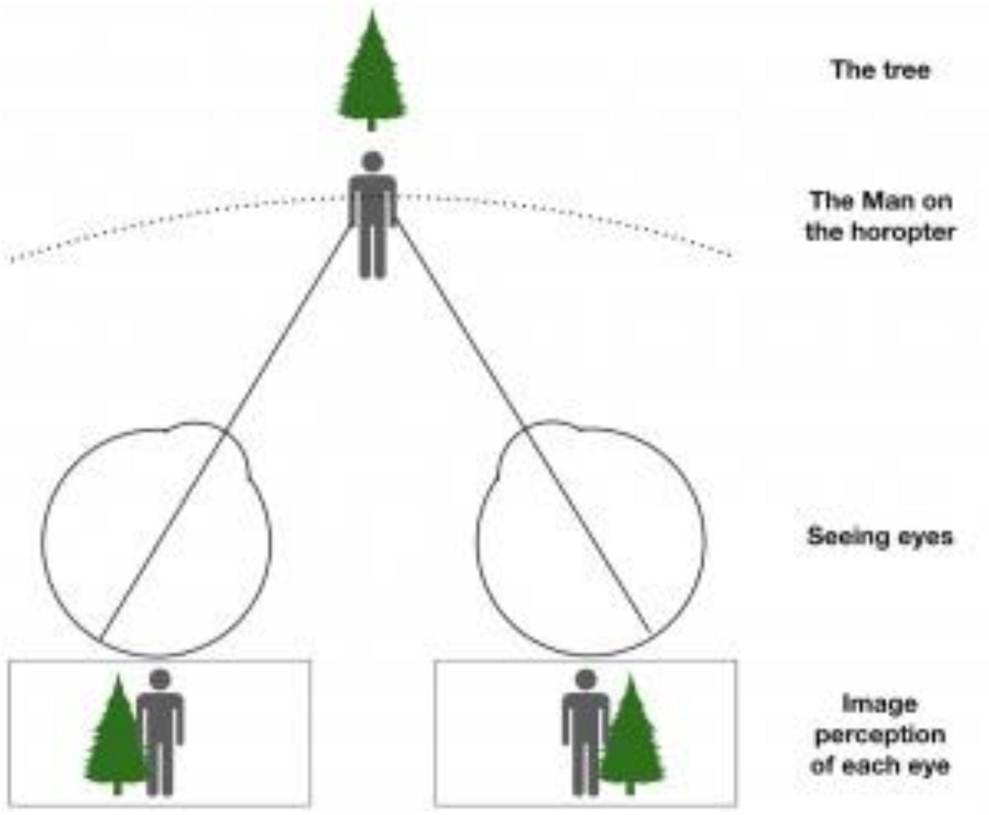
where

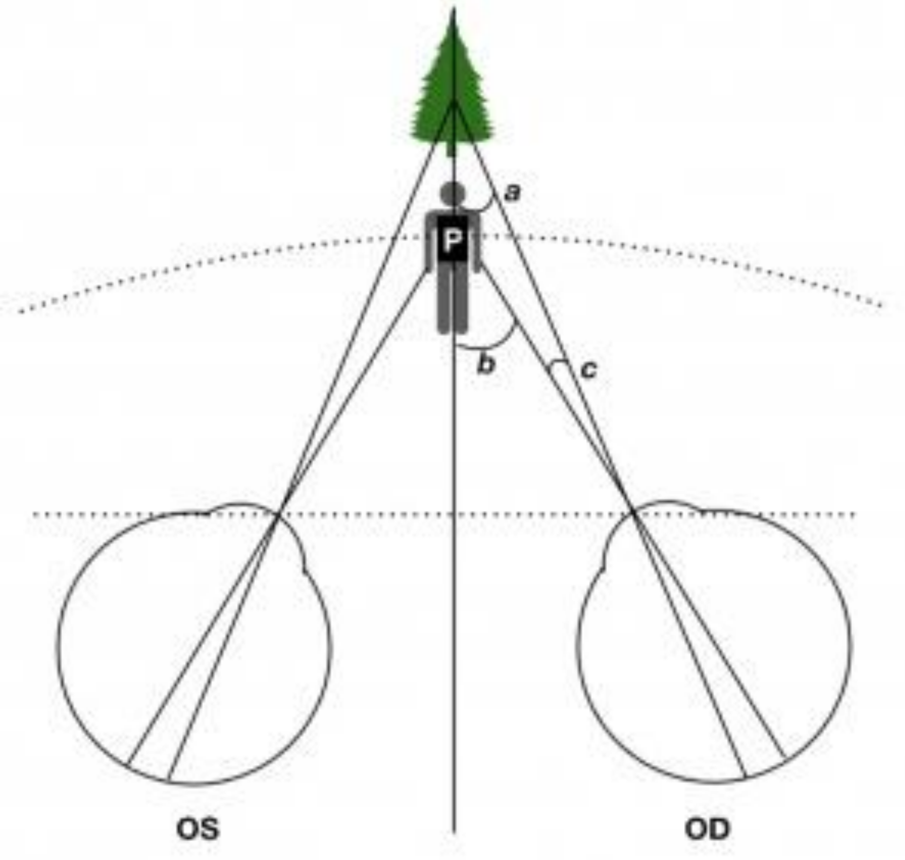
$$\nabla = \hat{\mathbf{i}} \frac{\partial}{\partial x} + \hat{\mathbf{j}} \frac{\partial}{\partial y} + \hat{\mathbf{k}} \frac{\partial}{\partial z}$$

Stereopsis

- Fusing the pictures recorded by our two eyes
- Exploiting the difference (or disparity) between them
- Allows us to gain a strong sense of depth
- Mimicing our ability to perform this task, known as stereopsis

Stereopsis


The tree
The Man on the horopter
Seeing eyes
Image perception of each eye


a
P
b
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OS
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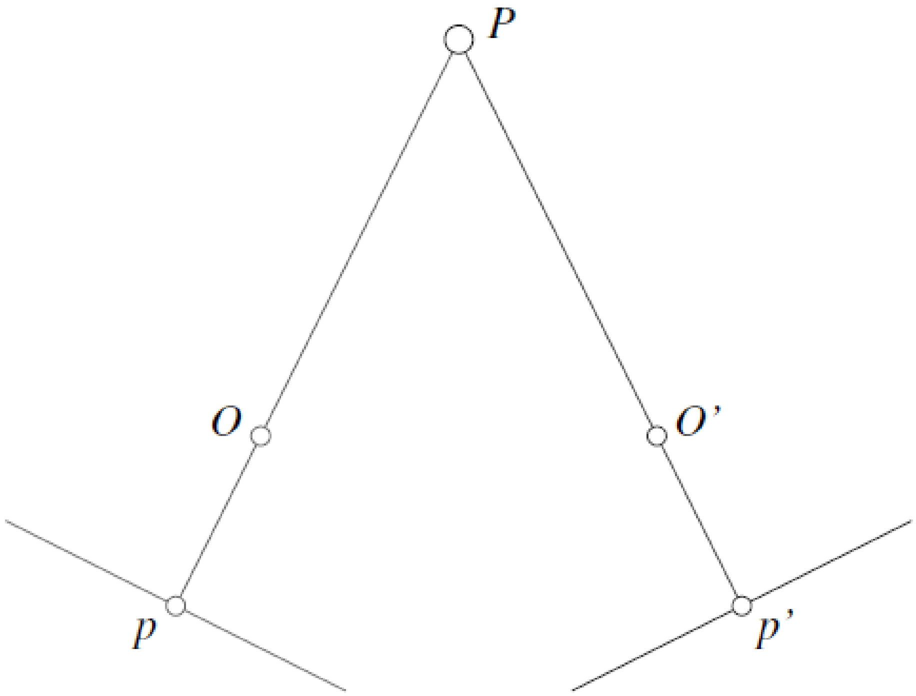
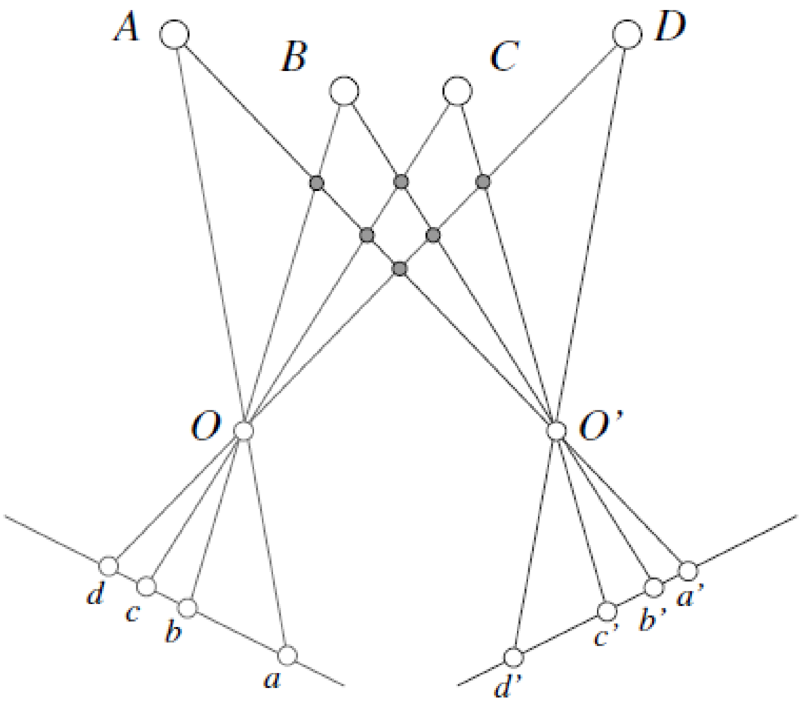
Robocup finals 2023

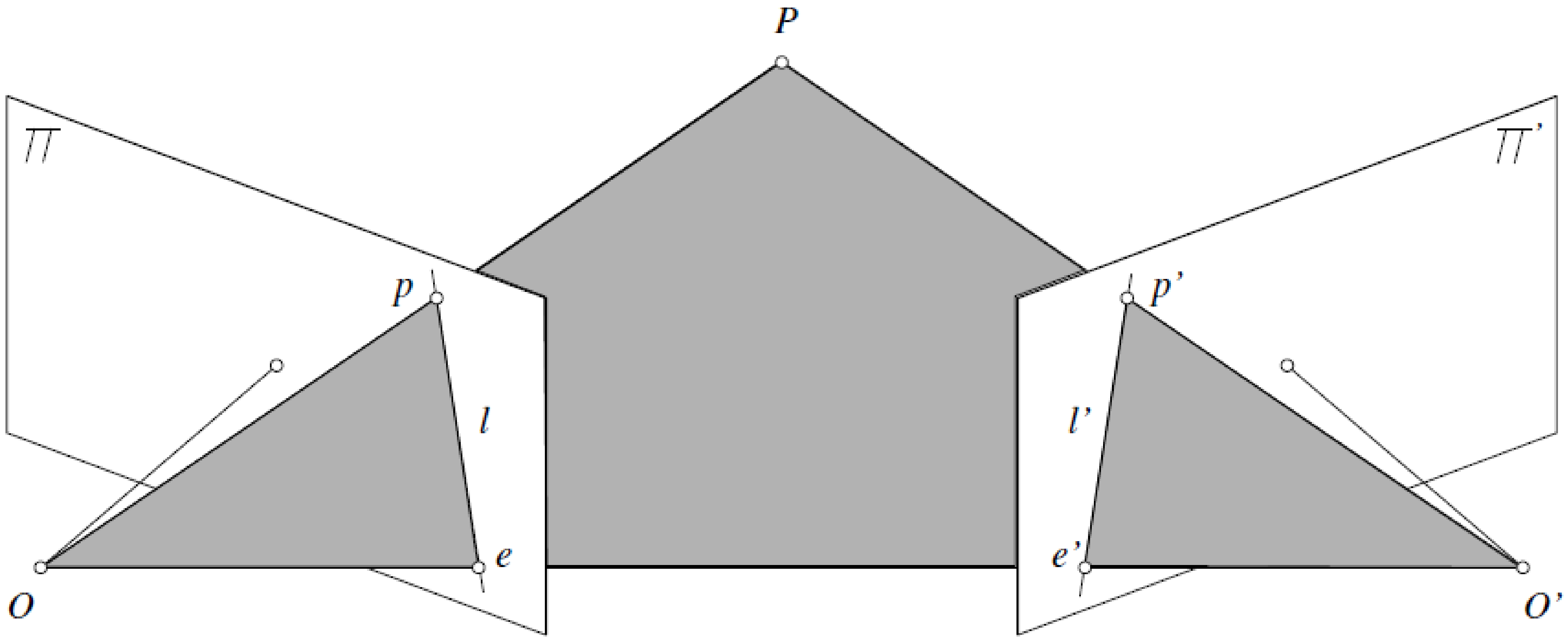
Humanoid robot playing tennis with human being

The binocular fusion problem

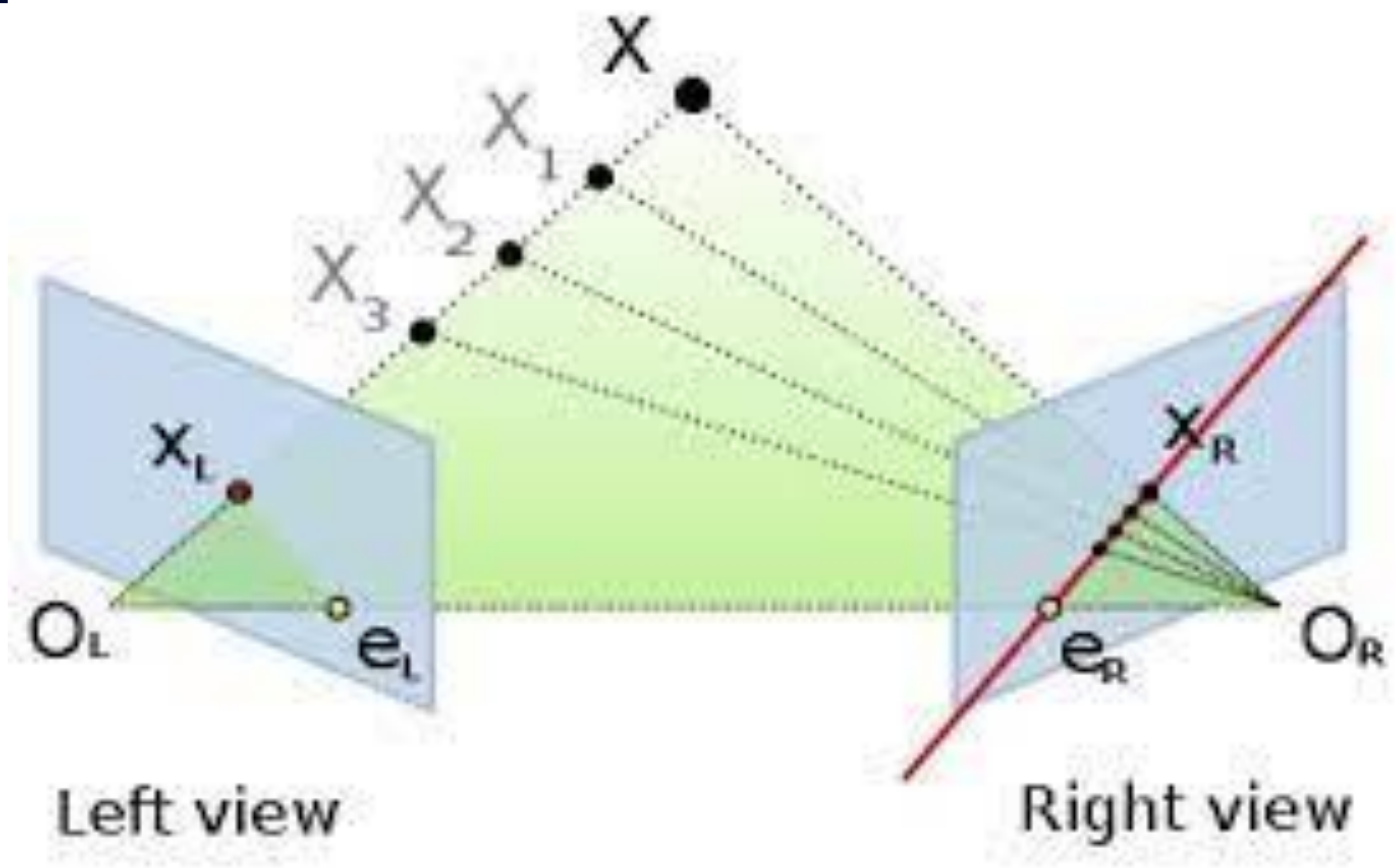




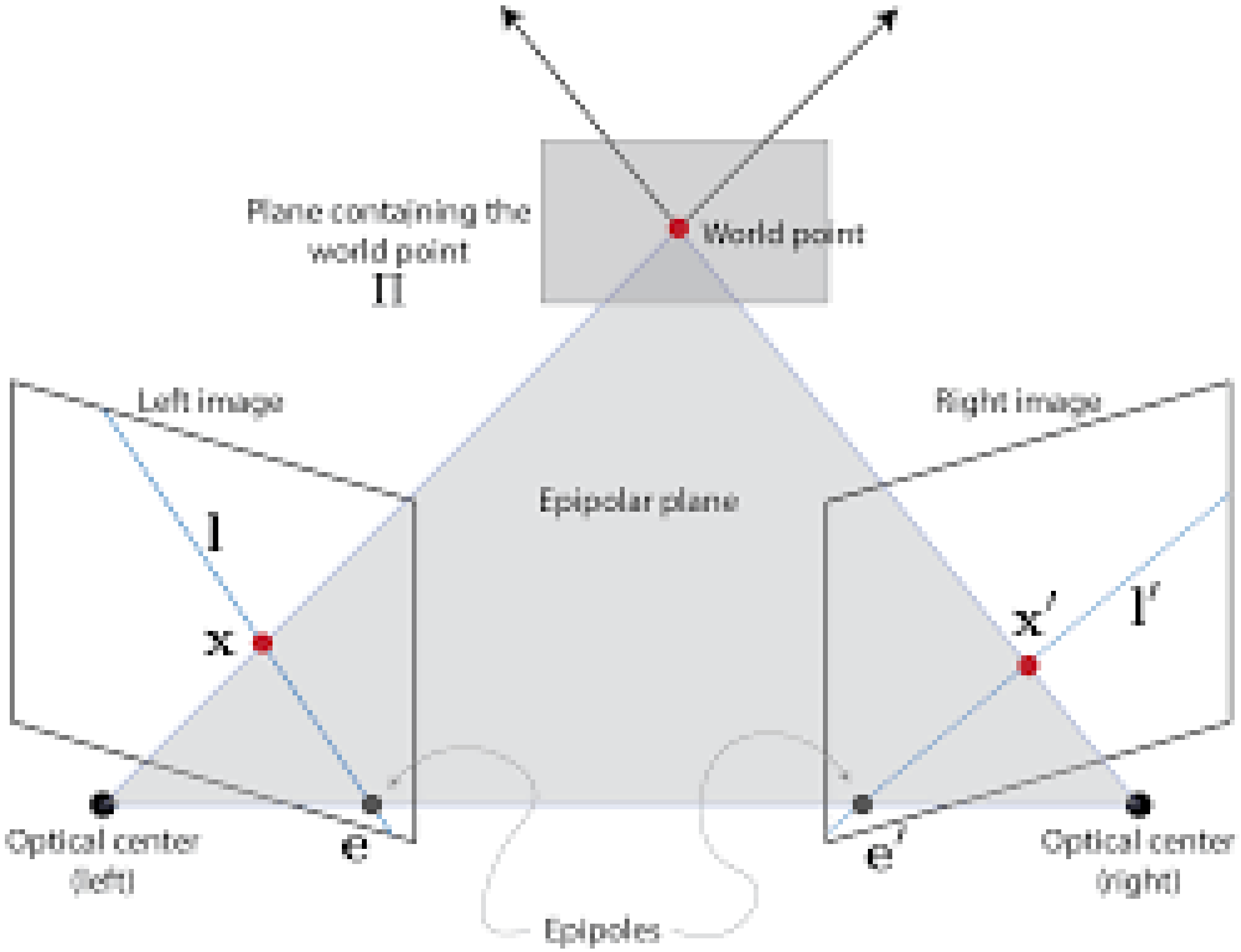
Epipolar geometry



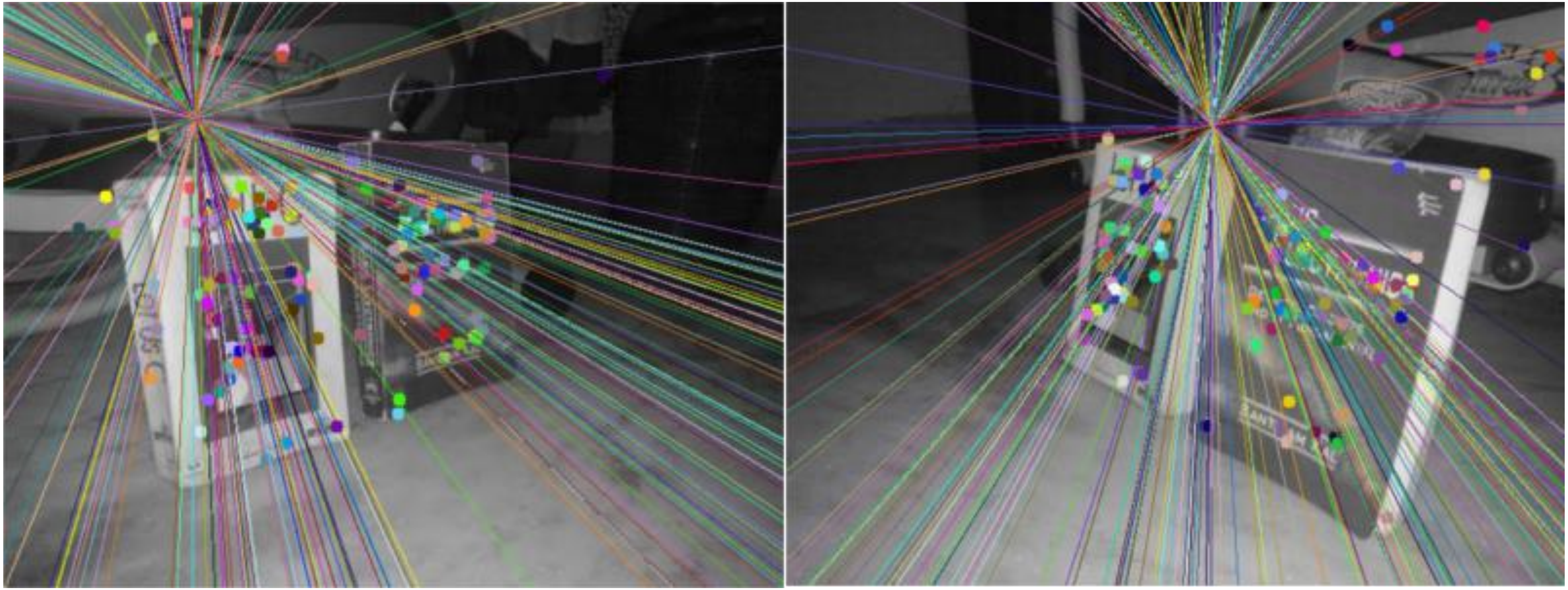
Epipolar geometry



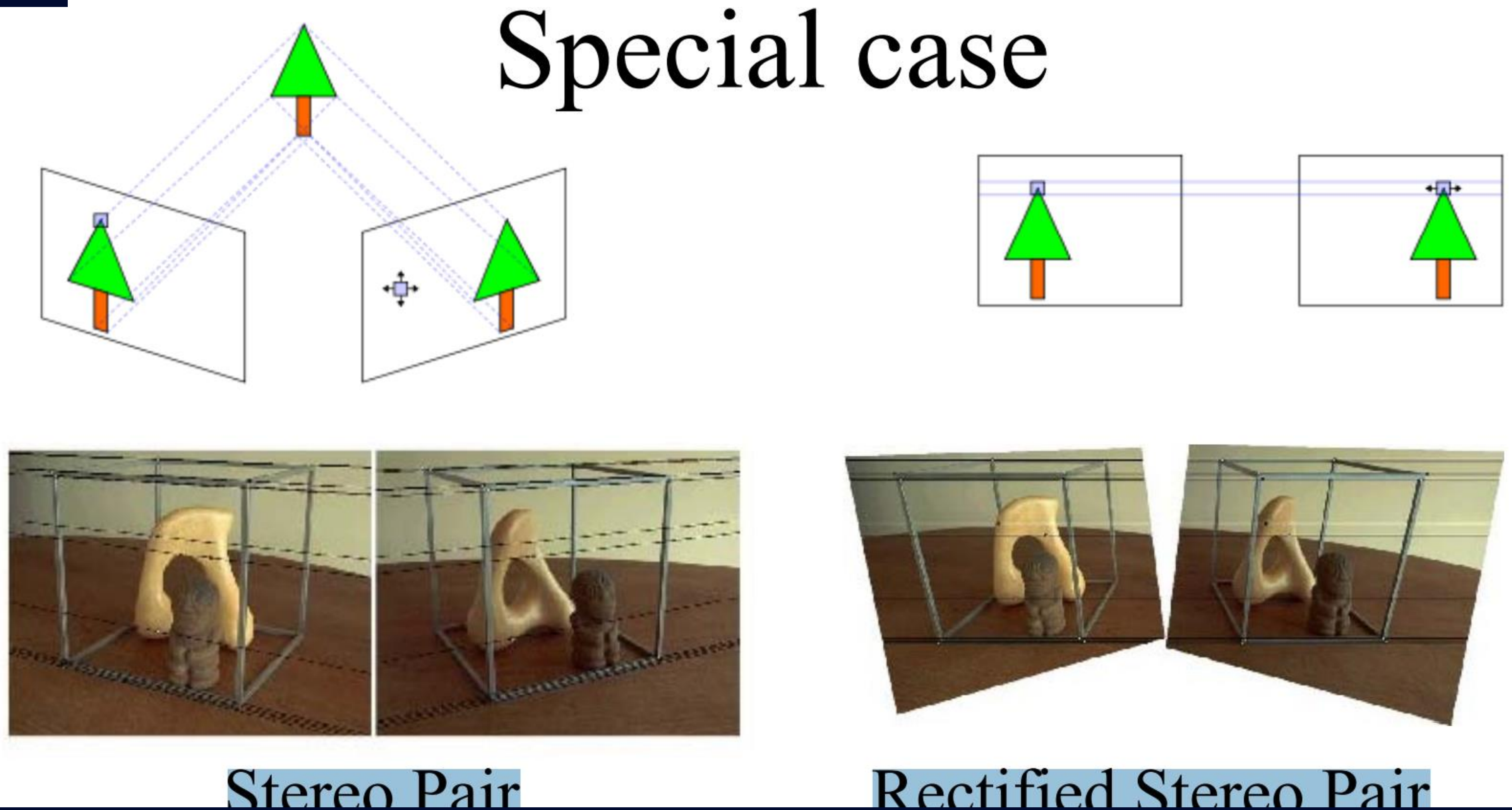
Epipolar geometry



Epipolar geometry



Stereo Pair znd Rectified Stereo Pair



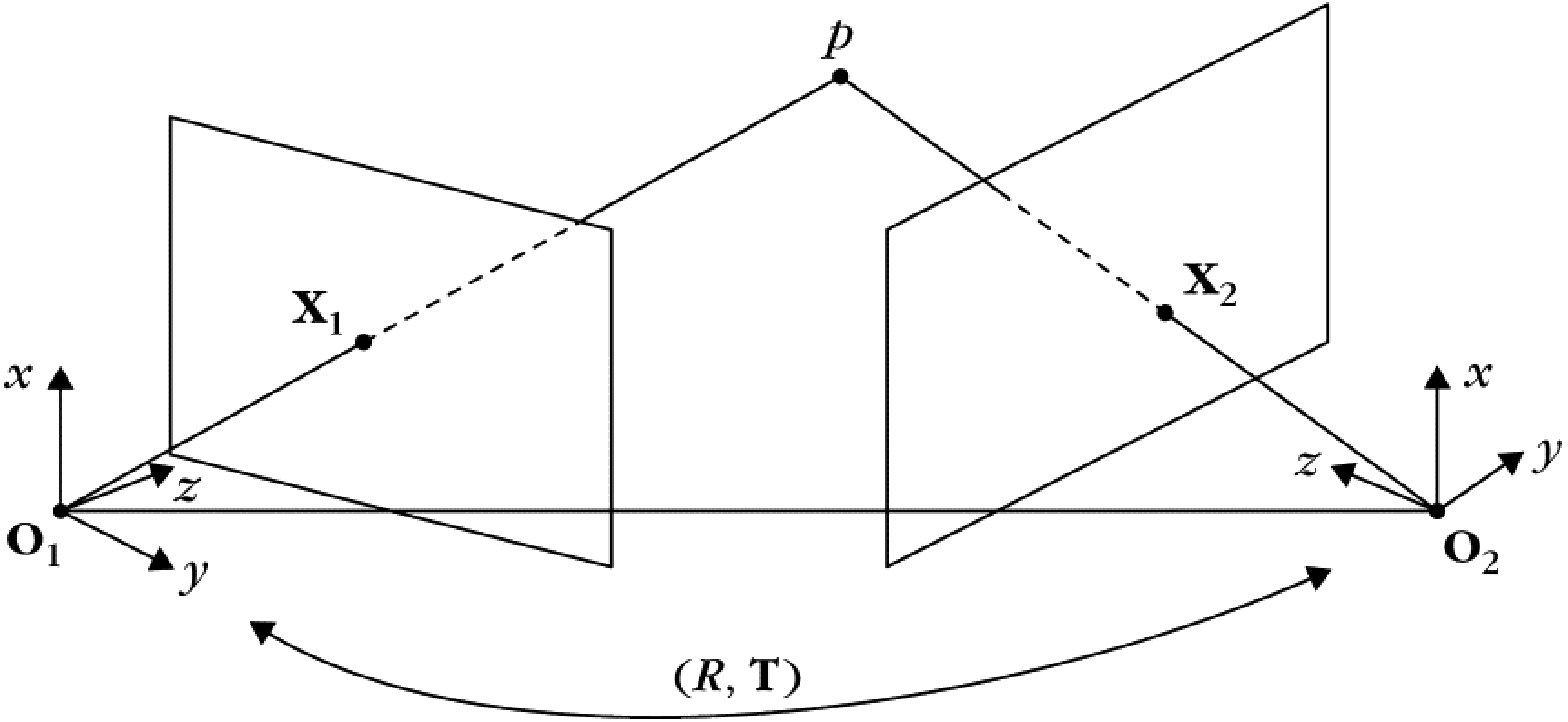
Binocular camera geometry and the epipolar constraint

- points e and e′ are called the epipoles of the two cameras
- e′ is projection of optical center O of 1st camera in image observed by 2nd camera
- if p and p′ are images of the same point,
- then p′ must lie on the epipolar line associated with p.

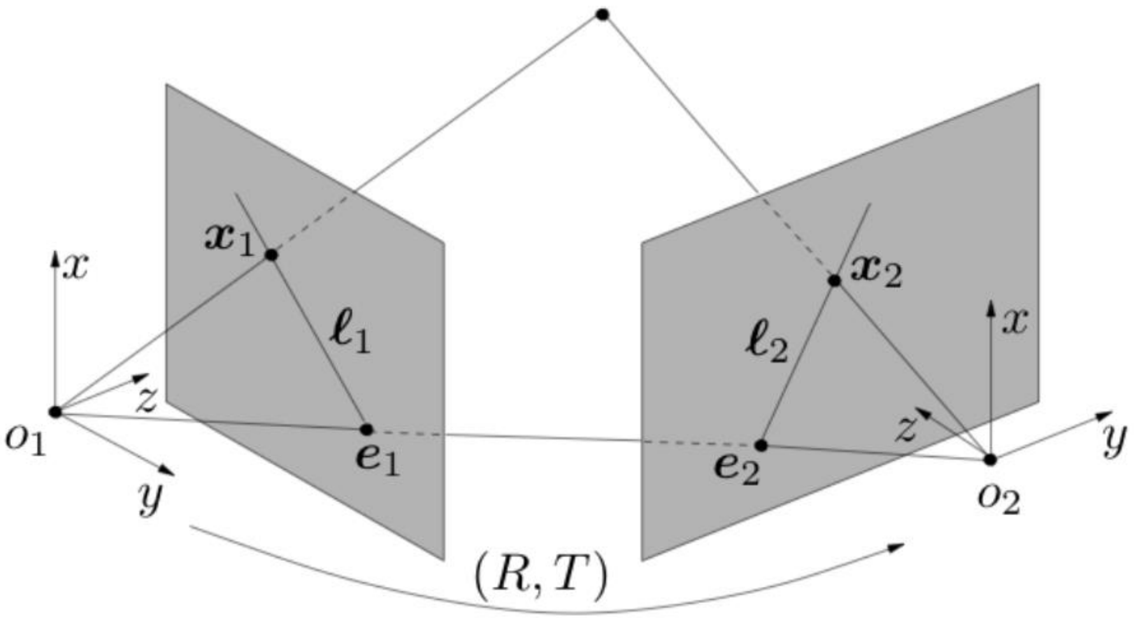
The Essential Matrix

- normalized image coordinates— take p = ˆp.
- three vectors $\overrightarrow{Op}$, $\overrightarrow{O'p'}$, and $\overrightarrow{OO'}$ must be coplanar.
- one of them must lie in the plane spanned by the other two
- $\overrightarrow{Op} \cdot [\overrightarrow{OO'} \times \overrightarrow{O'p'}] = 0.$

Epipolar geometry



Calibrated 2 view geometry

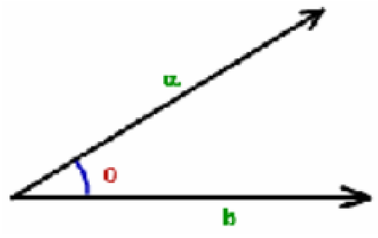


$$\boxed{\boldsymbol{X}_2 = R\boldsymbol{X}_1 + \boldsymbol{T}}$$

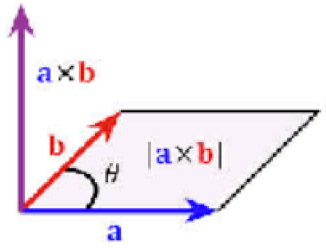
$$\boldsymbol{X}_1 = \lambda_1 \boldsymbol{x}_1, \quad \boldsymbol{X}_2 = \lambda_2 \boldsymbol{x}_2$$

Recall

Dot product: $\mathbf{a} \cdot \mathbf{b} = ||\mathbf{a}|| \; ||\mathbf{b}|| cos\theta$



Cross product: $\mathbf{a} \times \mathbf{b} = \|\mathbf{a}\| \, \|\mathbf{b}\| \sin\theta \; \mathbf{n}$



Cross product matrix: $\mathbf{a} \times \mathbf{b} = \begin{bmatrix} a_2b_3 - a_3b_2 \\ a_3b_1 - a_1b_3 \\ a_1b_2 - a_2b_1 \end{bmatrix} = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \equiv \hat{\mathbf{a}}\mathbf{b}$

Important property (skew symmetric): $\hat{\mathbf{a}}^T = -\hat{\mathbf{a}}$

The Essential Matrix

$$\overrightarrow{Op} \cdot [\overrightarrow{OO'} \times \overrightarrow{O'p'}] = 0.$$

$$\boldsymbol{p} \cdot [\boldsymbol{t} \times (\mathcal{R}\boldsymbol{p}')] = 0,$$

$$\boldsymbol{p}^T \mathcal{E} \boldsymbol{p}' = 0,$$

$$\mathcal{E} = [\boldsymbol{t}_\times]\mathcal{R},$$

[a×] denotes the skew-symmetric matrix such that [a×]x = a × x is the cross-product of the vectors a and x.

Derivation of essential matrix equation/ epipolar geometry constraint

$$\boxed{\boldsymbol{X}_2 = R\boldsymbol{X}_1 + \boldsymbol{T}}$$

$$\boldsymbol{X}_1 = \lambda_1 \boldsymbol{x}_1, \quad \boldsymbol{X}_2 = \lambda_2 \boldsymbol{x}_2$$

$$\lambda_2 \boldsymbol{x}_2 = R\lambda_1 \boldsymbol{x}_1 + \boldsymbol{T}$$

Take (left) cross product of both sides with T

$$\lambda_2 \widehat{T} \boldsymbol{x}_2 = \widehat{T} R \lambda_1 \boldsymbol{x}_1 + \underbrace{\widehat{T} T}_{=\mathbf{0}}$$

Take (left) dot product of both sides with $\boldsymbol{x}_2$

$$\lambda_2 \underbrace{\boldsymbol{x}_2^\top \widehat{T} \boldsymbol{x}_2}_{=0} = \boldsymbol{x}_2^\top \widehat{T} R \lambda_1 \boldsymbol{x}_1$$

$$\mathcal{E} = [\boldsymbol{t}_\times]\mathcal{R},$$

$$\boldsymbol{x}_2^\top \widehat{T} R \boldsymbol{x}_1 = 0$$

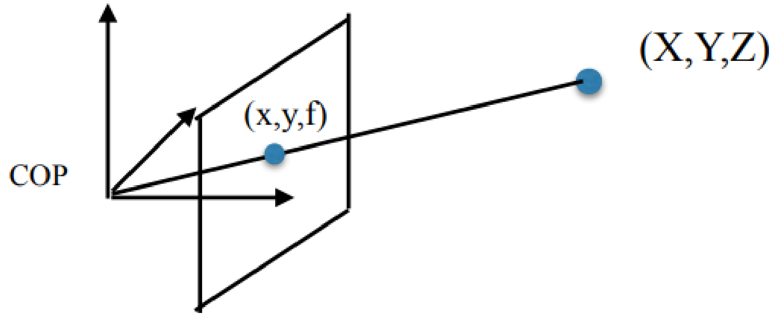
Key points in essential matrix 3*3

- l = ξ p′ coordinate vector of epipolarline l associated with p′ in the first image
- p· l = 0, expressing the fact that the point p lies on l.
- Essential matrices are singular
- because t is parallel to the coordinate vector e of the first epipole,
- $\mathcal{E}^T e \breve{=} -\mathcal{R}^T [t_\times] e = 0.$

The fundamental matrix

- Native image coordinates
- $p = \mathcal{K}\hat{p}$ and $p' = \mathcal{K}'\hat{p}'$,
- K and K' are the 3 × 3 calibration matrices associated with the two cameras
- $p^T \mathcal{F} p' = 0$, $\mathcal{F} = \mathcal{K}^{-T} \mathcal{E} \mathcal{K}'^{-1}$
- $l' = \mathcal{F} p'$ (resp. $l = \mathcal{F}^T p$)

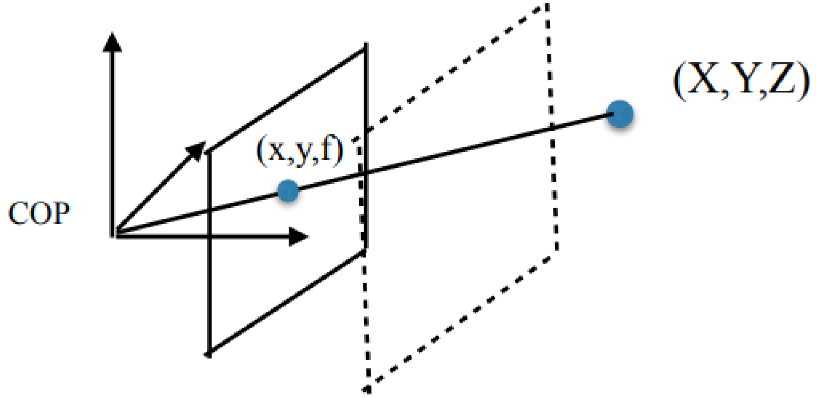
Projecting from camera coordinate system to image coordinates



$$\lambda \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} fs_x & fs_\theta & o_x \\ 0 & fs_y & o_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$\lambda \mathbf{x} = K\mathbf{X}$$

Projecting from camera coordinate system to normalized image coordinates

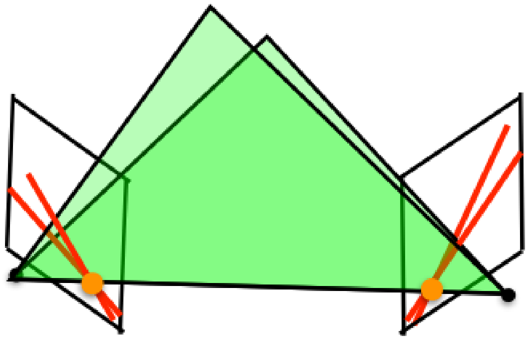


If K is known, work with warped image

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = K^{-1} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\lambda \mathbf{x}' = \mathbf{X}$$

The fundamental matrix



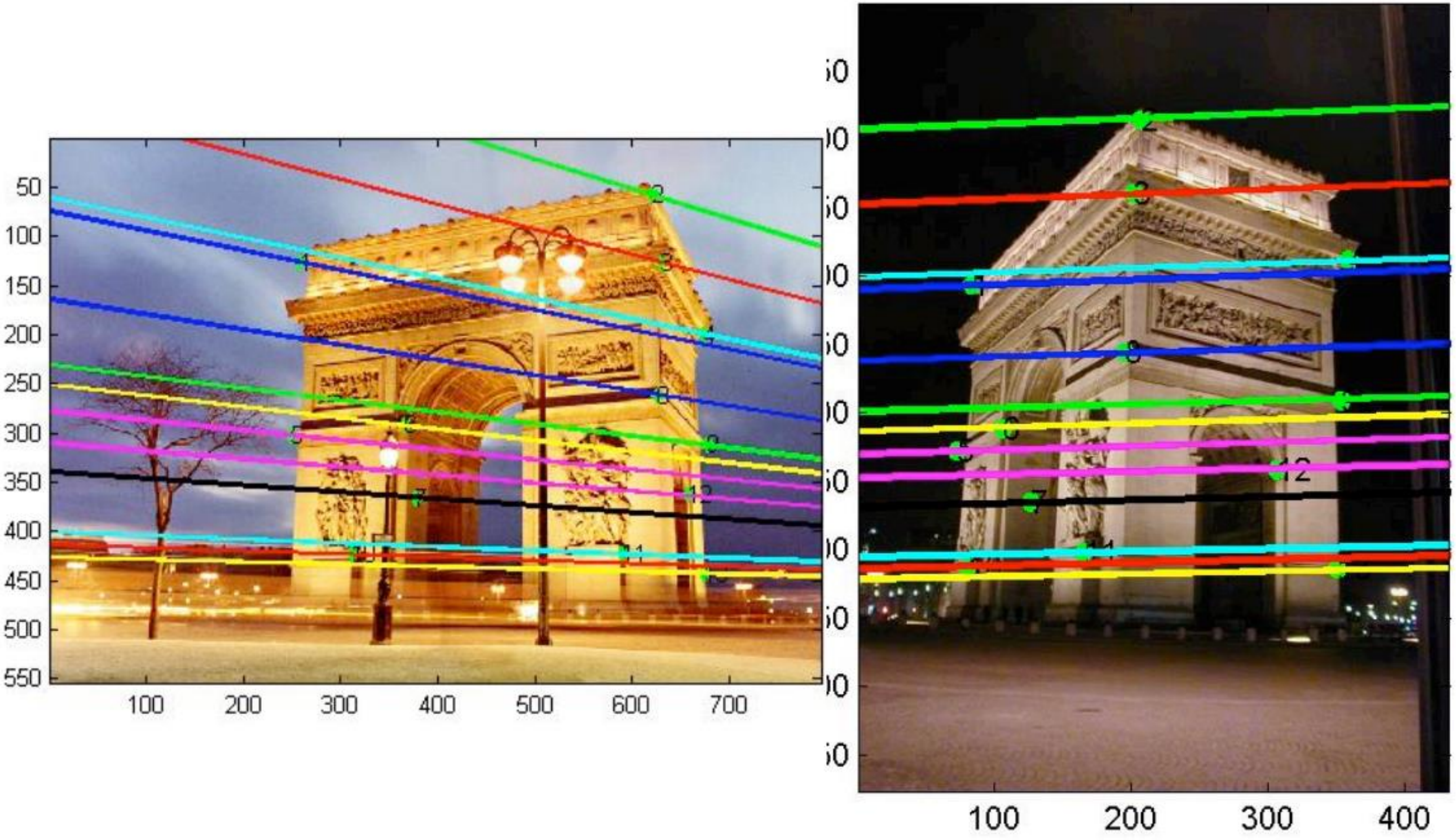
In uncalibrated case, we need to account for camera intrinsics:

$$\lambda \mathbf{x} = K\mathbf{X}$$

$$E = \hat{T}R$$

$$F = {K_2}^{-T} E K_1^{-1}$$

An example with fundamental matrix



An example with fundamental matrix

$$F = \begin{pmatrix} -0.00310695 & -0.0025646 & 2.96584 \\ -0.028094 & -0.00771621 & 56.3813 \\ 13.1905 & -29.2007 & -9999.79 \end{pmatrix} \begin{pmatrix} 343.53 \\ 221.70 \\ 1.0 \end{pmatrix}$$

x = 343.5300 y = 221.7005

$$\begin{matrix} 0.0001 \\ 0.0045 \\ -1.1942 \end{matrix} \rightarrow \begin{matrix} 0.0295 \\ 0.9996 \\ -265.1531 \end{matrix}$$

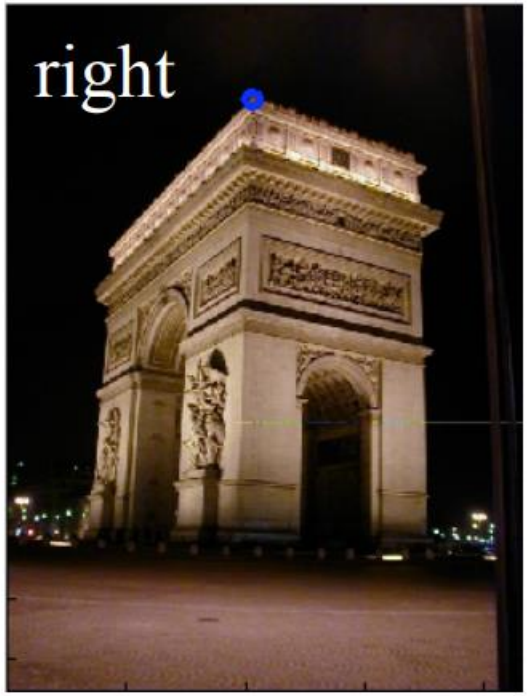
normalize so sum of squares of first two terms is 1 (optional)

An example with fundamental matrix

$$\begin{pmatrix} 205.5526 & 80.5 & 1.0 \end{pmatrix} \begin{pmatrix} -0.00310695 & -0.0025646 & 2.96584 \\ -0.028094 & -0.00771621 & 56.3813 \\ 13.1905 & -29.2007 & -9999.79 \end{pmatrix}$$

$$L = (0.0010 \quad -0.0030 \quad -0.4851)$$

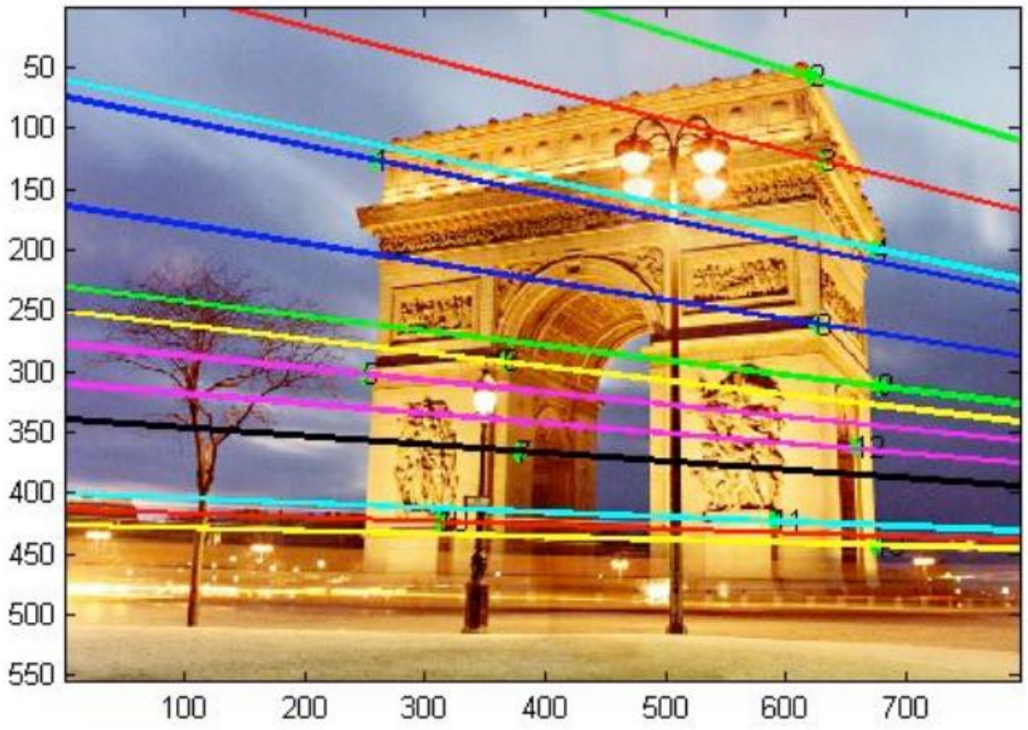
$$\rightarrow (0.3211 \quad -0.9470 \quad -151.39)$$



x = 205.5526 y = 80.5000

An example with fundamental matrix

where is the epipole?



$$F * e_L = 0$$

vector in the right nullspace of matrix F

However, due to noise, F may not be singular. So instead, next best thing is eigenvector associated with smallest eigenvalue of F

An example with fundamental matrix

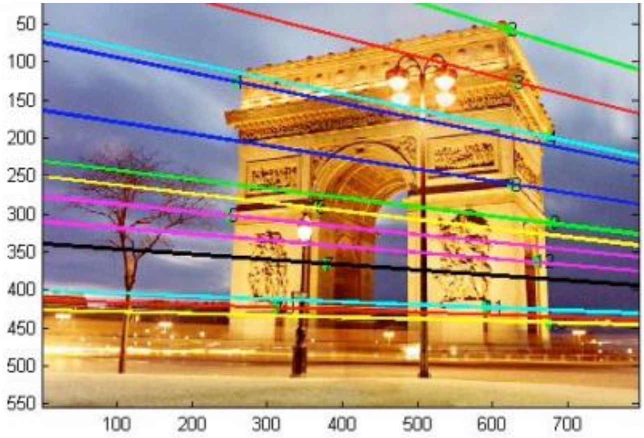
>> [u,d] = eigs(F' * F)

u =

$$\begin{matrix} -0.0013 & 0.2586 & \boxed{-0.9660} \\ 0.0029 & -0.9660 & \boxed{-0.2586} \\ 1.0000 & 0.0032 & \boxed{-0.0005} \end{matrix}$$

d = 1.0e8*

$$\begin{matrix} -1.0000 & 0 & 0 \\ 0 & -0.0000 & 0 \\ 0 & 0 & -0.0000 \end{matrix}$$



eigenvector associated with smallest eigenvalue

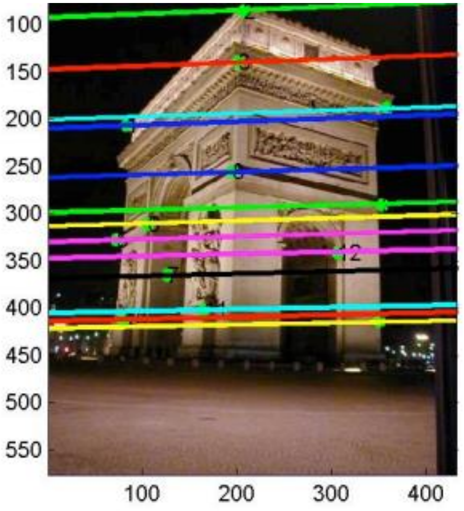
>> uu = u(:,3)

uu = (-0.9660 -0.2586 -0.0005)

>> uu / uu(3) : to get pixel coords

(1861.02 498.21 1.0)

An example with fundamental matrix



>> [u,d] = eigs(F * F')

$$u = \begin{array}{ccc} -0.0003 & -0.0618 & \boxed{-0.9981} \\ -0.0056 & -0.9981 & \boxed{0.0618} \\ 1.0000 & -0.0056 & \boxed{0.0001} \end{array} \qquad d = 1.0e8* \begin{array}{ccc} -1.0000 & 0 & 0 \\ 0 & -0.0000 & 0 \\ 0 & 0 & -0.0000 \end{array}$$

eigenvector associated with smallest eigenvalue

>> uu = u(:,3)

uu = (-0.9981 0.0618 0.0001)

>> uu / uu(3) : to get pixel coords

(-19021.8 1177.97 1.0)

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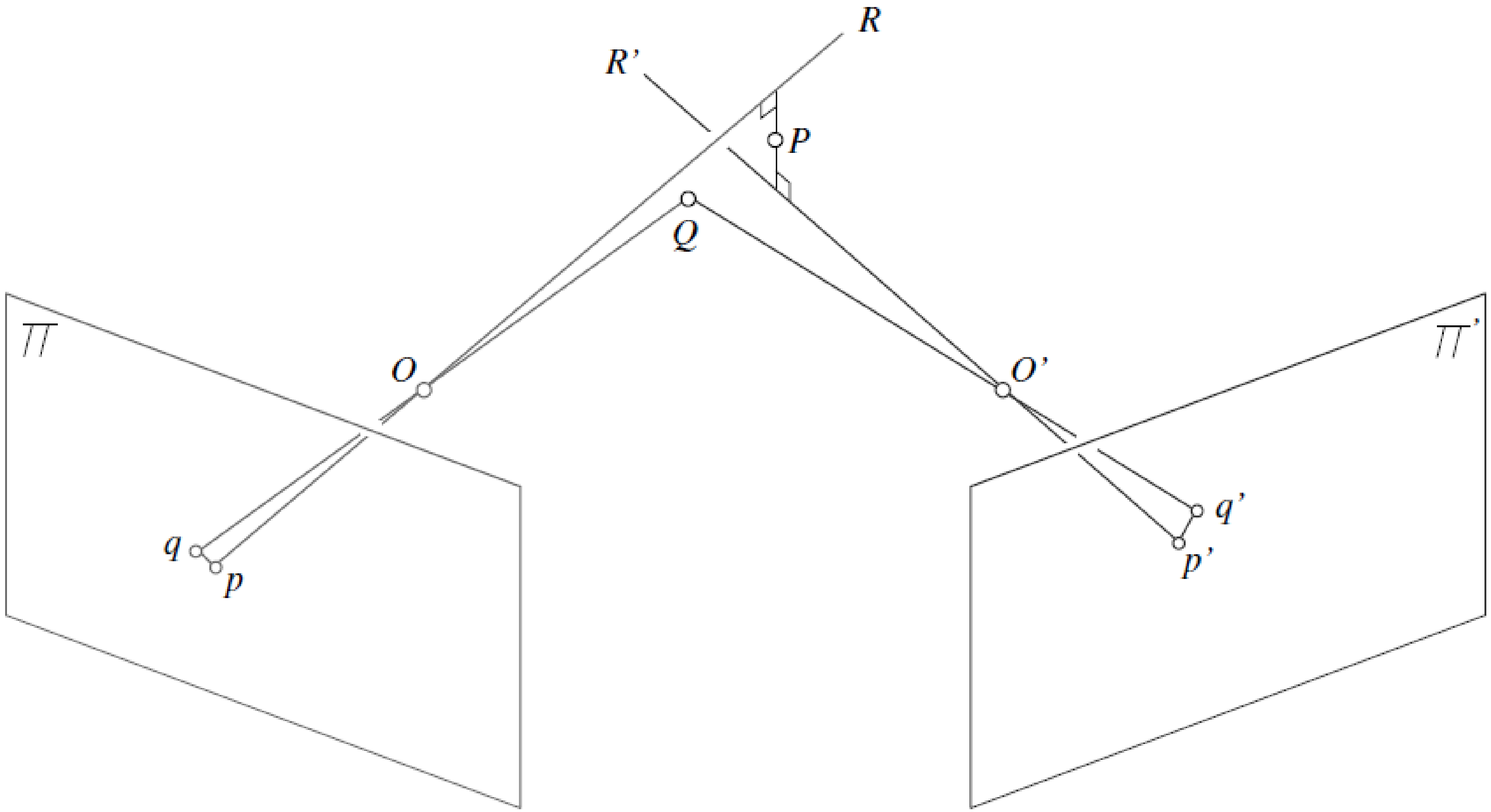
Triangulation in the presence of measurement errors



Binocular reconstruction

- Reconstruct the corresponding scene point by intersecting R = Op and R′ = O′p′
- the rays R and R′ never actually intersect in practice,
- consider the line segment perpendicular to R and R′ that intersects both rays
- mid-point P is the closest point to two rays and preimage of p and p′.

Alternatively, one can reconstruct a scene point using a purely algebraic approach

proach: given the projection matrices $\mathcal{M}$ and $\mathcal{M}'$ and the matching points p and p', we can rewrite the constraints $Z\boldsymbol{p} = \mathcal{M}\boldsymbol{P}$ and $Z'\boldsymbol{p}' = \mathcal{M}\boldsymbol{P}$ as

$$\begin{cases} \boldsymbol{p} \times \mathcal{M}\boldsymbol{P} = 0 \\ \boldsymbol{p}' \times \mathcal{M}'\boldsymbol{P} = 0 \end{cases} \iff \begin{pmatrix} [\boldsymbol{p}_\times]\mathcal{M} \\ [\boldsymbol{p}'_\times]\mathcal{M}' \end{pmatrix} \boldsymbol{P} = 0.$$

This is an overconstrained system of four independent linear equations in the homogeneous coordinates of P that is easily solved using the linear least-squares tech-

A rectified stereo pair

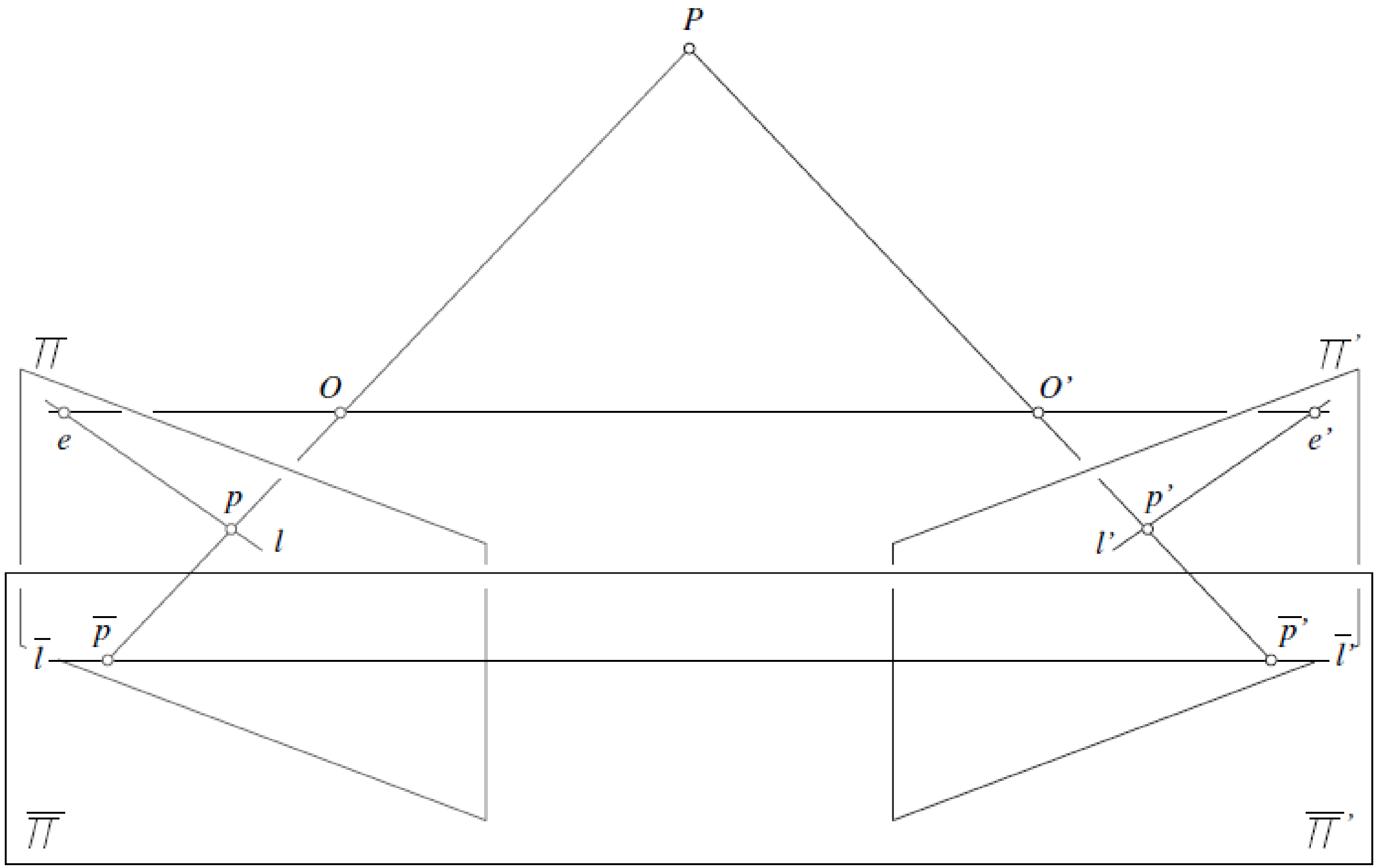


Image Rectification

- replaced by two equivalent pictures with a common image plane parallel
- to the baseline joining the two optical centers
- by projecting the original pictures onto the new image plane
- two degrees of freedom involved in the choice of the rectified image plane

Disparity and depth

- left and right images, with coordinates (x, y) and (x', y),
- disparity is defined as the difference $d = x' - x$.
- B denotes the distance between the optical centers,
- depth of P in the (normalized) coordinate system attached to the first camera
- $Z = -B/d$.
- Coordinate vector of the point P in the frame attached to the first camera
- $P = -(B/d)p$, where $p = (x, y, 1)T$

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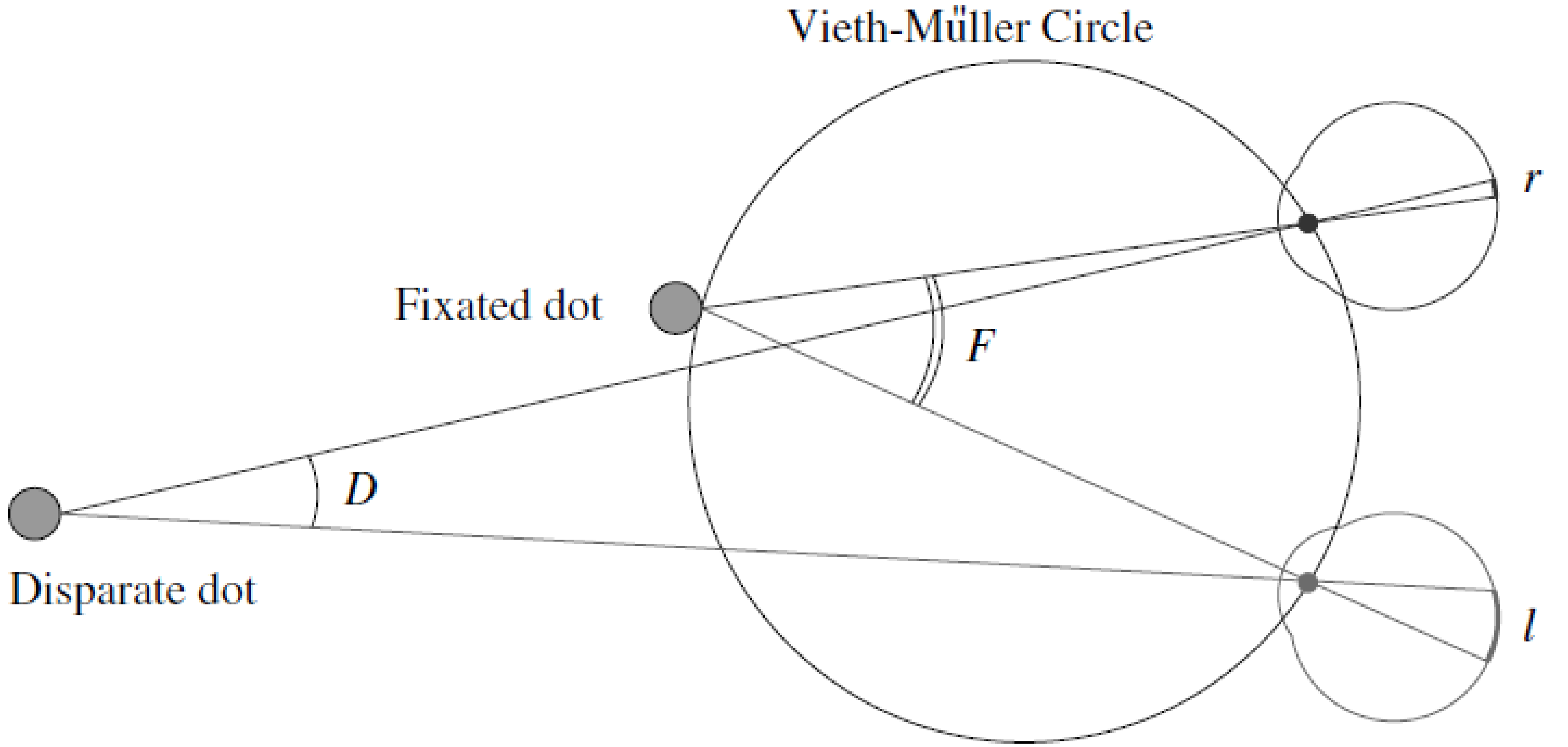
$$\nabla = \hat{\mathbf{i}} \frac{\partial}{\partial x} + \hat{\mathbf{j}} \frac{\partial}{\partial y} + \hat{\mathbf{k}} \frac{\partial}{\partial z}$$

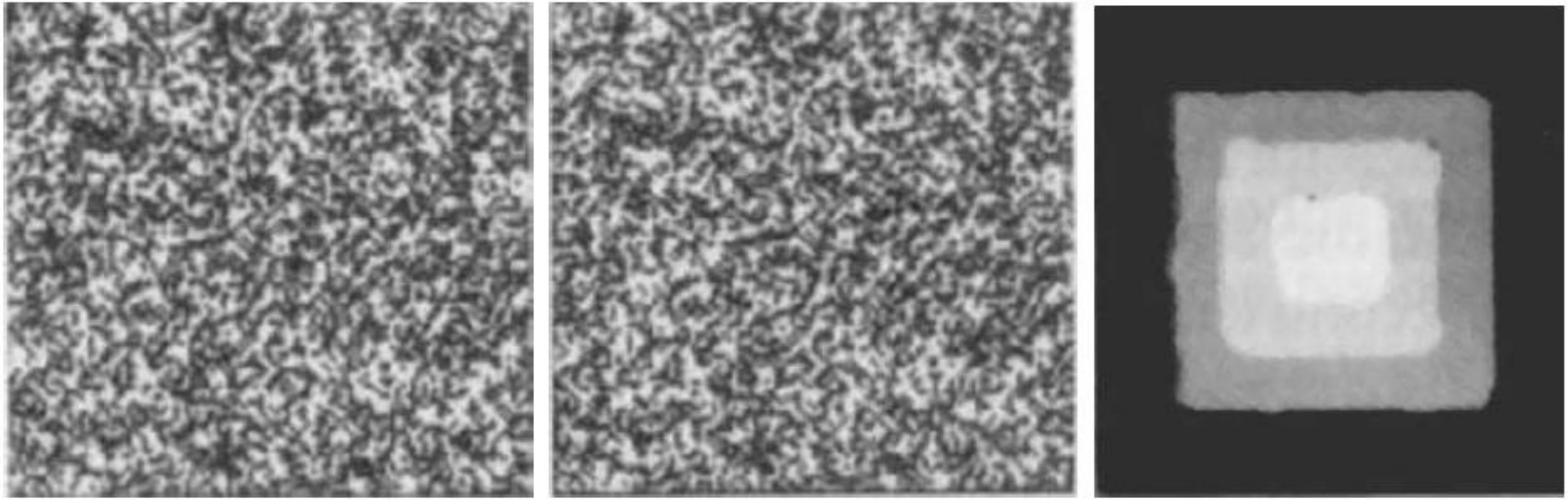
Human stereopsis

- l and r denote the (counterclockwise) angles
- disparity as d = r − l. Also, d = D − F,
- Points lying inside this circle have a positive disparity,
- to rank order dots that are near the fixation point according to their depth.

Vieth–M¨uller circle



two pictures forming a random dot stereogram



a random dot stereogram

- a pair of synthetic images obtained by randomly spraying black dots on white objects
- When viewed monocularly, the images appear completely random.
- when viewed stereoscopically, image pair gives impression of a square markedly
- Human binocular fusion cannot be explained by peripheral processes directly
- must involve the central nervous system and an imaginary cyclopean retina
- combines the left and right image stimuli as a single unit.

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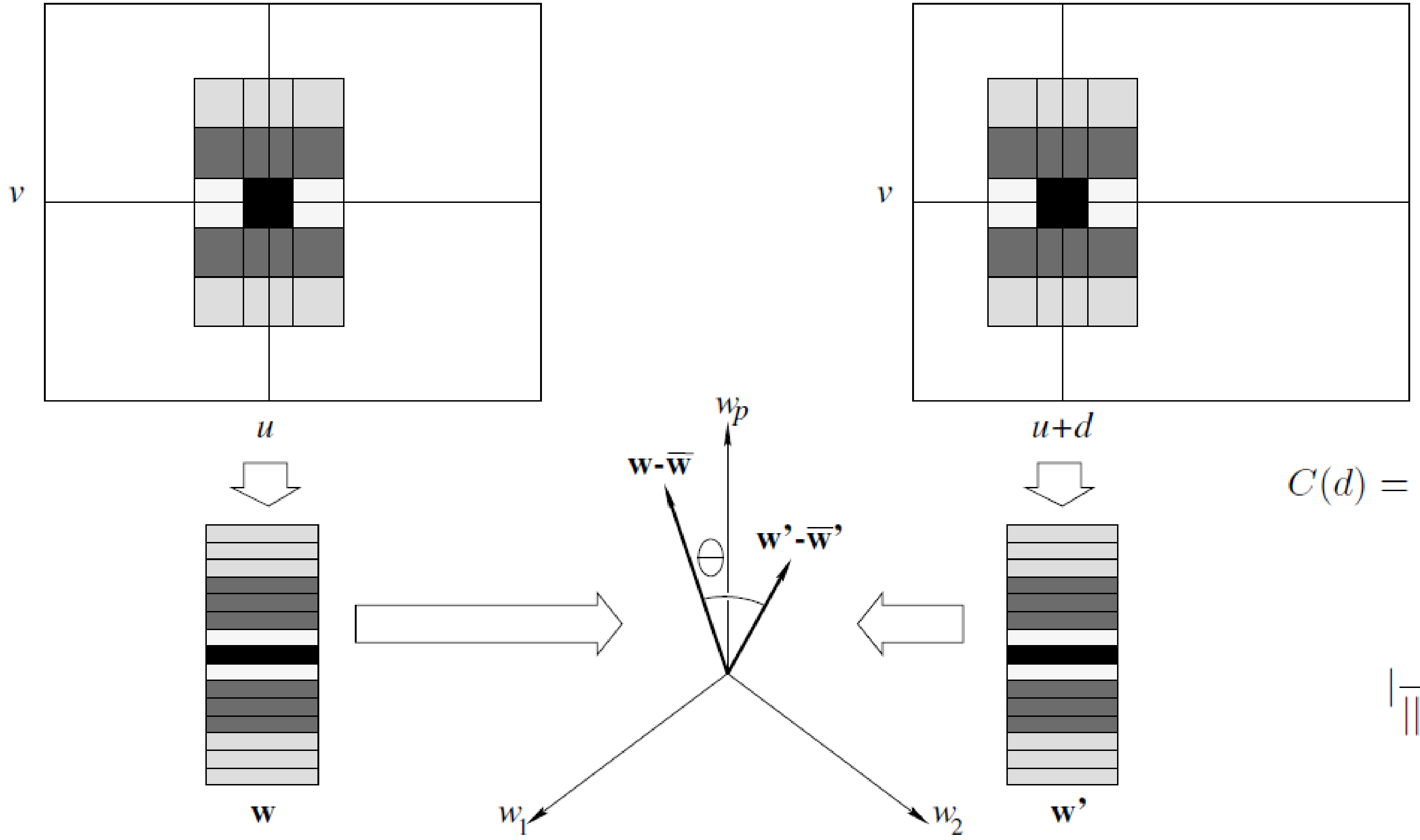
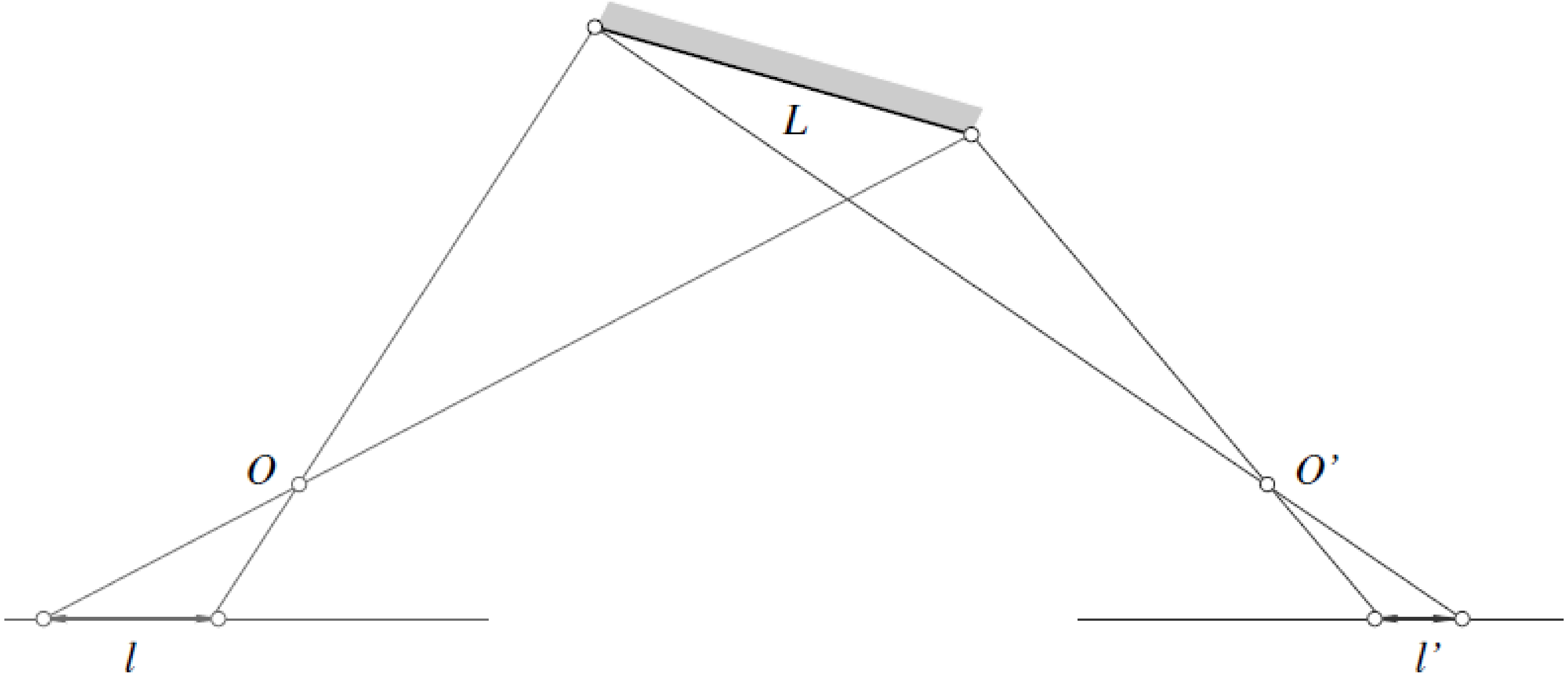
Correlation of two 3×5 windows along corresponding epipolar lines.



$$C(d) = \frac{1}{||w - \bar{w}||}\frac{1}{||w' - \bar{w}'||}[(w - \bar{w}) \cdot (w' - \bar{w}')],$$

$$|\frac{1}{||w - \bar{w}||}(w - \bar{w}) - \frac{1}{||w' - \bar{w}'||}(w' - \bar{w}')|^2,$$

The foreshortening of an oblique plane is not the same for the left and right cameras: l/L != l'/L.



Correlation-based stereo matching

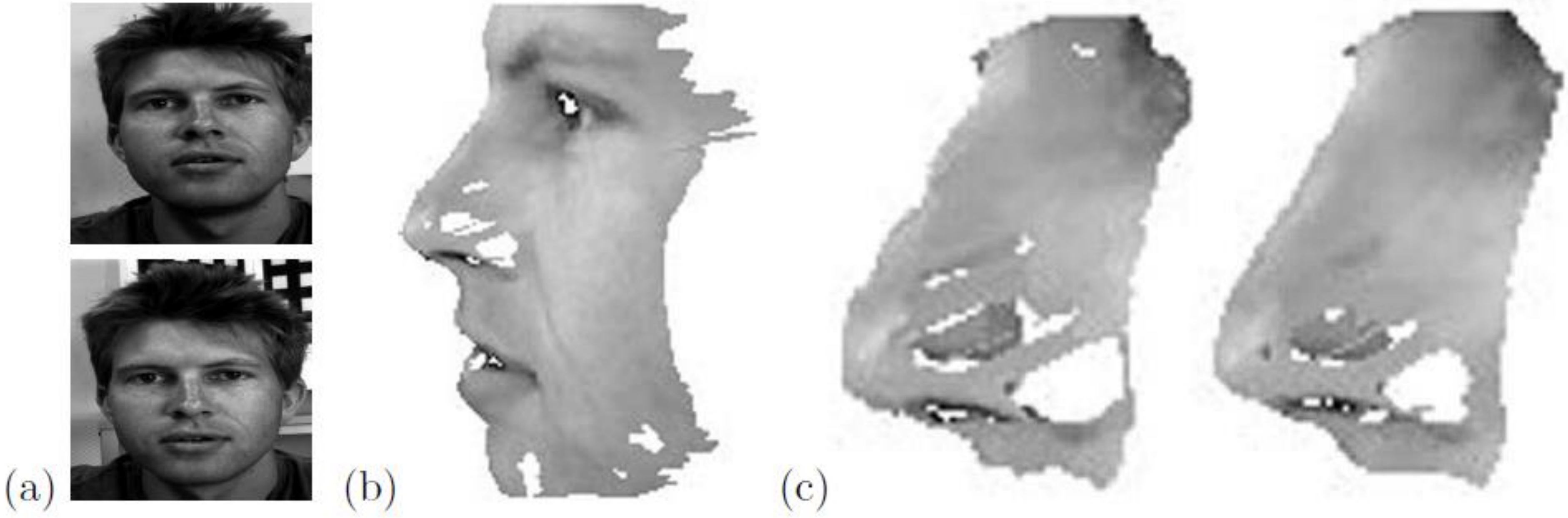
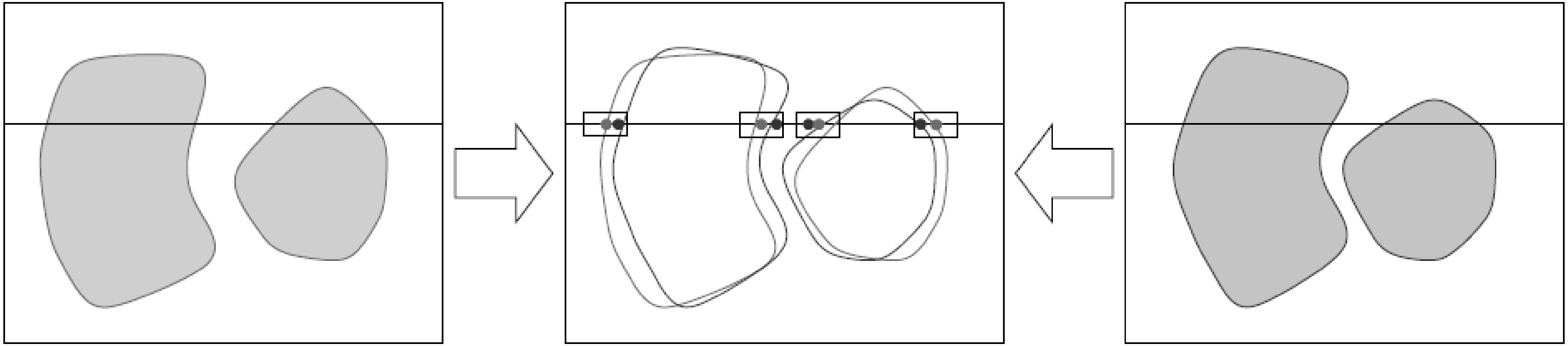


FIGURE 7.11: Correlation-based stereo matching: (a) a pair of stereo pictures; (b) a texture-mapped view of the reconstructed surface; (c) comparison of the regular (**left**) and refined (**right**) correlation methods in the nose region. The latter clearly gives better results. *Reprinted from "Computing Differential Properties of 3D Shapes from Stereopsis*

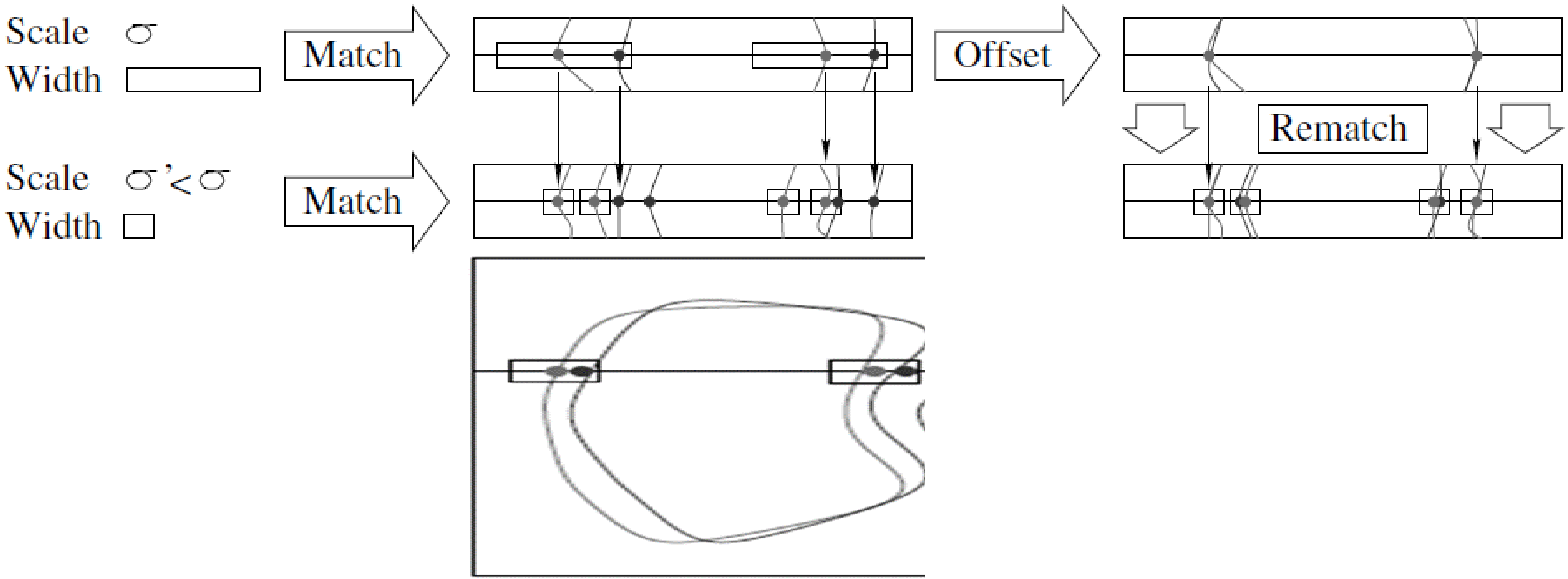
Algorithm 7.1: The Marr–Poggio (1979) Multi-Scale Binocular Fusion Algorithm.

1. Convolve the two (rectified) images with $\nabla^2 G_\sigma$ filters of increasing standard deviations $\sigma_1 < \sigma_2 < \sigma_3 < \sigma_4$.
2. Find zero crossings of the Laplacian along horizontal scanlines of the filtered images.
3. For each filter scale σ, match zero crossings with the same parity and roughly equal orientations in a $[-w_\sigma, +w_\sigma]$ disparity range, with $w_\sigma = 2\sqrt{2}\sigma$.
4. Use the disparities found at larger scales to offset the images in the neighborhood of matches and cause unmatched regions at smaller scales to come into correspondence.

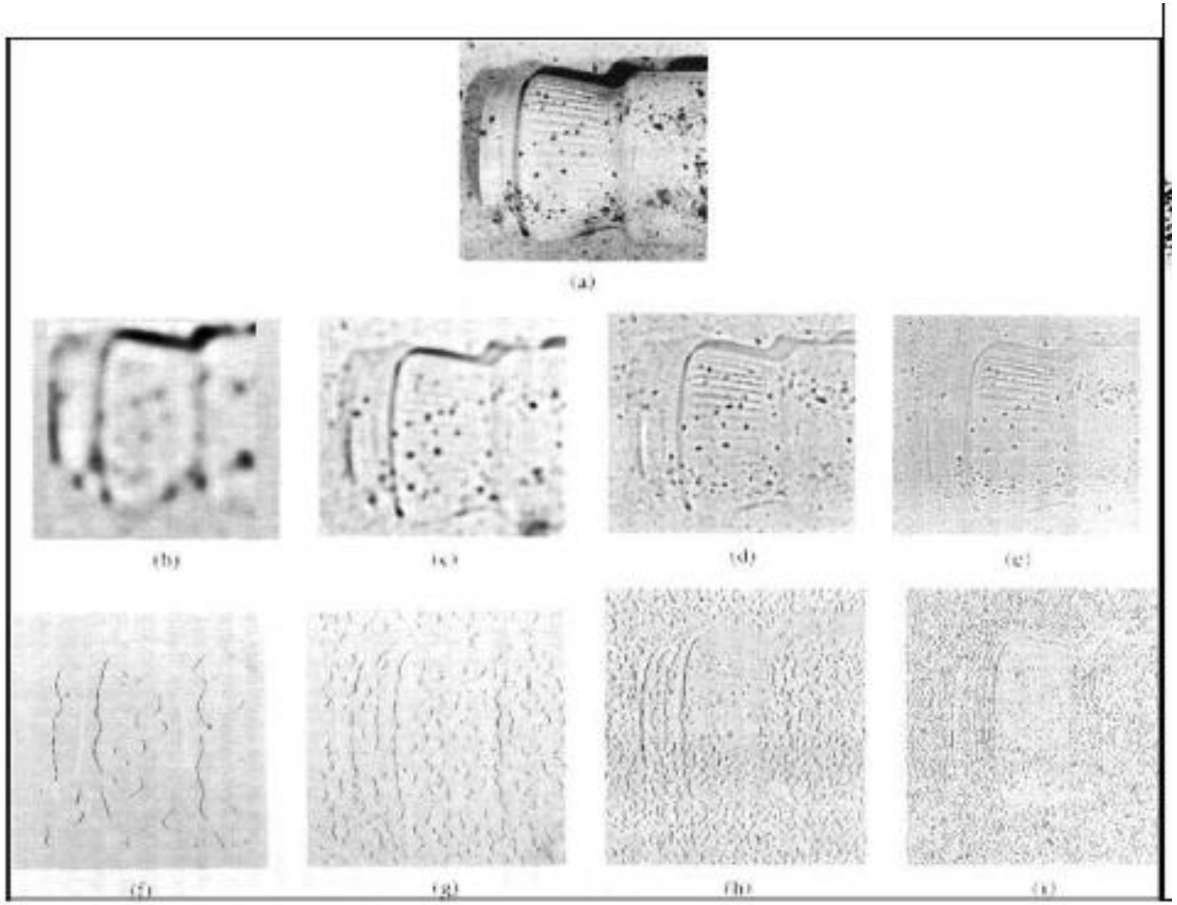
Matching zero crossings at a single scale



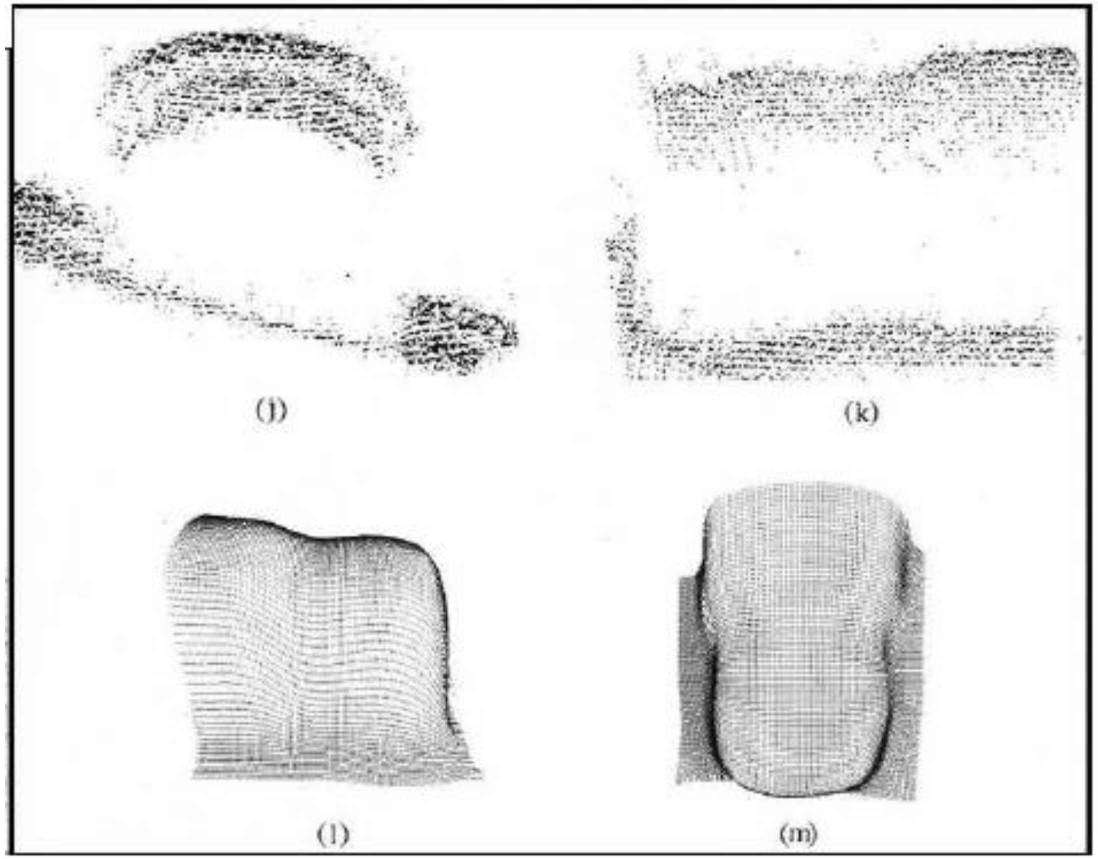
Matching zero crossings at multiple scales

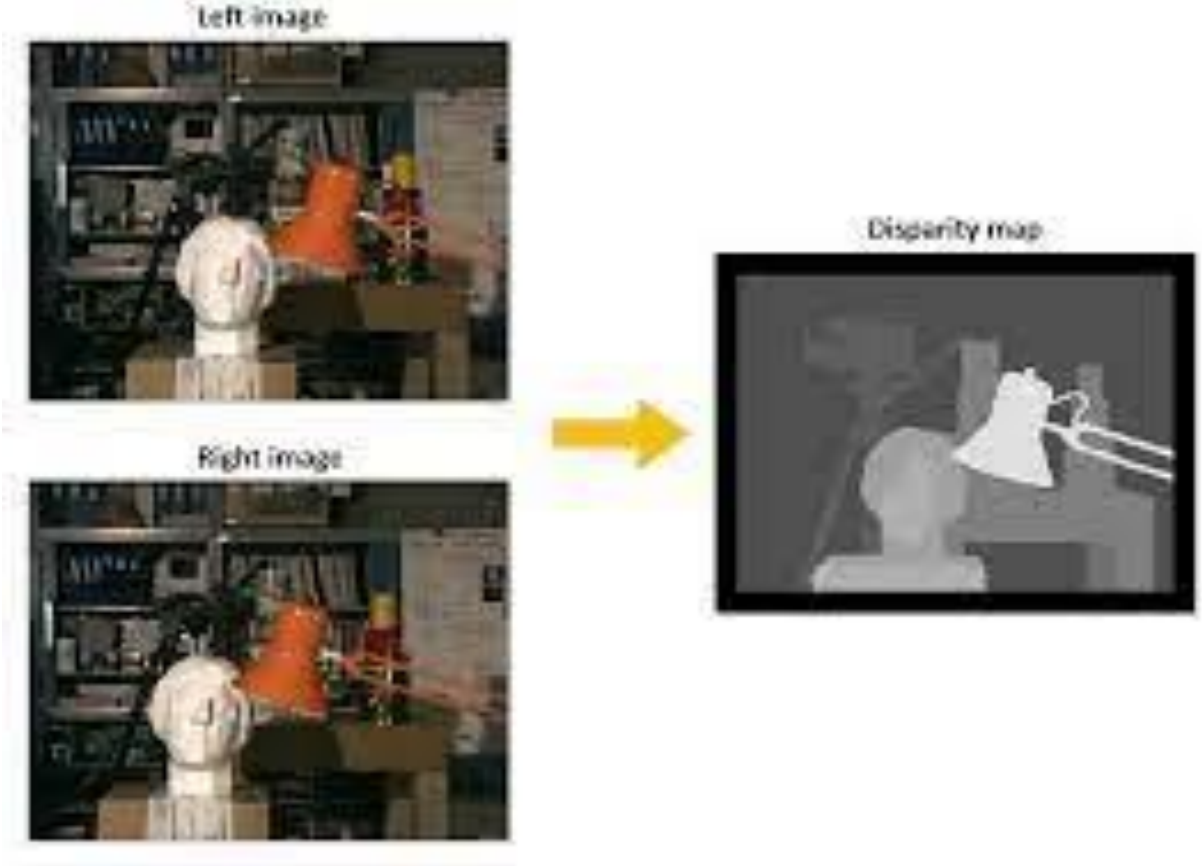


Output of four ∇2Gσ filters, and the corresponding zero crossings



Two views of the disparity map constructed by the matching process and two views of the surface obtained by interpolating the reconstructed points





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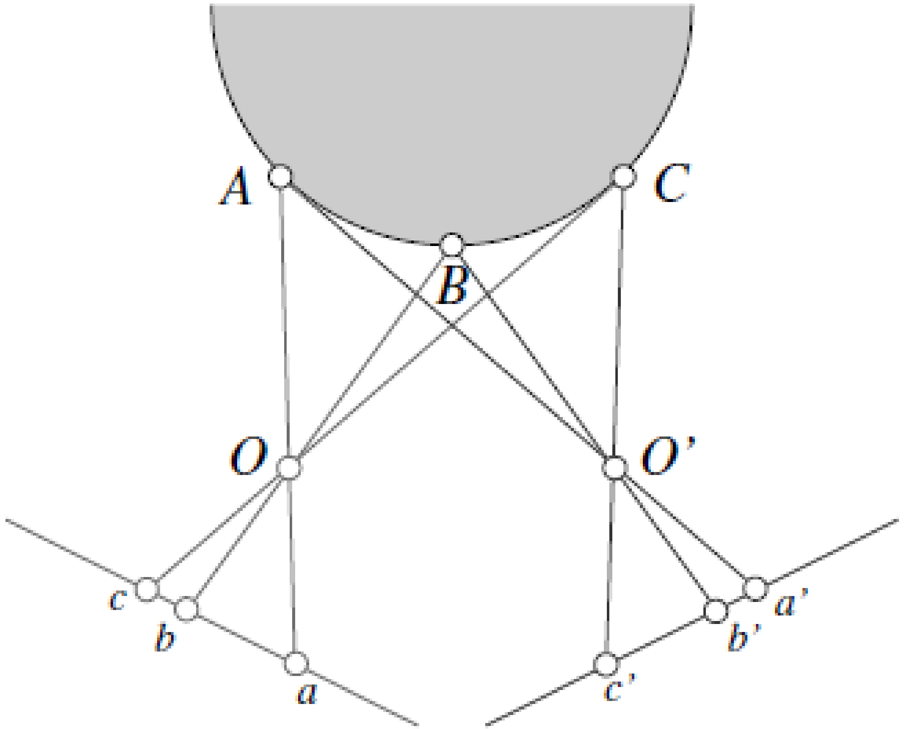
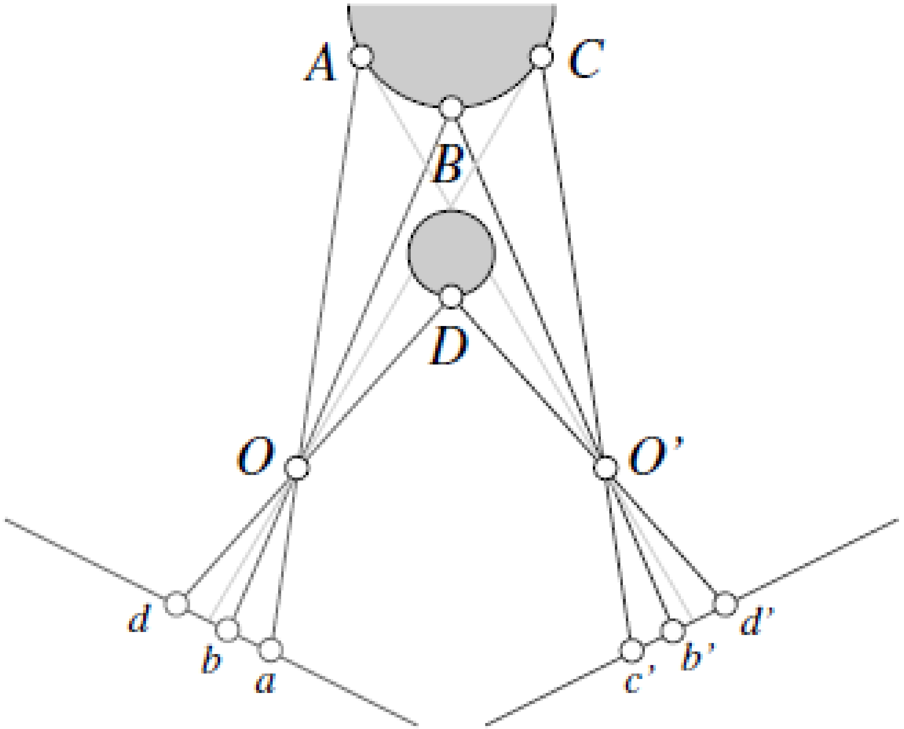
where

$$\nabla = \hat{\mathbf{i}} \frac{\partial}{\partial x} + \hat{\mathbf{j}} \frac{\partial}{\partial y} + \hat{\mathbf{k}} \frac{\partial}{\partial z}$$

Ordering Constraints

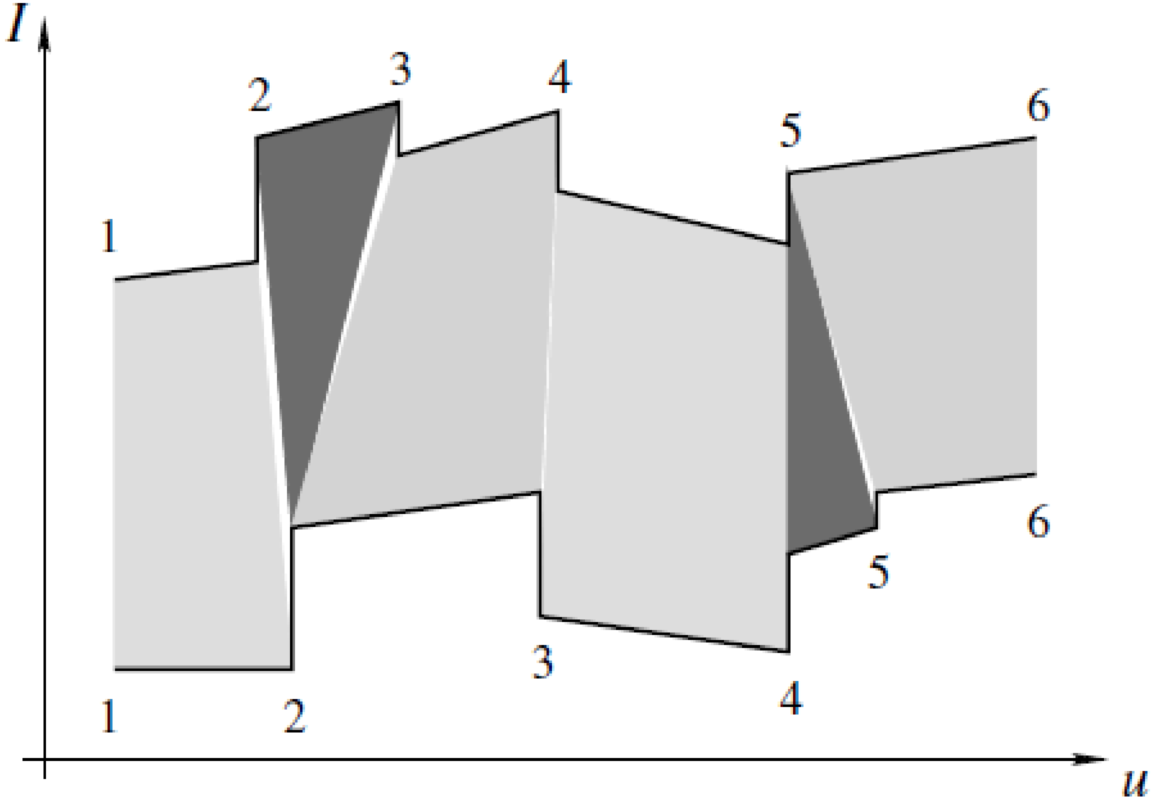


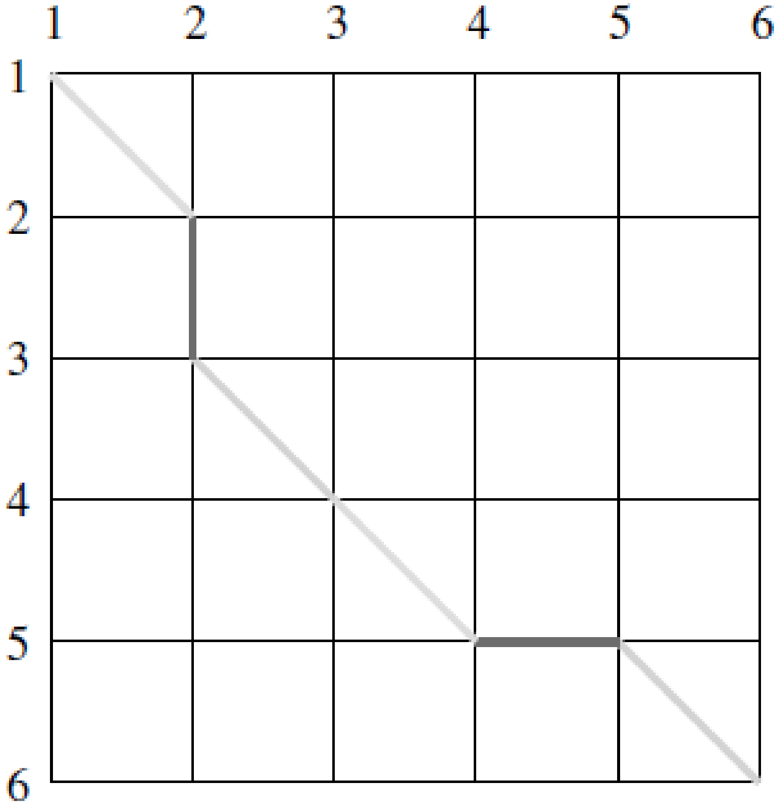


Ordering Constraints

- Order of matching image features along a pair of epipolar lines is
- The inverse of the order of the corresponding surface attributes along the curve
- the epipolar plane intersects the observed object’s boundary
- corresponding to missing correspondences associated with occlusion and/or noise.

Dynamic programming and stereopsis





A Dynamic-Programming Algorithm for Establishing Stereo Correspondences Between Two Corresponding Scanlines.

We assume the scanlines have m and n edge points, respectively (the endpoints of the scanlines are included for convenience). Two auxiliary functions are used: Inferior-Neighbors(k,l) returns the list of neighbors (i,j) of the node (k,l) such that $i \leq k$ and $j \leq l$, and Arc-Cost(i,j,k,l) evaluates and returns the cost of matching the intervals (i,k) and (j,l). For correctness, $C(1,1)$ should be initialized with a value of zero.

```
% Loop over all nodes (k, l) in ascending order.
for k = 1 to m do
  for l = 1 to n do
    % Initialize optimal cost C(k, l) and backward pointer B(k, l).
    C(k, l) ← +∞; B(k, l) ← nil;
    % Loop over all inferior neighbors (i, j) of (k, l).
    for (i, j) ∈ Inferior-Neighbors(k, l) do
      % Compute new path cost and update backward pointer if necessary.
      d ← C(i, j) + Arc-Cost(i, j, k, l);
      if d < C(k, l) then C(k, l) ← d; B(k, l) ← (i, j) endif;
      endfor;
    endfor;
  endfor;
% Construct optimal path by following backward pointers from (m, n).
P ← {(m, n)}; (i, j) ← (m, n);
while B(i, j) ≠ nil do (i, j) ← B(i, j); P ← {(i, j)} ∪ P endwhile.
```

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Energy function E : $D^n \rightarrow R$

Let us assume as usual that the two input images have been rectified, and define a graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ whose n nodes are the pixels of the first image and whose edges link pairs of adjacent pixels on the image grid (not necessarily on the same scanline). Given some allowed disparity range $\mathcal{D} = \{-K, \ldots, K\} \subset \mathbb{Z}$, we can define an energy function $E : \mathcal{D}^n \rightarrow \mathbb{R}$ by

$$E(\boldsymbol{d}) = \sum_{p \in \mathcal{V}} U_p(d_p) + \sum_{(p,q) \in \mathcal{E}} B_{pq}(d_p, d_q), \quad (7.4)$$

where $\boldsymbol{d}$ is a vector of n integer disparities d_p associated with pixels p, $U_p(d_p)$ (*unary term*) measures the discrepancy between pixel p in the left image and pixel $p + d_p$ in the second one, and $B_{pq}(d_p, d_q)$ (*binary term*) measures the discrepancy between the pair of assignments $p \rightarrow p + d_p$ and $q \rightarrow q + d_q$.[3] The first of these terms records the similarity between p and $p + dp$. It may be, for example, the sum of squared differences $U_p(d_p) = \sum_{q \in \mathcal{N}(p)} [I(q) - I'(q + dp)]^2$, where $\mathcal{N}(p)$ is some neighborhood of p. The second one is used to *regularize* the optimization process, making sure that the disparity function is smooth enough. For example, a sensible choice may be $B_{pq}(d_p, d_q) = \gamma_{pq}|d_p - d_q|$ for some $\gamma_{pq} > 0$.

Stereopsis

Contents

1) Binocular camera geometry and the epipolar constraints
2) Binocular reconstruction
3) Human stereopsis
4) Local methods for binocular fusion
5) Global methods for binocular fusion
6) Using more cameras
7) Application: robot navigation
8) Conclusion
9) Q&A

$$\nabla \cdot \mathbf{E} = \rho / \varepsilon_0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

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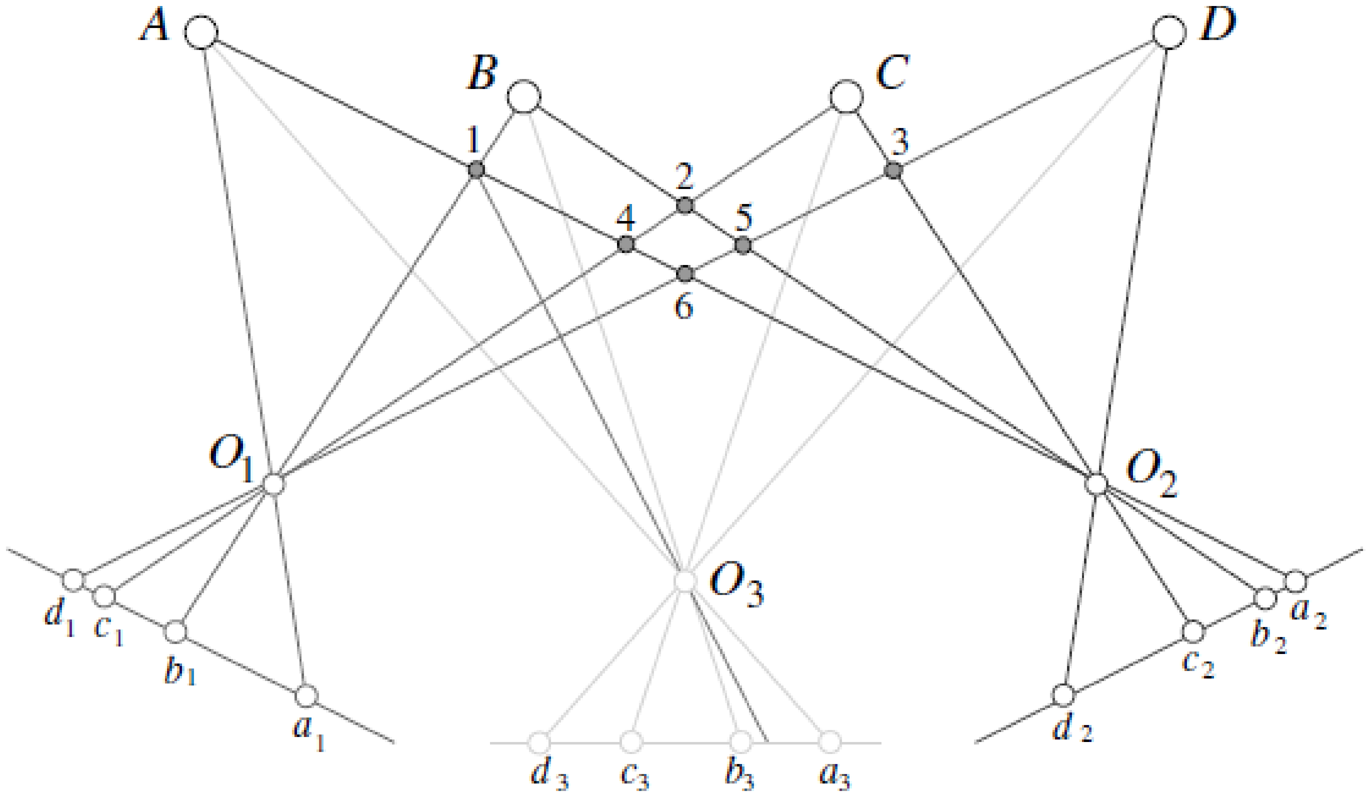
Using more cameras



Adding a third camera eliminates ambiguity inherent in two view point matching

- third image can be used to check hypothetical matches
- three-dimensional point associated with such a match is first reconstructed
- then reprojected into the third image
- If no compatible point lies nearby, then the match must be wrong.

A series of 10 images and the corresponding reconstruction.

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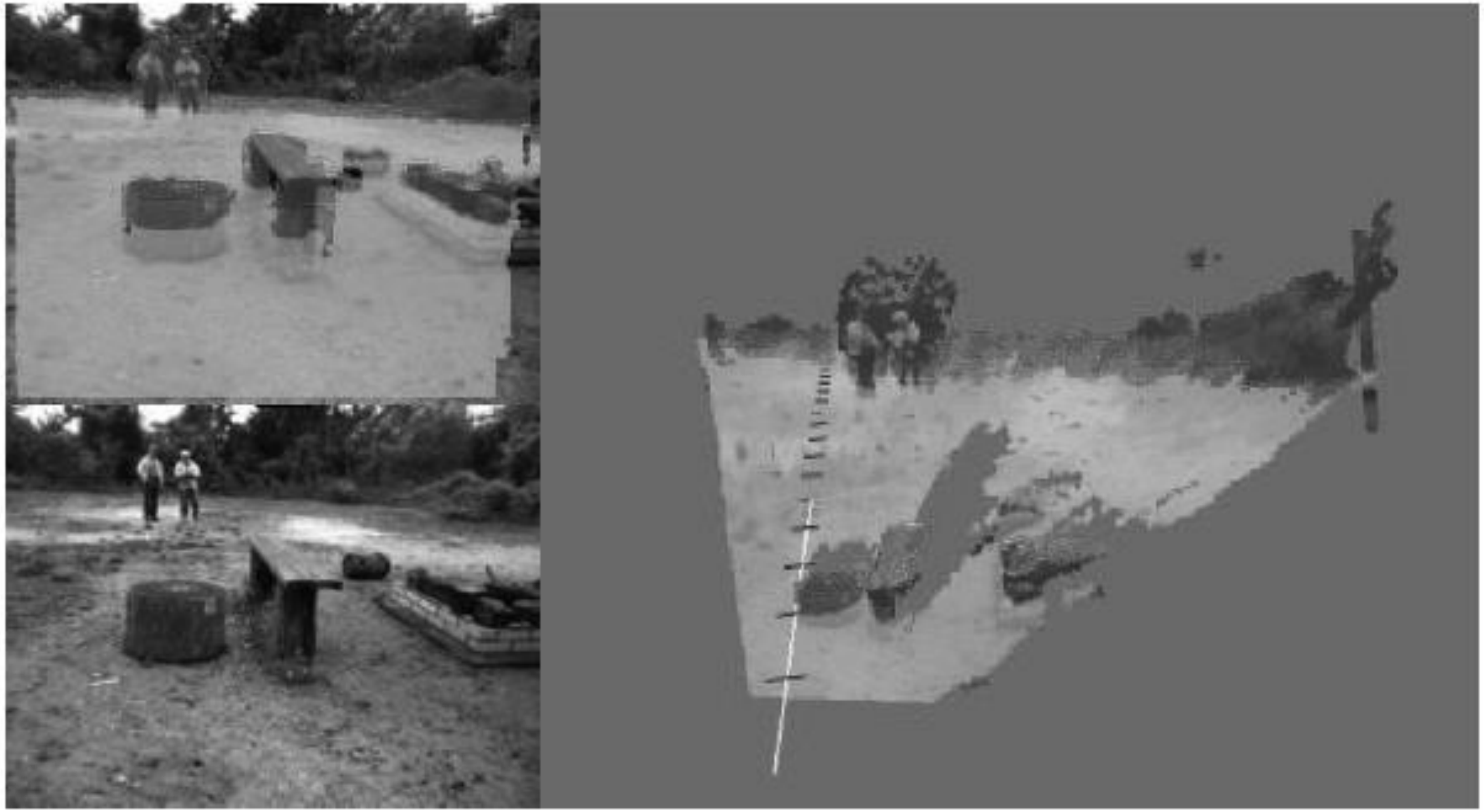
Robot navigation using the approach proposed in Hadsell et al. (2009)



Robot navigation

- separate binocular stereo process for each pair
- fusion algorithm is local, and uses sum of absolute differences as matching criterion
- With additional heuristics to filter out outliers
- The ground plane is found by a voting procedure before obstacles are detected

Conclusion

Plethora of applicatcions of computer vision

- code
- test
- learn

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Q&A

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