

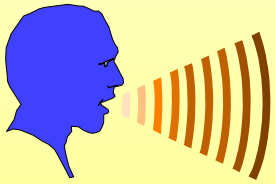


Video Processing & Communications

Two-Dimensional Motion Estimation (Part III: Advanced Techniques)

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Outline

- Deformable block matching algorithm (DBMA)
  - Node-based motion model
- Mesh-based motion estimation
  - Mesh-based motion representation
  - Mesh-based motion estimation
- Global motion estimation
  - Direct method
  - Indirect method
- Region-based motion estimation
- Summary

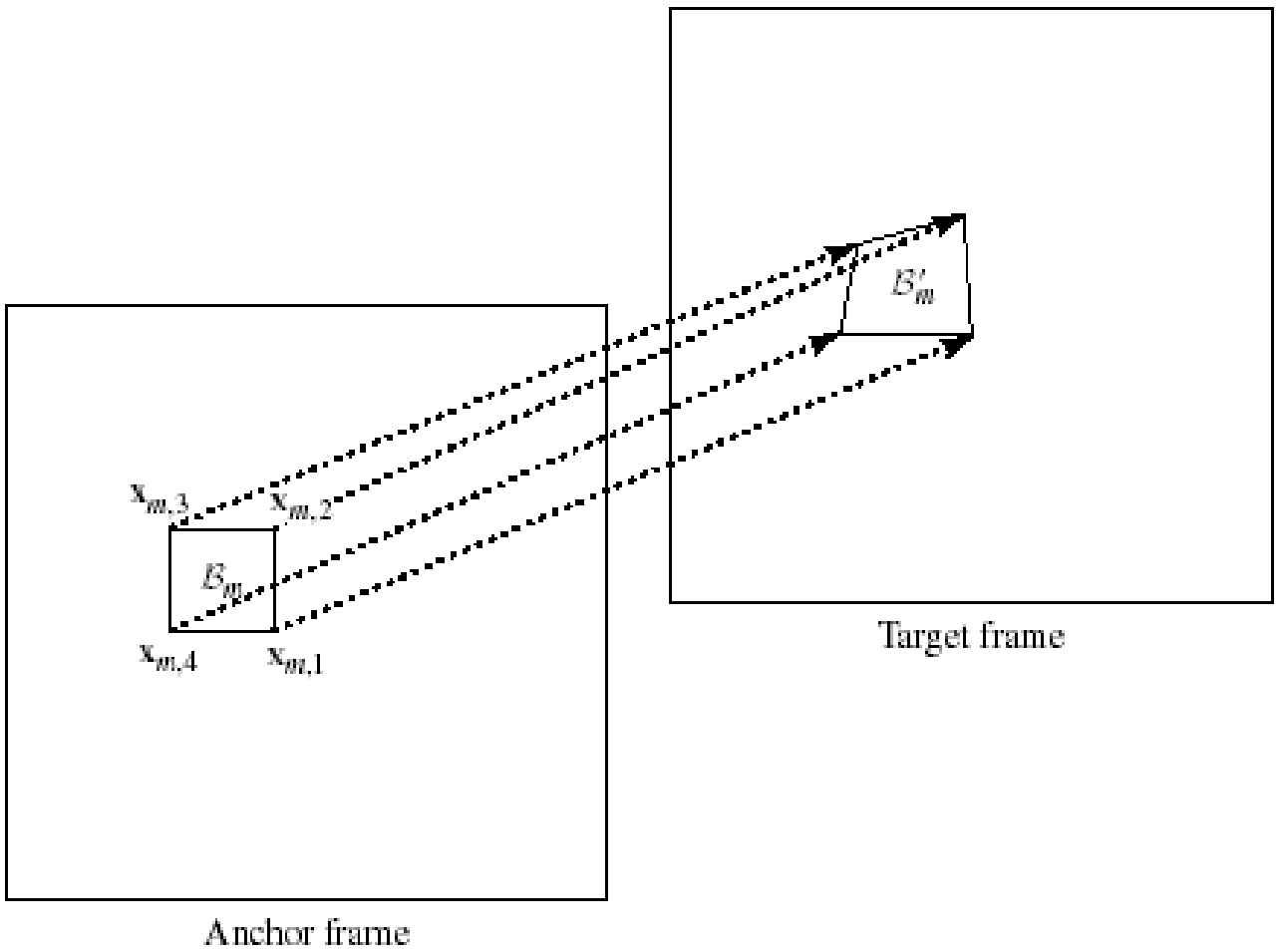
Problems with EBMA

- Blocking effect (discontinuity across block boundary) in the predicted image
  - Because the block-wise translation model is not accurate
  - Real motion in a block may be more complicated than translation
    - Fix: Deformable BMA
  - There may be multiple objects with different motions in a block
    - Fix:
      - region-based motion estimation
      - mesh-based using adaptive mesh
  - Intensity changes may be due to illumination effect
    - Should compensate for illumination effect before applying "constant intensity assumption"

Problems with EBMA (Cntd)

- Motion field somewhat chaotic
  - because MVs are estimated independently from block to block
  - Fix:
    - Imposing smoothness constraint explicitly
    - Multi-resolution approach
    - Mesh-based motion estimation
- Wrong MV in the flat region
  - because motion is indeterminate when spatial gradient is near zero
  - Ideally, should use non-regular partition
  - Fix: region based motion estimation

Deformable Block Matching Algorithm



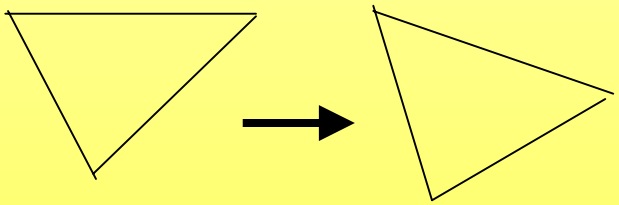
Overview of DBMA

- Three steps:
  - Partition the anchor frame into regular blocks
  - Model the motion in each block by a more complex motion
    - The 2-D motion caused by a flat surface patch undergoing rigid 3-D motion can be approximated well by projective mapping
    - Projective Mapping can be approximated by affine mapping and bilinear mapping
    - Various possible mappings can be described by a node-based motion model
  - Estimate the motion parameters block by block independently
    - Discontinuity problem cross block boundaries still remain
- Still cannot solve the problem of multiple motions within a block or changes due to illumination effect!

Affine and Bilinear Model

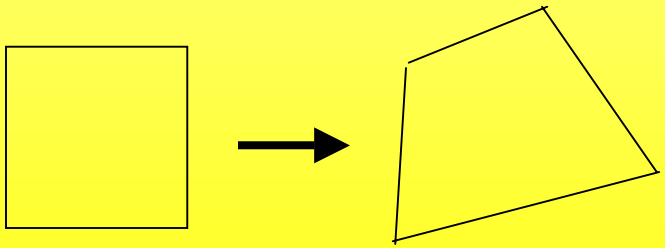
- Affine (6 parameters):
  - Good for mapping triangles to triangles

$$\begin{bmatrix} d_x(x,y) \\ d_y(x,y) \end{bmatrix} = \begin{bmatrix} a_0 + a_1 x + a_2 y \\ b_0 + b_1 x + b_2 y \end{bmatrix}$$



- Bilinear (8 parameters):
  - Good for mapping blocks to quadrangles

$$\begin{bmatrix} d_x(x,y) \\ d_y(x,y) \end{bmatrix} = \begin{bmatrix} a_0 + a_1 x + a_2 y + a_3 xy \\ b_0 + b_1 x + b_2 y + b_3 xy \end{bmatrix}$$



Difficulties in Estimating Affine and Bilinear Motion Parameters

- The coefficients need floating point precision
- The coefficients have different influence on the estimated motion
  - 0-th order coefficients (a0,b0) represent the translation component
  - Other coefficients' influence depend on the pixel coordinates

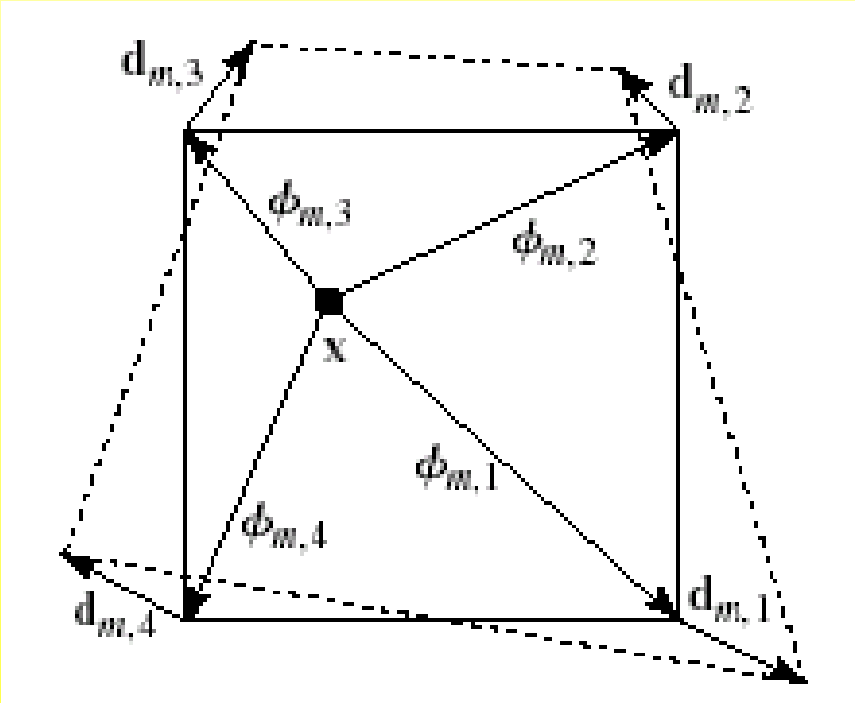
Node-Based Motion Model

Control nodes in this example: Block corners

Motion in other points are interpolated from the nodal MVs $\mathbf{d}_{m,k}$

Control node MVs can be described with integer or half-pel accuracy, all have same importance

Translation, affine, and bilinear are special case of this model



$$\mathbf{d}_m(\mathbf{x}) = \sum_{k=1}^{K} \phi_{m,k}(\mathbf{x})\mathbf{d}_{m,k}, \quad \mathbf{x} \in \mathcal{B}_m.$$

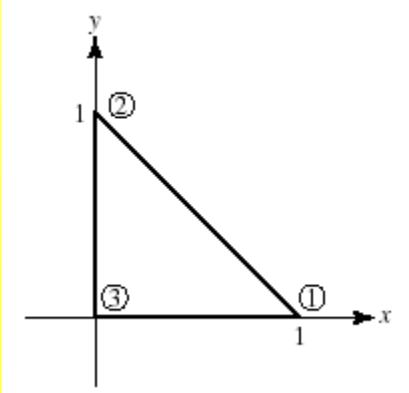
Interpolation Kernels

- Requirement:

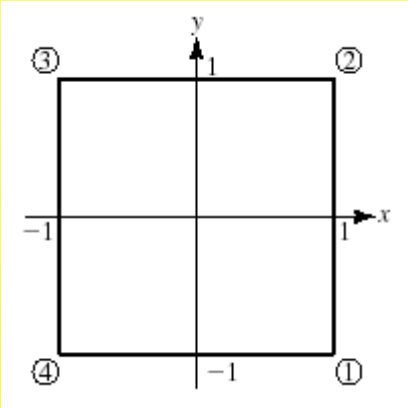
$$0 \le \phi_{m,k}(\mathbf{x}) \le 1, \quad \sum_k \phi_{m,k}(\mathbf{x}) = 1, \quad \forall \mathbf{x} \in \mathcal{B}_{1,m}, \qquad \phi_{m,k}(\mathbf{x}_l) = \delta_{k,l} = \begin{cases} 1 & k = l, \\ 0 & k \ne l. \end{cases}$$

- For standard triangular element:

$$\phi_1^t(x, y) = x, \quad \phi_2^t(x, y) = y, \quad \phi_3^t(x, y) = 1 - x - y.$$



- For standard quadrilateral element:



$$\phi_1^q(x, y) = (1 + x)(1 - y)/4, \quad \phi_2^q(x, y) = (1 + x)(1 + y)/4,$$
$$\phi_3^q(x, y) = (1 - x)(1 + y)/4, \quad \phi_4^q(x, y) = (1 - x)(1 - y)/4.$$

Estimation of Nodal Motions

- Objective function:

$$E(\mathbf{a}) = \sum_{\mathbf{x}\in\mathcal{B}} |\psi_2(\mathbf{w}(\mathbf{x};\mathbf{a})) - \psi_1(\mathbf{x})|^p,$$

$$\mathbf{a} = [\mathbf{d}_k, k \in \mathcal{K}]$$

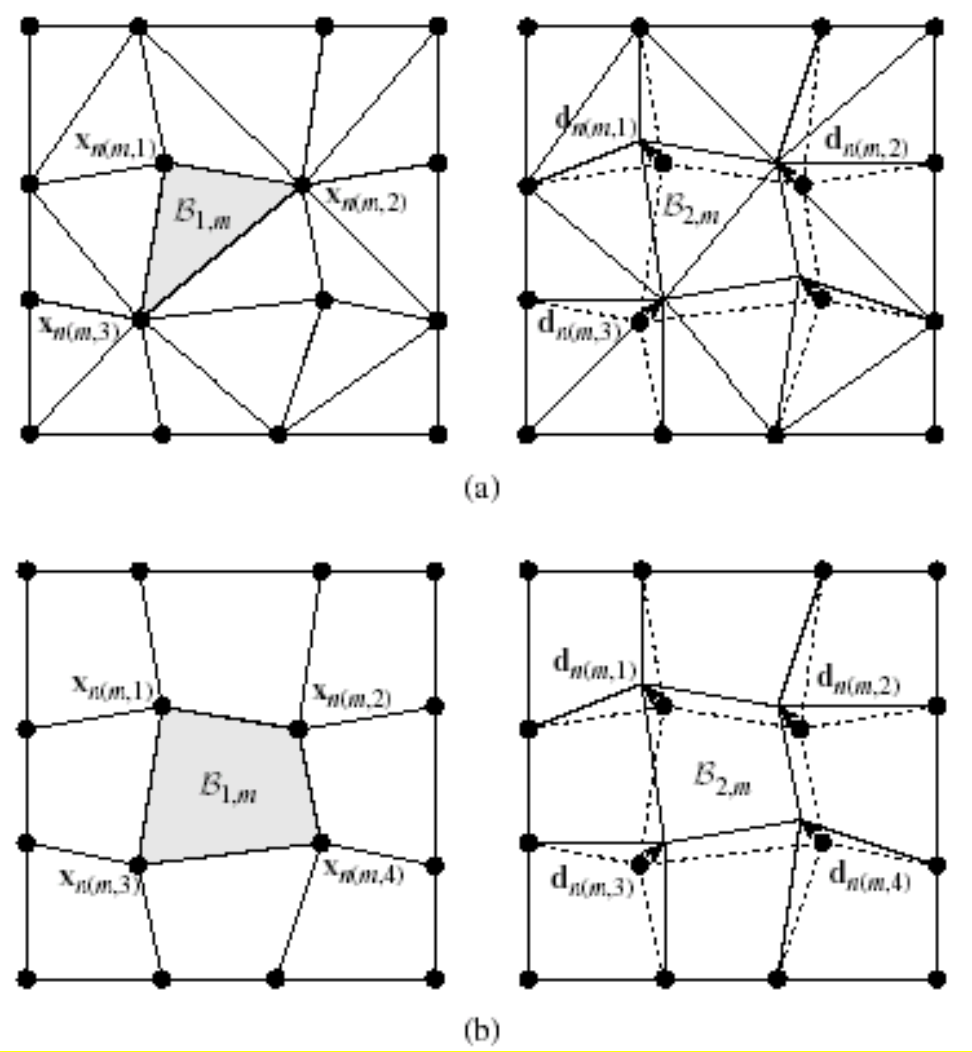
$$\mathbf{w}(\mathbf{x};\mathbf{a}) = \mathbf{x} + \sum_{k\in\mathcal{K}} \phi_k(\mathbf{x})\mathbf{d}_k.$$

- Search method:
  - Exhaustive search:
    - search K nodal MVs simultaneously in integer or half-pel accuracy, may not be feasible in practice
  - Gradient descent approach:
    - See textbook for the Newton-Raphson update algorithm
    - Solution depends on the initial solution. A good initial solution is the translation MV found using EBMA

Problems with DBMA

- Motion discontinuity across block boundaries, because nodal MVs are estimated independently from block to block
  - Fix: mesh-based motion estimation
  - First apply EBMA to all blocks
- Cannot do well on blocks with multiple moving objects or changes due to illumination effect
  - Three mode method
    - First apply EBMA to all blocks
    - Blocks with small EBMA errors have *translational motion*
    - Blocks with large EBMA errors may have *non-translational motion*
      - First apply DBMA to these blocks
      - Blocks still having errors are *non-motion compensable*
    - [Ref] O. Lee and Y. Wang, Motion compensated prediction using nodal based deformable block matching. J. Visual Communications and Image Representation (March 1995), 6:26-34

Mesh-Based Motion Estimation: Overview

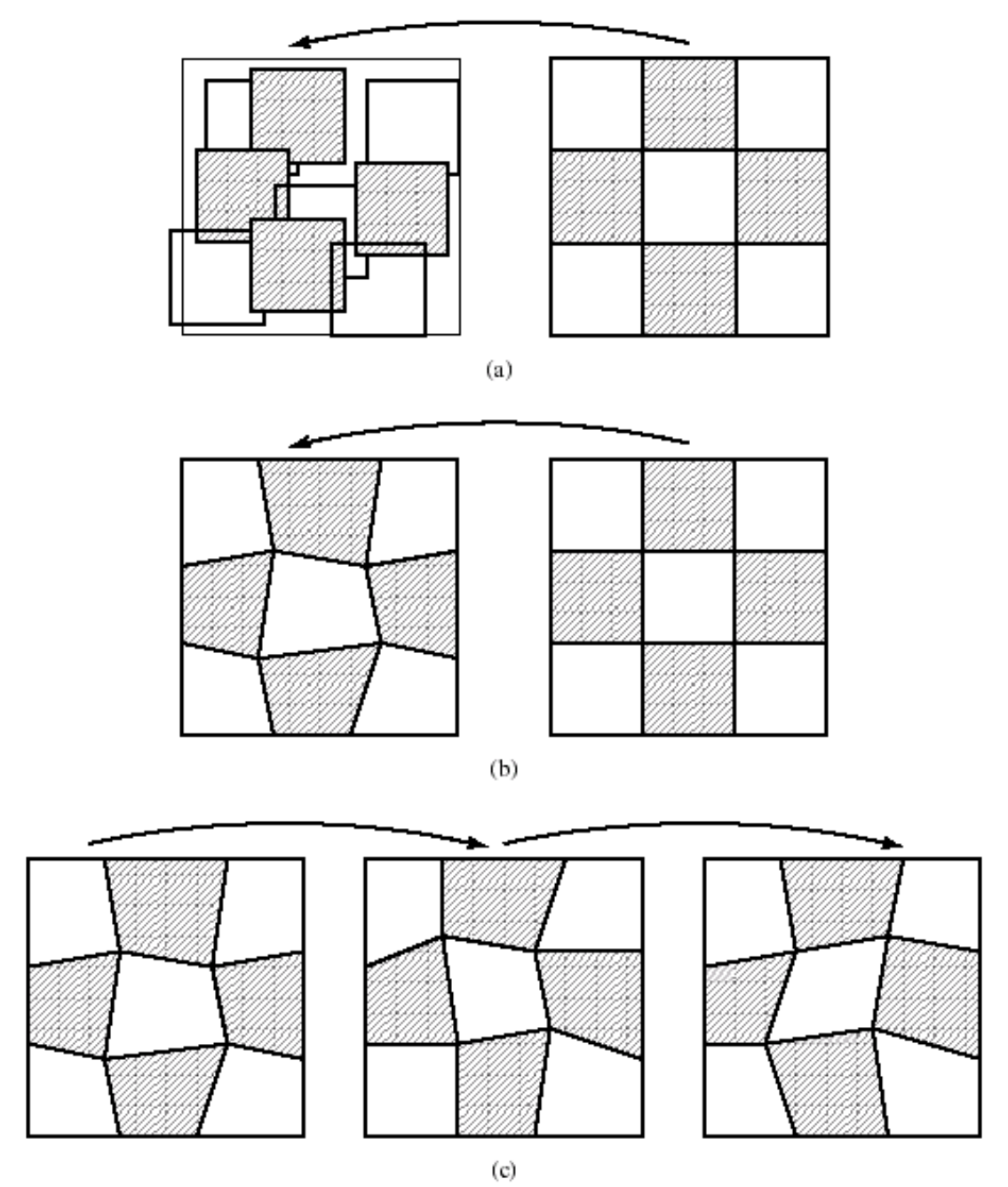


$$\mathbf{d}_m(\mathbf{x}) = \sum_{k \in \mathcal{K}} \phi_{m,k}(\mathbf{x}) \mathbf{d}_{n(m,k)}, \quad \mathbf{x} \in \mathcal{B}_{1,m},$$

(a) Using a triangular mesh

(b) Using a quadrilateral mesh

Mesh-based vs. block-based motion estimation



(a) block-based backward ME

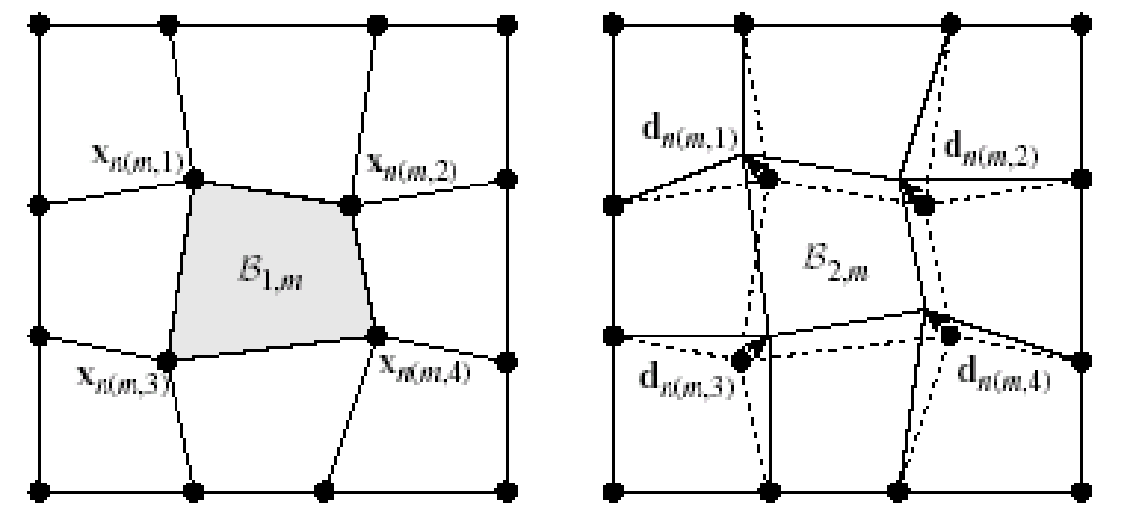
(b) mesh-based backward ME

(c) mesh-based forward ME

Mesh-Based Motion Model

- The motion in each element is interpolated from nodal MVs

$$\mathbf{d}_m(\mathbf{x}) = \sum_{k \in \mathcal{K}} \phi_{m,k}(\mathbf{x}) \mathbf{d}_{n(m,k)}, \quad \mathbf{x} \in \mathcal{B}_{1,m},$$



- Mesh-based vs. node-based model:
  - Mesh-based: Each node has a single MV, which influences the motion of all four adjacent elements
  - Node-based: Each node can have four different MVs depend on within with element it is considered

Mesh Generation and Motion Estimation

- Two problems:
  - Given a mesh in the anchor frame, determine nodal positions in the target frame – Motion estimation
  - Set up the mesh in the anchor frame, so that the mesh conforms with object boundaries – Mesh generation
    - Backward ME: can use either regular mesh or object adaptive mesh at each new frame
      - Motion estimation is easier with a regular mesh, but adaptive mesh can yield more accurate result
    - Forward ME:
      - only need to establish a mesh for the initial frame. Meshes in the following frames depend on the nodal MVs between successive frames.
      - To accommodate appearing/disappearing objects, the mesh geometry needs to be updated.
  - Only discuss motion estimation problem here

Estimation of Nodal Motion

- Unlike DBMA, all nodal MVs should be estimated simultaneously

$$E(\mathbf{d}_n, n \in \mathcal{N}) = \sum_{m \in \mathcal{M}} \sum_{\mathbf{x} \in \mathcal{B}_{1,m}} |\psi_2(\mathbf{w}_m(\mathbf{x})) - \psi_1(\mathbf{x})|^p,$$

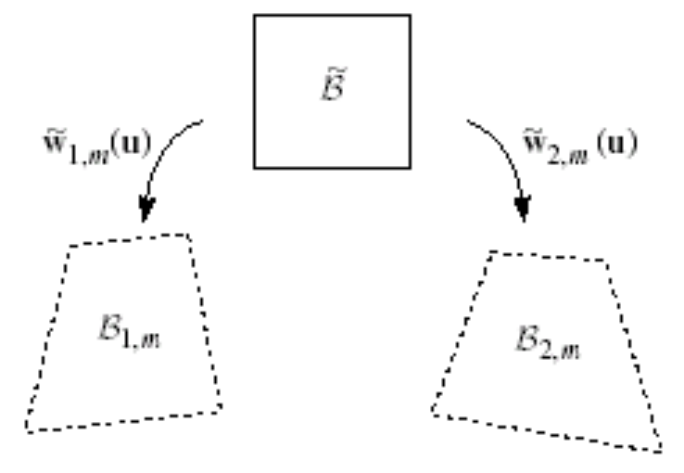
$$\mathbf{w}_m(\mathbf{x}) = \mathbf{x} + \sum_{k \in \mathcal{K}} \phi_{m,k}(\mathbf{x}) \mathbf{d}_{n(m,k)}, \quad \mathbf{x} \in \mathcal{B}_{1,m}.$$

- Unless the anchor frame uses a regular mesh, the interpolation kernels are complicated
- Using a mapping to master element:

$$E(\mathbf{d}_n, n \in \mathcal{N}) = \sum_{m \in \mathcal{M}} \sum_{\mathbf{u} \in \tilde{\mathcal{B}}} |\tilde{e}_m(\mathbf{u})|^p |J_m(\mathbf{u})|,$$

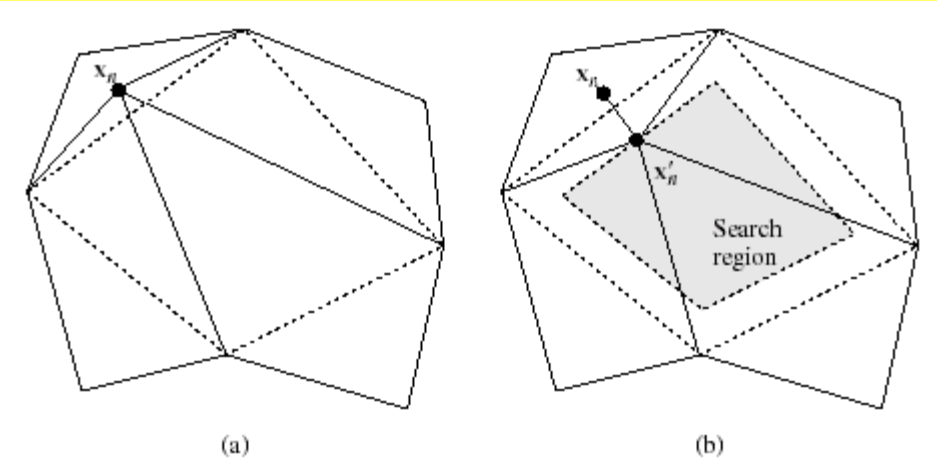
$$\tilde{e}_m(\mathbf{u}) = \psi_2(\tilde{\mathbf{w}}_{2,m}(\mathbf{u})) - \psi_1(\tilde{\mathbf{w}}_{1,m}(\mathbf{u}))$$

$$\tilde{\mathbf{w}}_{t,m}(\mathbf{u}) = \sum_{k \in \mathcal{K}} \tilde{\phi}_k(\mathbf{u}) \mathbf{x}_{t,n(m,k)}, \quad \mathbf{u} \in \tilde{\mathcal{B}}, \quad t = 1, 2.$$



Estimation of Nodal Motion (cntd)

- Simplification:
  - Update one node at a time, minimizing DFD over all adjacent elements
    - Gradient descent method [Wang and Lee 1994]
    - Exhaustive search [Wang and Ostermann 1998]
  - Update order is important
    - First update those nodes where motion can be estimated accurately (near edges)
  - Motion of this node should be constrained not to cause excessively deformed elements



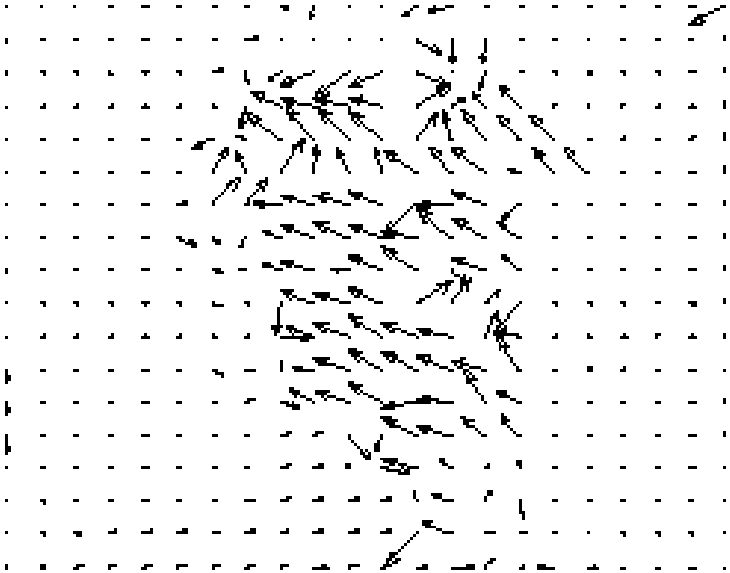
target frame

anchor frame

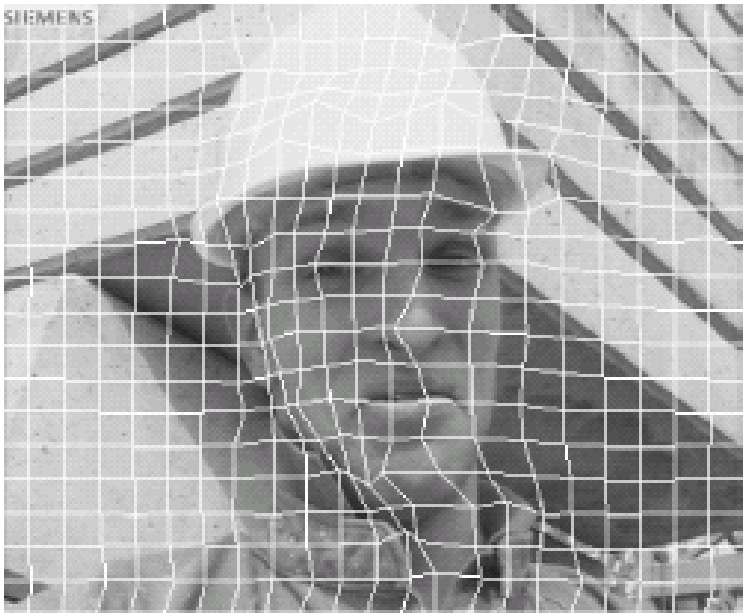
Motion field

Predicted anchor frame (29.86dB)

Example: Half-pel EBMA



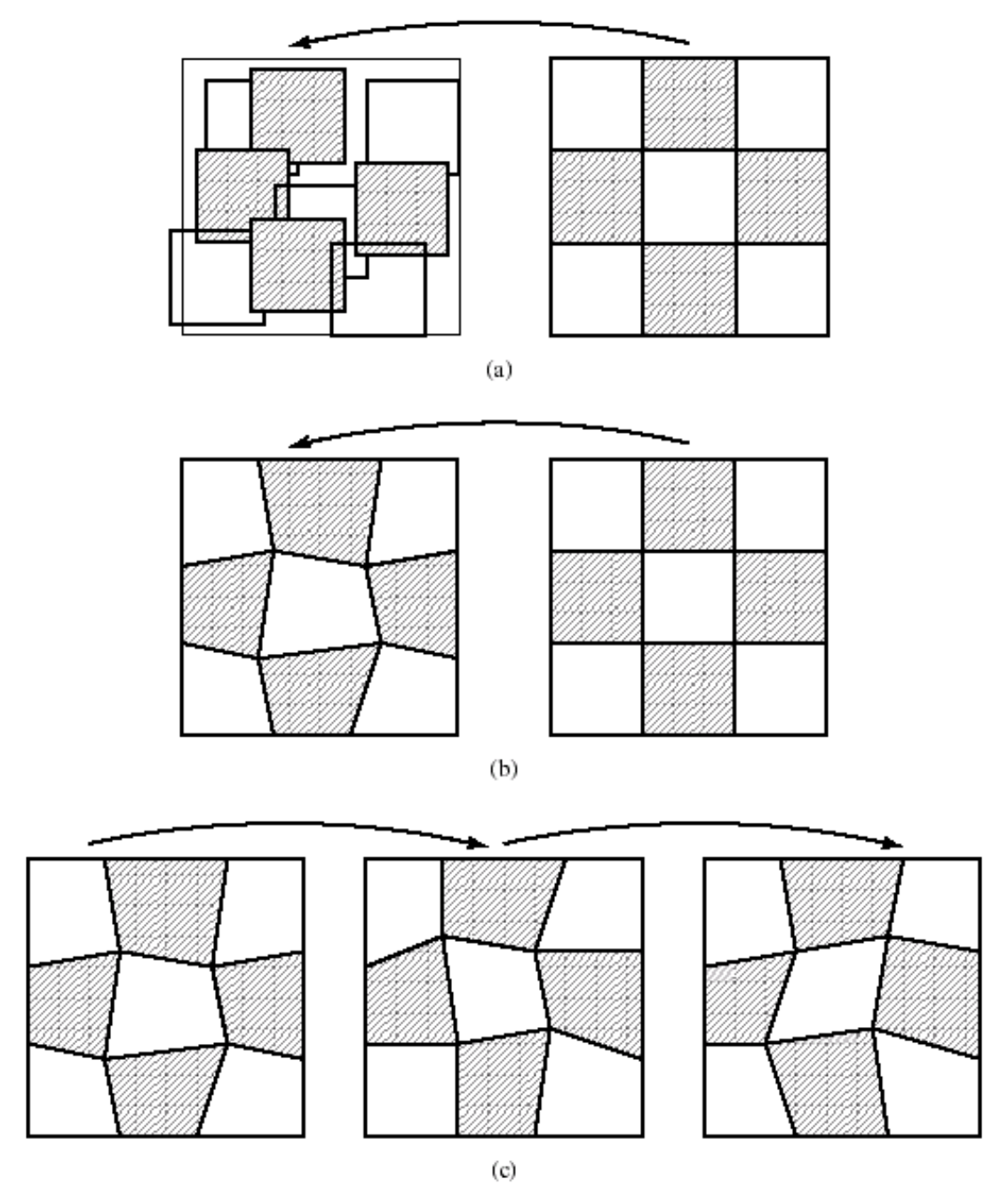
EBMA (29.86dB)



mesh-based method (29.72dB)

EBMA vs. Mesh-based Motion Estimation

Mesh-based vs. block-based motion estimation



(a) block-based backward ME

(b) mesh-based backward ME

(c) mesh-based forward ME

Global Motion Estimation

- Global motion:
  - Camera moving over a stationary scene
    - Most projected camera motions can be captured by affine mapping!
  - The scene moves in its entirety --- a rare event!
  - Typically, the scene can be decomposed into several major regions, each moving differently (region-based motion estimation)
- If there is indeed a global motion, or the region undergoing a coherent motion has been determined, we can determine the motion parameters
  - Direct estimation
  - Indirect estimation
- When a majority of pixels (but not all) undergo a coherent motion, one can iteratively determine the motion parameters and the pixels undergoing this motion
  - Robust estimator

Direct Estimation

- Parameterize the DFD error in terms of the motion parameters, and estimate these parameters by minimizing the DFD error

$$E_{\mathrm{DFD}} = \sum_{n \in \mathcal{N}} w_n |\psi_2(\mathbf{x}_n + \mathbf{d}(\mathbf{x}_n; \mathbf{a})) - \psi_1(\mathbf{x}_n)|^p$$

Weighting w_n coefficients depend on the importance of pixel $\mathbf{x}_n$.

Ex: Affine motion:

$$\begin{bmatrix} d_x(\mathbf{x}_n;\mathbf{a}) \\ d_y(\mathbf{x}_n;\mathbf{a}) \end{bmatrix} = \begin{bmatrix} a_0 + a_1 x_n + a_2 y_n \\ b_0 + b_1 x_n + b_2 y_n \end{bmatrix}, \quad \mathbf{a} = [a_0, a_1, a_2, b_0, b_1, b_2]^T$$

Exhaustive search or gradient descent method can be used to find **a** that minimizes E_{DFD}

Indirect Estimation

- First find the dense motion field using pixel-based or block-based approach (e.g. EBMA)
- Then parameterize the resulting motion field using the motion model through least squares fitting

$$E_{fit} = \sum w_n (\mathbf{d}(\mathbf{x}_n;\mathbf{a}) - \mathbf{d}_n)^2$$

Affine motion:

$$\mathbf{d}(\mathbf{x}_n;\mathbf{a}) = [\mathbf{A}_n]\mathbf{a},$$

$$[\mathbf{A}_n] = \begin{bmatrix} 1 & x_n & y_n & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & x_n & y_n \end{bmatrix}$$

$$\frac{\partial E_{fit}}{\partial \mathbf{a}} = \sum w_n [\mathbf{A}_n]^T ([\mathbf{A}_n]\mathbf{a} - \mathbf{d}_n) = 0$$

$$\mathbf{a} = \left(\sum w_n [\mathbf{A}_n]^T [\mathbf{A}_n]\right)^{-1} \left(\sum w_n [\mathbf{A}_n]^T \mathbf{d}_n\right)$$

Weighting w_n coefficients depend on the accuracy of estimated motion at $\mathbf{x}_n$.

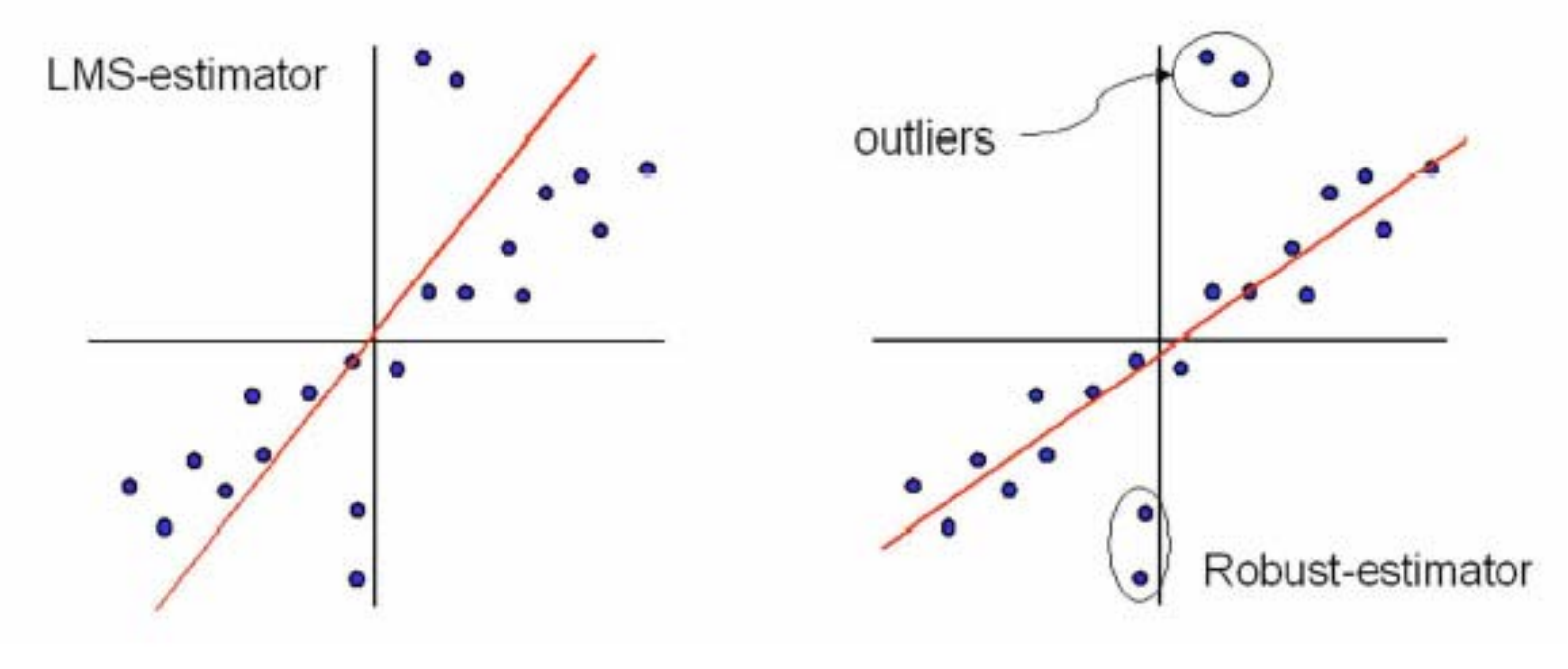
Robust Estimator

Essence: iteratively removing “outlier” pixels.

1. Set the region to include all pixels in a frame
2. Apply the direct or indirect method method over all pixels in the region
3. Evaluate errors (E_{DFD} or E_{fit}) at all pixels in the region
4. Eliminate “outlier” pixels with large errors
5. Repeat steps 2-4 for the remaining pixels in the region

Details: Hard threshold vs. soft threshold. See textbook.

Illustration of Robust Estimator



Fitting a line to the data points by using LMS and robust estimators. Courtesy of Fatih Porikli

Region-Based Motion Estimation

- Assumption: the scene consists of multiple objects, with the region corresponding to each object (or sub-object) having a coherent motion
  - Physically more correct than block-based, mesh-based, global motion model
- Method:
  - Region First: Segment the frame into multiple regions based on texture/edges, then estimate motion in each region using the global motion estimation method
  - Motion First: Estimate a dense motion field, then segment the motion field so that motion in each region can be accurately modeled by a single set of parameters
  - Joint region-segmentation and motion estimation: iterate the two processes

Summary

- Fundamentals:
  - Optical flow equation
    - Derived from constant intensity and small motion assumption
    - Ambiguity in motion estimation
  - How to represent motion:
    - Pixel-based, block-based, region-based, global, etc.
  - Estimation criterion:
    - DFD (constant intensity)
    - OF (constant intensity+small motion)
    - Bayesian (MAP, DFD+motion smoothness)
  - Search method:
    - Exhaustive search, gradient-descent, multi-resolution (next lecture)

Summary (Cntd)

- Basic techniques:
  - Pixel-based motion estimation
  - Block-based motion estimation
    - EBMA, integer-pel vs. half-pel accuracy, Fast algorithms
  - Multiresolution approach
    - Avoid local minima, smooth motion field, reduced computation
- More advanced techniques
  - Deformable block matching algorithm (DBMA)
    - To allow more complex motion within each block
  - Mesh-based motion estimation
    - To enforce continuity of motion across block boundaries
  - Global motion estimation
    - Good for estimating camera motion
  - Region-based motion estimation
    - More physically correct: allow different motion in each sub-object region
- Application in Video Coding

Homework

- Reading assignment
  - Read Secs. 6.5-6.8,6.10
  - Go through and verify the gradient descent algorithm presented for DBMM (Eqs. 6.5.2-6.5.6).
  - Go through the derivation of the objective function definition (Eq. 6.6.6-6.6.8) for mesh-based motion estimation carefully, and verify the gradient function given in Eq. 6.6.9.