Particle Video:
Long-Range Video Motion Estimation
using Point Trajectories

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Long-Range Motion Estimation
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Applications

Photoshop, etc.

Particle-based editor
Applications

- Super-resolution
- Noise removal
- High dynamic range video
- Image filtering
- Video segmentation
- Matting / rotoscoping
- Object removal

[Capel and Zisserman 2001]

[Bennett and McMillan 2005]

[Jue Wang et al. 2004]

[Criminisi et al. 2003]
Long-range motion estimation is a step toward a larger goal: video decomposition.
Design Goals
Design Goals
Design Goals
Related Work

Feature Tracking

Optical Flow

Particle Video
Related Work: Optical Flow

Temporal smoothness assumption


[Elad and Feuer 1998]
Related Work: Optical Flow

Rank-based optical flow

[Irani 1999, Brand 2001]
Related Work: Optical Flow

Occlusion labeling:

- Pixel dissimilarity
  [Silva and Santos-Victor 2001, Xiao et al. 2006]
- Forward / backward mismatch
  [Alvarez et al. 2002]

Fig. 2. One of the synthetic scenes used in the experiments. Left two images: input; middle right: ground truth optical flow; right: ground truth occlusions

[Stretcha et al. 2004]
Particle Approach

• Particles are small
• Adaptive density
• Does not assume temporal motion smoothness
Particle Approach

- Triangulation implicitly represents particle grouping
- Non-parametric
- Not layer-based
- No segmentation
- Not planar or rigid components
Optical Flow as Input
An Optical Flow Algorithm

At each resolution level:
- Variational flow update
  - Similar to [Brox et al. 2004]
- Label occluded regions
- Bilateral flow filter
  - Similar to [Xiao et al. 2006]

(see paper for more details)
Optical Flow Results
Particle Video Algorithm

Optical Flow

Particle Video
Particle Video Steps

- Propagate
- Link
- Optimize
- Prune
- Add
Particle Propagation

Forward propagation:

\[
\begin{align*}
    x_i(t) &= x_i(t - 1) + u(x_i(t - 1), y_i(t - 1), t - 1), \\
    y_i(t) &= y_i(t - 1) + v(x_i(t - 1), y_i(t - 1), t - 1).
\end{align*}
\]

Particles in occluded regions are not propagated.
Particle Linking

- Delaunay Triangulation [Lischinski 1994]
- Create link if Delaunay edge exists in current frame or adjacent frame
Particle Linking

Link Weighting based on Flow Gradient

(lighter = stronger)
Particle Linking
Particle Optimization

Optimization objective function:

\[ E(i,t) = \sum_{k \in K_i(t)} E^{[k]}_{Data}(i,t) + \alpha_d \sum_{j \in L_i(t)} E_{Distort}(i,j,t) \]
Data term:

\[ E_{Data}^{[k]}(i,t) = \Psi( [I^{[k]}(x_i(t), y_i(t), t) - \hat{c}_i^{[k]}(t)]^2 ) \]
Particle Optimization: Data

Data term:

\[ E_{Data}^{[k]}(i, t) = \Psi([I^{[k]}(x_i(t), y_i(t), t) - \hat{c}_i^{[k]}(t)]^2) \]

\[ \uparrow \]

Observed Channel Value  Filtered Channel Value

![Graph showing channel value over frame index](image)
Particle Optimization: Distortion

Distortion term:

\[ E_{Distort}(i, j, t) = l_{ij}(t) \Psi \left( [u_i(t) - u_j(t)]^2 + [v_i(t) - v_j(t)]^2 \right) \]
Particle Optimization

Loop until convergence:

- Solve system for $dx_i(t)$, $dy_i(t)$ using SOR:

\[
\begin{align*}
\frac{\delta E}{\delta dx_i(t)} &= 0, \\
\frac{\delta E}{\delta dy_i(t)} &= 0 \mid i \in P, t \in F
\end{align*}
\]

- $x_i(t) \leftarrow x_i(t) + dx_i(t)$
- $y_i(t) \leftarrow y_i(t) + dy_i(t)$
- Update link weights, etc.

(see paper for more details)
Particle Pruning

![Graph showing Particle Energy over Time with a Threshold]
Particle Pruning

Above Threshold: Deactivate

Particle Energy

Time

Threshold

Propagate  Link  Optimize  Prune  Add
Particle Addition

Particle Placement
Particle Addition

Scale Map
Particle Video Algorithm

Propagate  Link  Optimize  Prune  Add
Evaluation Videos
Results / Evaluation

Construct videos that return to the start frame:

1, 2, 3, ...

..., N-1, N, N-1, ...

...3, 2, 1
Results / Evaluation

Particle distance: red
Concatenated flow distance: green
Fraction surviving: yellow
Results / Evaluation
Results / Evaluation
Results / Evaluation
Results / Evaluation
Results / Evaluation
Results / Evaluation
Results / Evaluation
Results / Evaluation
Failure Modes
Failure Modes
Limitations / Future Work

**Issue:** occlusion handling

**Possible solution:** analyze local motion histories to distinguish good/bad distortion

**Issue:** flow dependence

**Possible solution:** hybrid flow / particle optimization
Limitations / Future Work

**Issue:** appearance changes due to reflectance and scaling

**Possible solution:** invariant feature descriptors for particles away from occlusions

Other areas of exploration:
- Faster algorithms (currently 40 seconds/frame)
- Geometric constraints
- Batch particle positioning
- Evaluation on synthetic sequences
Summary

• Particles can represent complex motion and geometry
• Particle representation is useful for application algorithms
• Different from other representations (vector fields, rigid components, layers, tracked feature patches)
More Info

http://rvsn.csail.mit.edu/pv


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