Freehand HDR Imaging of Moving Scenes with Simultaneous Resolution Enhancement

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Motivation (1)

High Dynamic Range (HDR) Imaging
(e.g. Debevec and Malik, SIGGRAPH 1997)

\begin{itemize}
\item \textbf{Given:} exposure series (set of images with varying exposure times)
\item \textbf{Wanted:} scene radiances (HDR image)
\hfill \textbullet \ \text{overcome low dynamic range of sensor} \Rightarrow \text{details in dark and bright regions}
\end{itemize}

three images of an exposure series \hfill (courtesy of Paul Debevec) \hfill tone mapped HDR result
HDR Imaging in Practice

♦ Problem: HDR methods require **aligned** (registered) exposure series
  • often violated in practice: camera shake, moving objects

⇒ Need for alignment strategies
Overview

Structure

现有的对齐策略

PART I: Optic Flow-based Alignment

PART II: Joint Super-resolution and HDR Reconstruction

结论和展望

现有的对齐策略

对齐需要找到图像之间的位移

常见的匹配标准由于曝光差异而失效

已经提出了不同的策略:

- 全局变换，来自均值阈值位图 (Ward, JGT 2003)
- 从特征匹配的 homography (Tomaszewska and Mantiuk, WSCG 2007 / Hugin)
  ⇒ 不能处理移动对象，任意摄像头运动
- 全局对齐，用局部 optic flow 精化 (Kang et al., SIGGRAPH 2003)
  ⇒ 严重依赖于全局初始化，没有在平坦区域的精化
- block matching 使用曝光不变的分数 (Menzel and Guthe, VMV 2007)
  ⇒ 因缺乏平滑性假设而受到副作用
Optic Flow-based Alignment

Idea: Adapt energy-based optic flow method for estimating displacements

Many advantages:

- dense displacement fields (important for moving objects)
- highly accurate
- robust under outliers (noise, saturation, occlusions)
- explicit smoothness assumption (fill in information)
- efficient sequential and parallel implementations
Energy-based Optic Flow

- **Given**: exposure series $g_k(i, j)$, with $k = 1, \ldots, m$ for $m$ exposures
- **Wanted**: displacement fields $(u_k, v_k)$ between $g_k$ and reference image $g_r$

**Strategy**: Find displacements $(u_k, v_k)$ by minimising the energy

$$E(u_k, v_k) = \sum_{\text{pixels}} \left[ D(u_k, v_k) + \alpha S(\nabla u_k, \nabla v_k) \right]$$

- data term $D(u_k, v_k)$ models constancy assumption on image features
- smoothness term $S(\nabla u_k, \nabla v_k)$ penalises fluctuations in displacements

Modelling the Data Term

- **Idea**: Handle varying exposure times by matching image edges
  - gradient $\nabla g = (D_x g, D_y g)^\top$ should remain constant under displacements
  - does not require to operate on radiances $\Rightarrow$ no camera calibration needed

**Corresponding data term**:

$$D(u_k, v_k) = \Psi \left( \left| \nabla g_k(i + u_k, j + v_k) - \nabla g_r(i, j) \right|^2 \right)$$

- sub-quadratic penaliser $\Psi(s^2) = \sqrt{s^2 + \varepsilon^2}$ reduces influence of outliers

**Extension**: normalisation to prevent weighting by image gradients
Modelling the Smoothness Term

- Smoothness term fills in displacements in flat regions, e.g., saturations
- Data term gives no information as image gradients vanish
- Also regularises the displacements by penalising large gradients:

\[ S(\nabla u_k, \nabla v_k) = \Psi(|\nabla u_k|^2 + |\nabla v_k|^2) \]

- sub-quadratic penaliser \( \Psi(s^2) = \sqrt{s^2 + \varepsilon^2} \) gives sharp displacement edges

\[ g_3 \text{ (reference)} \] \[ g_4 \] \[ \text{dense flow from } g_3 \text{ to } g_4 \]

Comparison to Literature

- Real world, freehand exposure series (severe camera shake, moving clouds)

\[ g_1 \] \[ g_3 \text{ (reference)} \] \[ g_5 \]
**Comparison to Literature**

- Tone mapped HDR reconstructions after alignment with different strategies

![Optic Flow-based Alignment (6)](image1)

![Optic Flow-based Alignment (7)](image2)

**More Results** *(using fixed parameters)*

- Real world, freehand exposure series *(Window)*

![Optic Flow-based Alignment (7)](image3)
More Results *(using fixed parameters)*

- Real world, freehand exposure series (*MPI*)

![Real world, freehand exposure series](image)

Optic Flow-based Alignment (9)

Limitations

- Minimisation of energy proceeds in a coarse-to-fine warping scheme
- Naturally yields problems with estimating large displacements of small objects
Joint Super-resolution and HDR Reconstruction

- Optic flow-based alignment: dense displacements with subpixel precision
- Opens the door for super-resolution (SR) techniques
- Idea: Combine SR and HDR methods in a joint SR-HDR method
- Turns the problem of displacements in the exposure series into an advantage
Energy-based Joint SR-HDR Reconstruction

- **Given:** low-resolution exposure series $g_k$ and zoom factor $z > 1$
- **Wanted:** Super-resolved radiances $F$
- **Strategy:** Find $F$ by minimising the energy

$$E(F) = \sum_{\text{pixels}} \left[ D(F) + \lambda S(\nabla F) \right]$$

- data term $D(F)$ combines SR and HDR observation models
- smoothness term $S(\nabla F)$ fills in information (saturation, no LR information)

Towards a Joint SR-HDR Data Term

- **Super-resolution observation model:**

  $$RBW_k G = g_k$$

  - $W_k$: warping by displacements
  - $B$: blurring due to optical blur, motion blur, sensor PSF
  - $R$: restriction (downsampling) to LR grid

- **HDR observation model:**

  $$f = \frac{I(g_k)}{t_k}$$

  - $I$: inverse camera response function
  - $t_k$: exposure time
Joint SR-HDR Data Term

- Joint SR-HDR data term

\[ D(F) = \sum_{\text{exposures } k} c(g_k) \Psi \left( \frac{\text{RBW}_k F - \frac{I(g_k)}{t_k}}{\text{SR}} \frac{t_k}{\text{HDR}} \right)^2 \]

- \( c(g_k) \): HDR weighting function reducing influence of less reliable (dark and bright) pixels

- \( \Psi(s^2) = \sqrt{s^2 + \epsilon^2} \): sub-quadratic penaliser reducing influence of outliers

A Novel Anisotropic Smoothness Term

- Smoothness term is important to fill in missing information, e.g. at saturations

- Anisotropic smoothness term adapts smoothing direction to image structures
  - strong smoothing along edges (quadratic penalisation)
  - reduced smoothing across edges (sub-quadratic penalisation)

- Edge direction: consider upsampled HDR reconstruction of exposure series
  - gives vector \( v_1 \) pointing across edges, \( v_2 \) pointing along edges

- Proposed smoothness term

\[ S(\nabla F) = \Psi \left( \frac{(v_1^\top \nabla F)^2}{\text{across}} \right) + \left( \frac{(v_2^\top \nabla F)^2}{\text{along}} \right) \]

with Charbonnier penaliser \( \Psi(s^2) = 2 \mu^2 \sqrt{1 + (s^2/\mu^2)} \)
Results (using fixed parameters except for $\lambda$)

- Real world, freehand exposure series (Street)

  $g_1$  $g_6$ (reference)  $g_{12}$

  pure HDR  joint SR-HDR

  $\lambda = 0.4, z = 2$

Results (using fixed parameters except for $\lambda$)

- Real world, freehand exposure series (Flower)

  $g_1$  $g_4$ (reference)  $g_8$

  pure HDR  joint SR-HDR

  $\lambda = 0.6, z = 2$
Conclusions and Outlook

Take Home Messages

- Modern optic flow methods are well-suited for aligning HDR exposure series
- Sub-pixel accuracy of displacement fields enables resolution enhancement

Future Work

- Address large displacements of small objects
- Port to mobile platforms (iPhone, Android phone)

Thank You!

- More information:
  
  http://www.mia.uni-saarland.de/Research/SR-HDR