# Temporally consistent gradient domain video editing

G. Facciolo, R. Sadek, A. Bugeau and V. Caselles

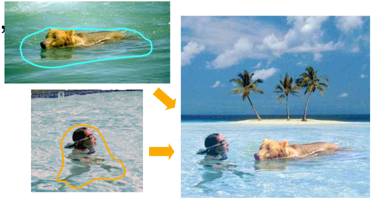
Universitat Pompeu Fabra
Image Processing Group
http://gpi.upf.edu/

EMMCVPR 2011
St. Petersburg - 2011 July, 26th

# Motivation

Gradient domain image edit [Perez et. al., Georgiev, Hagenburg et. al.]...

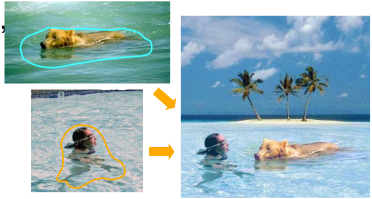
- applications: seamless compositing, tone mapping, shadow removal, matting, inpainting...
- manipulate image gradients
- blend seams



# Motivation

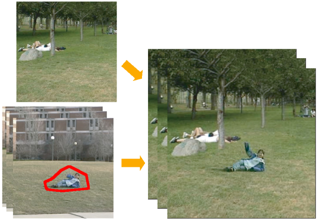
Gradient domain image edit [Perez et. al., Georgiev, Hagenburg et. al.]...

- applications: seamless compositing, tone mapping, shadow removal, matting, inpainting...
- manipulate image gradients
- blend seams



Extension to video [Wang et. al., Bhat et. al.]...

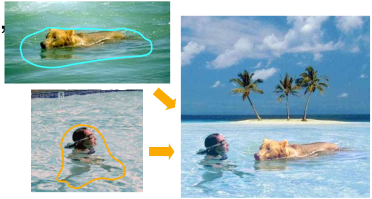
- applications: inpainting correction, nonphotorealistic rendering, object insertion/removal, flickering removal...
- temporal consistency
- attach to temporal neighbors



# Motivation

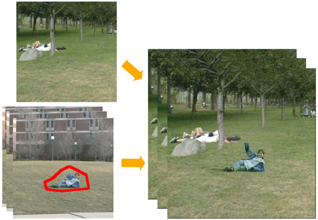
Gradient domain image edit [Perez et. al., Georgiev, Hagenburg et. al.]...

- applications: seamless compositing, tone mapping, shadow removal, matting, inpainting...
- manipulate image gradients
- blend seams



Extension to video [Wang et. al., Bhat et. al.]...

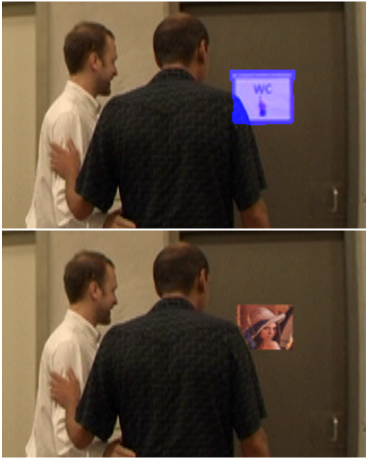
- applications: inpainting correction, nonphotorealistic rendering, object insertion/removal, flickering removal...
- temporal consistency
- attach to temporal neighbors
- [Werlberger et al. EMMCVPR11]



# Motivation: Considered tasks

Inpainting correction
(enforce temp. consist.)

Object insertion/removal



# Outline

Model

Discretization and limitations

Deblurring Convective Derivative (DCD)

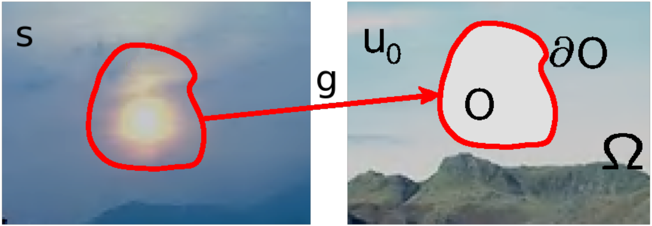
Experiments

Conclusions and future work

# Reminder: Poisson edit

$$\min_u \int_{O \subset \Omega} \|\nabla u - g\|^2 \mathrm{d}x \qquad \text{with} \qquad \underbrace{u|_{\partial O} = u_0}_{\text{Dirichlet boundary cond.}}$$

- $O \subset \Omega \subset \mathbb{R}^2$: edit domain
- $u : O \to R$: solution image
- $u_0 : \Omega \to \mathbb{R}$: target image
- $g : O \to \mathbb{R}^2$: guidance field (i.e. $\nabla s$)



# Reminder: Poisson edit

$$\min_u \int_{O\subset\Omega} \|\nabla u - g\|^2 \mathrm{d}x \qquad \text{with} \qquad \underbrace{u|_{\partial O} = u_0}_{\text{Dirichlet boundary cond.}}$$

- $O \subset \Omega \subset \mathbb{R}^2$: edit domain
- $u : O \to R$: solution image
- $u_0 : \Omega \to \mathbb{R}$: target image
- $g : O \to \mathbb{R}^2$: guidance field (i.e. $\nabla s$)

# Model: Temporal consistency

## Temporal consistency hypothesis

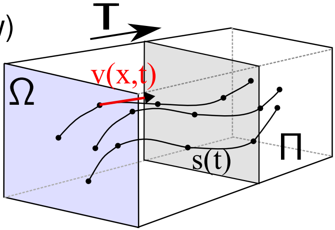
Regarding the video as a volume ( $\Pi := \Omega \times \mathbb{T}$ );
Points should "look uniform" along their trajectories $s(t)$ in time:

$$\frac{\mathrm{d}}{\mathrm{d}t} u(s(t), t) = 0 \qquad u : \Pi \to \mathbb{R}$$

- Applying chain's rule

$$\partial_v u(x,t) := v(x,t) \cdot \nabla_x u(x,t) + \partial_t u(x,t) = 0$$

- $v(x,t)$: velocity field (optical flow) characterizes all the trajectories
- $\partial_v u$: convective derivative
- enforce constant intensity minimizing $|\partial_v u(x,t)| \quad \forall (x,t)$

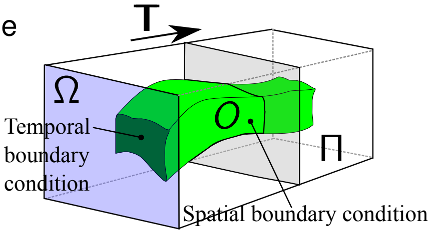


# Model: Gradient domain video edit

$$\min_u \int_{\mathbb{T}} \int_{O_t} \beta \|\nabla_x u(x,t) - g(x,t)\|^p + |\partial_v u(x,t)|^p \, \mathrm{d}x \, \mathrm{d}t$$

$$\text{s.t. } u|_{\partial O} = u_0$$

- $O \subset \Pi \subset \mathbb{R}^3$: edit domain (slice $O_r = \{x | (x,t) \in O; t = r\}$)
- $g: \ O \to \mathbb{R}^2$: spatial guidance field
- $u: \ O \to \mathbb{R}$: solution image
- $u_0 : \Pi \to \mathbb{R}$: target image
- $v: \ \Pi \to \mathbb{R}^2$: optical flow
- $p = \{1, 2\}$ and $\beta \geq 0$



# Model: Gradient domain video edit

$$\min_{u} \int_{\mathbb{T}} \int_{O_t} \beta \underbrace{\|\nabla_x u(x,t) - g(x,t)\|^p}_{\text{spatial consist.}} + \underbrace{|\partial_v u(x,t)|^p}_{\text{temporal consist.}} \,\mathrm{d}x\,\mathrm{d}t$$

# Model: Gradient domain video edit

$$\min_u \int_{\mathbb{T}} \int_{O_t} \beta \underbrace{\|\nabla_x u(x,t) - g(x,t)\|^p}_{\text{spatial consist.}} + \underbrace{|\partial_v u(x,t)|^p}_{\text{temporal consist.}} \, \mathrm{d}x \, \mathrm{d}t$$

$\beta$ balances spatial/temporal terms

- $\beta > 0$ : temporal consistency and spatial term attach. to $g$
- $\beta = 0$ : only temporal consistency (propagate from TBC)

# Model: Gradient domain video edit

$$\min_u \int_{\mathbb{T}} \int_{O_t} \beta \underbrace{\|\nabla_x u(x,t) - g(x,t)\|^p}_{\text{spatial consist.}} + \underbrace{|\partial_v u(x,t)|^p}_{\text{temporal consist.}} \, \mathrm{d}x \, \mathrm{d}t$$

$\beta$ balances spatial/temporal terms

- $\beta > 0$ : temporal consistency and spatial term attach. to $g$
- $\beta = 0$ : only temporal consistency (propagate from TBC)

Error penalty

- $p = 2$ : smooth interpolation of inconsistencies from BC
- $p = 1$ : allow discontinuities in $O$

# Model: Gradient domain video edit

$$\min_u \int_{\mathbb{T}} \int_{O_t} \beta \underbrace{\|\nabla_x u(x,t) - g(x,t)\|^p}_{\text{spatial consist.}} + \underbrace{|\partial_v u(x,t)|^p}_{\text{temporal consist.}} \,\mathrm{d}x\,\mathrm{d}t$$

$\beta$ balances spatial/temporal terms

- $\beta > 0$ : temporal consistency and spatial term attach. to $g$
- $\beta = 0$ : only temporal consistency (propagate from TBC)

Error penalty

- $p = 2$ : smooth interpolation of inconsistencies from BC
- $p = 1$ : allow discontinuities in $O$

Some temporal inconsistencies not considered by this model

- illumination changes, specularities
- occlusions

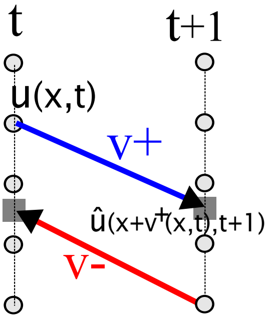
# Discretization

- Spatial gradient discretized with forward differences: $\nabla_x u$
- Convective derivative

  $\partial_v^+ u(x,t) := \hat{u}(x + v^+(x,t), t+1) - u(x,t)$

  ◦ $\hat{u}(x,t)$ interpolation of $u(\cdot,t)$ at $x$

  ◦ $v^+(x,t)$ forward optical flow (backward $v^-$ also available)

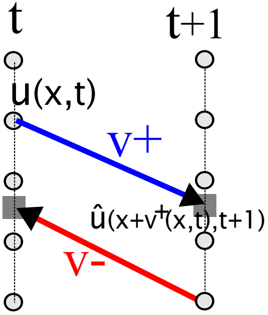


# Discretization

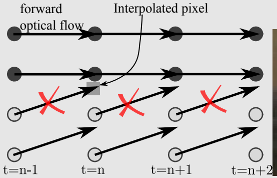
- Spatial gradient discretized with forward differences: $\nabla_x u$
- Convective derivative

$$\partial_v^+ u(x,t) := \hat{u}(x + v^+(x,t), t+1) - u(x,t)$$

  - ◦ $\hat{u}(x,t)$ interpolation of $u(\cdot,t)$ at $x$
  - ◦ $v^+(x,t)$ forward optical flow (backward $v^-$ also available)




**Remove flow vectors corresponding to occlusions in $u_0$**




# Example: Inpainting correction

inpainted sequence

without temporal consistency $\beta = \infty$

with temporal consistency $\beta = 1$

# Discretization of the convective derivative

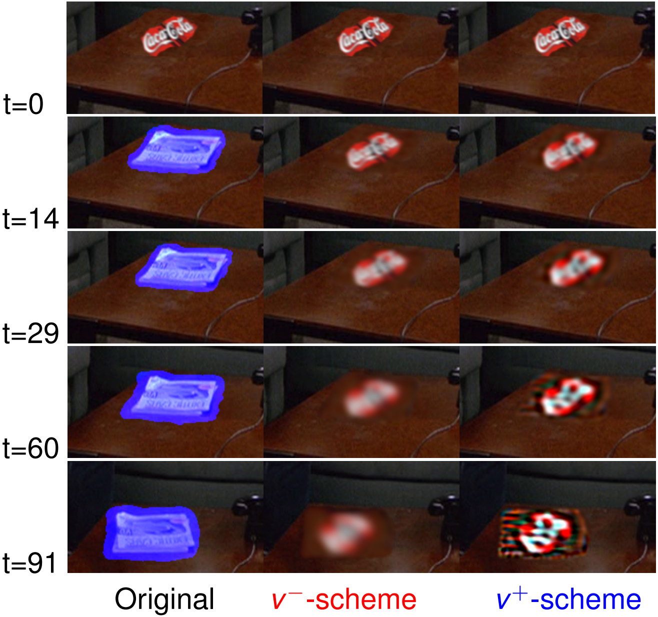
**How does the temporal consistency influence the results?**

- Set $\beta = 0$, to evaluate what does do

$$\min_u \int_{\mathbb{T}} \int_{O_t} \beta \|\nabla_x u(x,t) - g(x,t)\|^p + |\partial_v u(x,t)|^p \mathrm{d}x \, \mathrm{d}t$$

- No guiding filed $g$ in this experiment
- Temporal propagation from BC at frame $t = 0$, using $p = 2$
- Test convective derivative discretizations using $v^+$ and $v^-$

# Discretization of the convective derivative

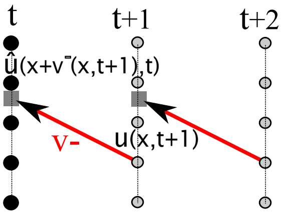


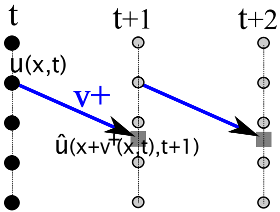
# Discretization of the convective derivative

- Conceptual experiment: two frames video, $p = 2$
- Denote $M_{v^{-/+}} u(\cdot, t)$ the interpolations $\hat{u}(\cdot, t)$
- Then minimizing $\sum |\partial_{v^{-/+}} u(x, t)|^2$

$$\sum |\hat{u}(x+v^-(x, t+1), t) - u(x, t+1)|^2 = \|M_{v^-} u(\cdot, t) - u(\cdot, t+1)\|^2$$

corresponds to apply $M_{v^-}$ (or inverse of $M_{v^+}$) to $u(\cdot, t)$



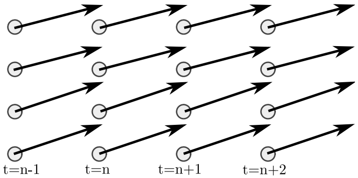

Key Obs.: have somewhat opposed effects: blur and “sharpen”

# Deblurring Convective Derivative

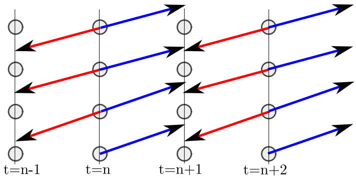
The idea is to alternate

- $v^+$-scheme at even frames (sharpens) with
- $v^-$-scheme at odd frames (blurs)

to moderate each other's effects



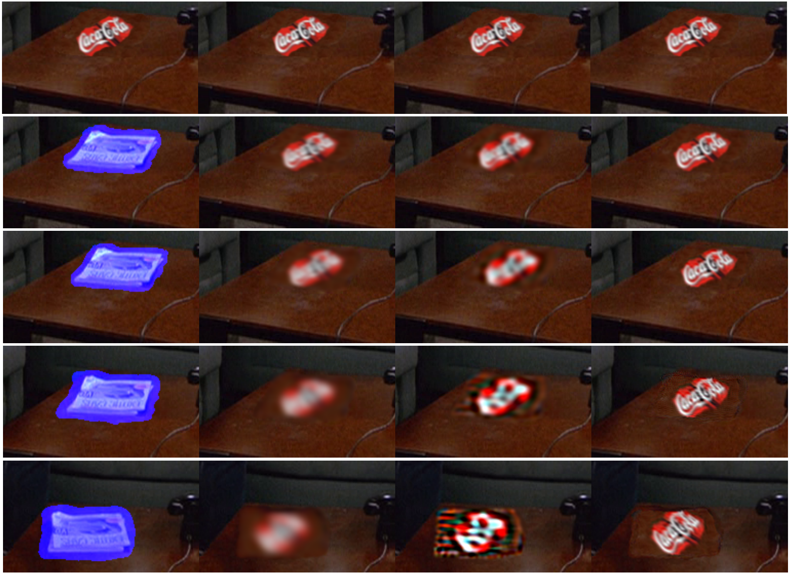

$v^+$-scheme




DCD

# Deblurring Convective Derivative

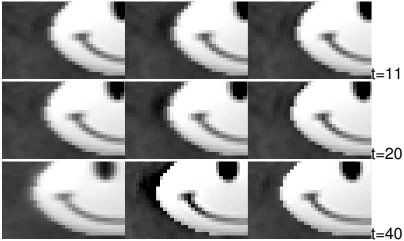
t=0
t=14
t=29
t=60
t=91



Original | $v^-$-scheme | $v^+$-scheme | DCD

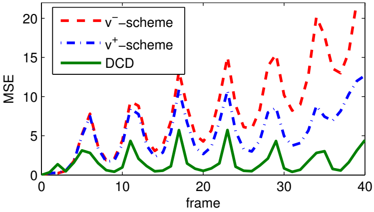
# Deblurring Convective Derivative

- DCD reduce artifacts in the case $\beta = 0$
- But also improves results when $\beta \neq 0$




$v^-$ $v^+$ DCD

$p = 2,\ \beta = 0.01$




- Can be applied sequentially on pair of frames

# Deblurring Convective Derivative

In the case $\beta = 0$, due to the “inverse” steps

- odd frames will always contain some high freq. artifacts
- the result will eventually degenerate

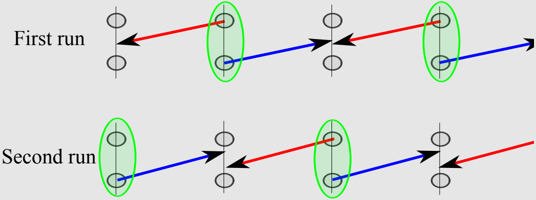
# Deblurring Convective Derivative

In the case $\beta = 0$, due to the "inverse" steps

- odd frames will always contain some high freq. artifacts
- the result will eventually degenerate

## Reduce artifacts at odd frames

- Post-process filtering the high frequency artifacts
- Running twice inverting order, and keep only blurred frames

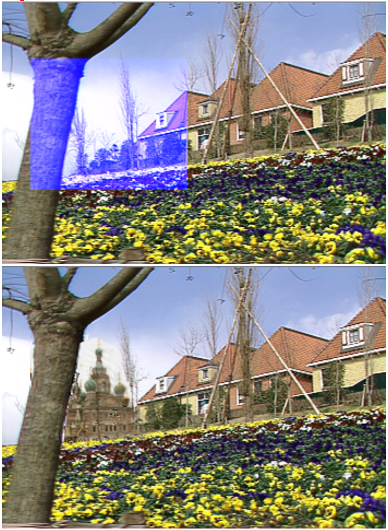


# Experiments: insertion/removal

$\beta \sim 0,\ p = 1$

$\beta \sim 0,\ p = 1$

# Experiments: insertion



$\beta \sim 0, p = 2$

# Future directions

- Other interpolations other than bilinear
- Reduce the artifacts at “deblurred” frames
- Our algorithm relies extensively on the optical flow, reduce artifacts in the optical flow
- Use DCD for imposing temporal consistency of gradients

# Conclusions

- Presented a functional for gradient domain video editing with temporal consistency
- Proposed discretization: Deblurring Convective Derivative
  - Allow to reduce the artifacts introduced by the discretization of the temporal consistency term
  - Computationally inexpensive
  - Improves results both for $\beta = 0$ and $\beta > 0$

# Conclusions

- Presented a functional for gradient domain video editing with temporal consistency
- Proposed discretization: Deblurring Convective Derivative
  - Allow to reduce the artifacts introduced by the discretization of the temporal consistency term
  - Computationally inexpensive
  - Improves results both for $\beta = 0$ and $\beta > 0$

# Thank you.

More @ `http://gpi.upf.edu/static/emmcvpr11/`