Approaches used to measure quality of multifocus image fusion

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OP Výzkum a vývoj pro inovace

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Multifocus image fusion I

Multifocus images

Multiple images obtained with different focus
(No rotation, no shift, no scale change)

Example


Multifocus image fusion II

Types

- Mosaic - each pixel is the "best" information in at least one image
- Real-life - there might be no ideal image for pixel

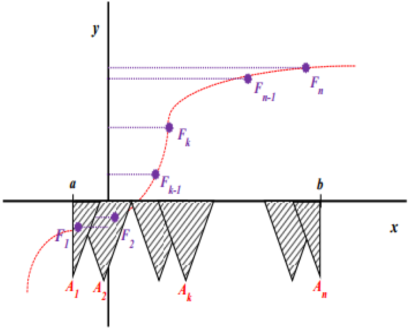
Example

F-Transform schematically

- **Original function** $f : [a,b] \to [c,d]$
- **Fuzzy partition** $A_1, \dots, A_n$ of $[a,b]$
- **F-Transform Components** $F_1, \dots, F_n$
- **Transformation:** $f \Rightarrow \mathbf{F}_n[f]$

x	A_1	A_2	$\cdots$	A_n
$\mathbf{F}_n[f]$	F_1	F_2	$\cdots$	F_n

- **Result:** $\mathbf{F}_n[f] = (F_1, \dots, F_n)$



F-transform formally

Direct and inverse F-Transform

$$F[u](A_k \times B_l) = \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} u(i,j) A_k(i) B_l(j)}{\sum_{i=1}^{N} \sum_{j=1}^{M} A_k(i) B_l(j)}, \tag{1}$$

$$u_{nm}(i,j) = \sum_{k=1}^{n} \sum_{l=1}^{m} F[u]_{kl} A_k(i) B_l(j). \tag{2}$$

Basic usage in image processing

1. Calculate components c of input image u
2. Calculate reconstructed image u_r from components c
3. Calculate residuals $r = u_r - u$

Image fusion using F-Transform

Algorithm description

1. Calculate residuals for each input image
2. Calculate residuals from residuals for each input image (obtained next "level")
3. ... continue interatively until residuals are not significant
4. For each "level" take highest residuals in absolute values
5. Reconstruct image as sum highest residuals

Properties

- Very time consuming
- Precise for complex images
- May contain artifacts in case of simple images $\Rightarrow$ improvements done

Fusion example - input

Fusion example - output

Fusion example - which is the best?

Fusion - evaluation

Possible defects

- Result image (or its parts) is out of focus
- Artifacts existing in result image

How to measure quality?

- Solution based on automatically calculated measures
  - Is there "best" image to compare
  - There is no best image to compare
- Solution based on human experts
  - (Subjective? Who is expert?)

Fusion - evaluation

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... quick remark about measures

... about measures

- Distortion measures - higher means lower quality (bigger distortion)
- Quality measures - higher means better quality (lower distortion)

Automatically calculated measures - mosaic images I

Commonly used measures

- Mean square error

$$MSE = \frac{1}{n * m} \sum_{x=1}^{n} \sum_{y=1}^{m} (u(x,y) - \hat{u}(x,y))^2$$

- Peak signal to noise ratio

$$PSNR = 20 * log_{10} \frac{255}{\sqrt{MSE}}$$

- Structural similarity

$$SSIM(x,y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)}$$

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Automatically calculated measures - mosaic images II

Information-weighted MSE & PSNR [Wang (2004)]

$$\text{IW-MSE} = \prod_{j=1}^{M} \left[\frac{\sum_i w_{j,i}(u_{j,i} - \hat{u}_{j,i})}{\sum_i w_{j,i}} \right]^{\beta_j}$$

$$\text{IW-PSNR} = 20 * log_{10} \frac{255}{\sqrt{IWMSE}}$$

Automatically calculated measures - mosaic images III

Multiscale structural similarity [Wang (2004)]

Evaluated SSIM in multiple scales

- Brightness (luminance) $l(x,y) = \frac{2\mu_x\mu_y + C_1}{\mu_x^2+\mu_y^2+C_1}$
- Contrast $c(x,y) = \frac{2\sigma_x\sigma_y + C_2}{\sigma_x^2+\sigma_y^2+C_2}$
- Similarity $s(x,y) = \frac{\sigma_{xy} + C_3}{\sigma_x\sigma_y+C_3}$
- Local

$$\mathrm{SSIM}_j = \frac{1}{N_j}\sum_i \left[l(\mathbf{u}_{j,i}, \hat{\mathbf{u}}_{j,i}) c(\mathbf{u}_{j,i}, \hat{\mathbf{u}}_{j,i}) s(\mathbf{u}_{j,i}, \hat{\mathbf{u}}_{j,i}) \right]$$

- Result

$$\text{MS-SSIM} = \prod_{j=1}^{M} (\mathrm{SSIM}_j)^{\beta_j}$$

Automatically calculated measures - mosaic images III

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- Result

$$\mathsf{MS\text{-}SSIM} = \prod_{j=1}^{M} (\mathsf{SSIM}_j)^{\beta_j}$$

Automatically calculated measures - mosaic images IV

Multiscale weighted structural similarity [Wang (2004)]

Evaluated information weighted SSIM in multiple scales

- Brightness, contrast, similarity stays the same
- Local value now weighted

$$\text{IW-SSIM}_j = \frac{\sum_i w_{j,i} c(\mathbf{u}_{j,i}, \hat{\mathbf{u}}_{j,i}) s(\mathbf{u}_{j,i}, \hat{\mathbf{u}}_{j,i})}{\sum_i w_{j,i}}, \forall j < M$$

- Result

$$\text{IW-SSIM} = \prod_{j=1}^{M} (\text{IW-SSIM}_j)^{\beta_j}$$

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Automatically calculated measures - mosaic images IV

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- Result

$$\text{IW-SSIM} = \prod_{j=1}^{M} (\text{IW-SSIM}_j)^{\beta_j}$$

Commonly used measures - results

Commonly used measures

Image	Size	MSE	PSNR	SSIM
reference	256x177	0.000	(Inf)	1.000
input A	256x177	243.581	24.264	0.886
input B	256x177	120.663	27.315	0.936
fused	256x177	10.993	37.748	0.992
reference	1024x708	0.000	(Inf)	1.000
input A	1024x708	340.879	22.804	0.871
input B	1024x708	195.902	25.210	0.994
fused	1024x708	30.969	33.222	0.988

Information weighted measures - results

Information weighted measures

Image	Size	SSIM	IW-PSNR	MS-SSIM	IW-SSIM
reference	256x177	1.000	–.—	1	1
input A	256x177	0.886	20.900	0.933	0.836
input B	256x177	0.936	**38.888**	0.985	0,944
fused	256x177	0.992	32.097	0.997	0.995
reference	1024x708	1.000	–.—	1	1
input A	1024x708	0.871	14.244	0.889	0.655
input B	1024x708	0.994	21.997	0.954	0.837
fused	1024x708	0.988	28.148	0.988	0,975
blur 3	1024x708	0.939	28.849	0.984	0.939
blur 10	1024x708	0.905	17.854	0.930	0.714
blur 25	1024x708	0.805	13.368	0.842	0.490

Mosaic fusion results

A1 obtained by DCT [Haghighat (2011)]

Mosaic fusion results

A2 obtained by DCT [Haghighat (2011)]

Mosaic fusion results

B obtained by wavelet-based statistical sharpness measure [Tian (2012)]

Mosaic fusion results

C obtained by bilateral gradiend-based sharpness [Tian (2011)]

Mosaic fusion results

D obtained by laplacian-based fusion [Xiao (2009)]

Mosaic fusion results

Original F-Transform based fusion (origin)

Mosaic fusion results

Residual F-Transform based fusion (residual)

Mosaic fusion results

Invasive A - F-Transform based fusion

Mosaic fusion results

Invasive B - F-Transform based fusion

Mosaic fusion results

Invasive C - F-Transform based fusion

Mosaic fusion results

Invasive D - F-Transform based fusion

Fused images - results

Fused images - results

Image	SSIM	IW-PSNR	MS-SSIM	IW-SSIM
orig.bmp	1	–.—	1.000	1.000
D.bmp	0.991	27.183	0.991	0.977
Forigin.bmp	0.990	25.636	0.989	0.971
FinvasiveB.bmp	0.992	26.687	0.991	0.976
A1.bmp	0.988	25,835	0.988	0.955
FinvasiveD.bmp	0.982	22.180	0.982	0.951
FinvasiveA.bmp	0.982	22.532	0.982	0.950
Fresidual.bmp	0.973	21.705	0.975	0.925
A2.bmp	0.975	23.316	0.971	0.925
FinvasiveC.bmp	0.972	20.624	0.974	0.915
B.bmp	0.968	20.860	0.967	0.902
C.bmp	0.946	18.091	0.953	0.862

Automatically calculated metrics - non-mosaic images

How to evaluate focus

Camera uses focus measure to autofocus

- Phase detection
- Contrast detection - intensity differences between neighbor pixels increasing with correct focus $\Rightarrow$ no default image needed

Autofocus measurement methods

Many approaches, references implementations [Petruz (2012)]

- Image contrast / curvature [Nanda (2001), Helmli (2001)]
- Gray level variance/normalized/locality [Krotkov (1986), Santos (1997), Pech (2000)]
- Histogram range / entrophy [Firestone (1991), Krotkov (1986)]
- Energy of gradient [Subbarao (1992)]
- Thresholded gradient, squared gradient [Santos (1997), Eskicioglu (1995)]
- Steerable filter-based measure [Minhas (2009)]
- Gaussian derivative [Geusebroek (2000)]
- Laplacian energy / variance / diagonal [Subbarao (1992), Pech (2000), Thelen (2009)]
- DCT energy mesasure / ratio [Shen (2006), Lee (2009)]
- Wavelet sum / variance / ratio [Yang (2003), Yang (2003), Xie (2004)]
- ... + 9 more

Autofocus measurement methods - results I

Autofocus measures - demo images

Image	SFIL ($\times 10^{17}$)	GRAE	WAVV	ACMO
reference	5.867	10.649	47.370	30 720.427
input A	3.547	4.218	10.963	30 720.648
input B	4.863	7.406	34.692	30 724.082
fused	5.526	10.013	47.136	30 722.849
blur 3	5.408	7.999	0.354	30 721.009
blur 10	3.990	3.164	0.154	30 730.036
blur 25	2.542	0.973	0.155	30 724.739

SFIL – Steerable filters-based [Minhas (2009)]
GRAE – Energy of gradient [Subbarao (1992)]
WAVV – Wavelet variance [Yang (2003)]
ACMO – Absolute central moment [Shirvaikar (2004)]

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Autofocus measurement methods - results II

Autofocus measures - fused images

Image	SFIL ($\times 10^{16}$)	GRAE	WAVV
input A.bmp	308.302	4.331	0.494
input B.bmp	317.491	5.421	1.194
orig.bmp	415.314	9.715	4.176
D.bmp	407.490	7.968	1.367
Forigin.bmp	404.429	7.866	1.417
FinvasiveB.bmp	393.407	7.534	1.315
FinvasiveD.bmp	365.260	9.712	5.360
B.bmp	325.765	6.099	4.164
A1.bmp	408.299	7.943	1.402
Fresidual.bmp	347.895	5.239	0.864
A2.bmp	417.827	8.631	2.113
FinvasiveC.bmp	368.989	6.859	1.748

Autofocus methods - summary

Acceptable measures (in case of no artifacts)

- Steerable filtering-based approach
- DCT energy, DCT ratio
- Gaussian derivative
- Gray level local variance

Unacceptable measures

Detecting directly sharpness of image

- Wavelets...
- Contrast...
- Histogram...
- Laplacian...

Who is human expert?

Who is human expert?

- Multiple subjects evaluate images differently
  - Some prefer improved contrast in image
  - Some do not see (or ignore) artifacts
  - Sometimes difference is too small
- So which one is better?

Just Noticeable Difference

Just Noticeable Difference

- Based on perceptual sensitivity (E.H. Webber, G.T. Fecher)
- Test based on

$$img_{test} = img_{ref} + k * (img_{dmg} - img_{ref})$$

- Subject must decide if img_{test} or img_{ref} is better
- With success > 75%, difference is 1 JND, with success >93.75%, difference is 2 JND
- Difference 2 JND is "noticeable"

This may be useful to define minimal significant measure difference.

Conclusion

- In case of reference image, IW-SSIM characteristic can be used
- In case of non-mosaic input, DCT based measures, gaussian derivative or gray-level-local-variance can be used
- Artifacts cause results should be processed carefully

Future

- Measure the robustness of selected algorithms
- Look for other types of algorithms than focus-oriented

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