Display-induced motion artefacts

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Moving image quality in mobile devices

• Mobile TV – Living-room experience
  • Saturated colours and high moving image quality
• Personal Multimedia Players (PMP)
• Fast-moving games
• Video capture
• New displays with wide field-of-view
  • Near-to-the-eye (NED) displays
  • Personal projectors
• UI with scrolling, panning, and window moving
• Ubiquitous readability
  • Walking, low temperatures
• Long battery life → low display power consumption
Motion artefacts in displays

- Edge blur
- Resolution loss
- Judder
- Ringing
- Ghosting
- Wire-frame flickering
- Chromatic and grey-scale abberation
- Colour break-up (saccadic and pursuit)
- Dynamic false contours
- Moving image resolution
Edge blur

**Static image**

**Motion blur**

**Graphs**

- **Left graph**: Greyscale value vs. Horizontal pixel for a static image.
  - Vertical axis: Greyscale value
  - Horizontal axis: Horizontal pixel
  - Graph shows a step change.

- **Right graph**: Greyscale value vs. Horizontal pixel for motion blur.
  - Vertical axis: Greyscale value
  - Horizontal axis: Horizontal pixel
  - Graph shows a gradient change.
**Origins of edge blur**

**Incomplete erasure of previous frame**
- Limited liquid crystal response
- Big problem for mobile displays at low temperatures

**Complete erasure of previous frame**
- Continuous motion anticipated by the eyes – intensity averaging along the arrows
- BUT, object movement is always quantised
Blur reduction by impulse driving

- Stroboscopic effect reduces blur even with retinal averaging
- BUT, trade-off with average luminance
Resolution loss

- Effective resolution measured by MTF
  - Modulation depth as a function of spatial frequency
  - Modulation affected by many factors

\[ n_r = 1.1568 \]

Contrast Modulation, \( C_n(\%) \)

Grille Line Width (pixels)
Blur demo test scroll pattern
Judder (edge flicker)

- Temporal mismatch between step-wise motion on screen and continuous pursuit by the eyes
- Smooth pursuit eye movements follow bright parts of image
- Edge flicker at frame rate with sawtooth luminance
- Reduction of judder
  - Limit pan/zoom speed
  - Reduce contrast and focus
  - Temporal upsampling
  - Inter-frame fading - Movieola™
- Judder can be used artistically

Figure courtesy of James Larimer

Space-Time Diagram of Perfectly Pursued Moving Line
Brightness represents line intensity

Figure courtesy of James Larimer
Motion blur with ringing

Causes:
- Electro-optical over drive
- High-pass filtering
Wire-frame flickering

• Assymetric rise and fall times
• Rare artefact mainly in engineering applications

• Demo: 1x1 grille scroll
Chromatic and grey-scale aberration

• Mixing of levels of adjacent pixels
• Same origin as blur but manifests itself as colour change
• Dominant in high-frequency, high-contrast content

• Demo: red box on green, dark red text scroll
Field-sequential colour

$\Delta T =$ field period

B

G

R

LCD

Display image

Temporally fused colours

T

T + $\Delta T$

T + 2$\Delta T$

Time
Advantages of field-sequential colour

- $\geq 3x$ pixel density possible
- 4-5x pixel transmittance
- Wide gamut
- Scalable number of primaries
- Fully tunable chromaticities
- White balancing without loss of colour depth
- High moving image quality
- Rotationally invariant pixels
- Monochrome reflective mode
- Cost reduction
  - No colour filters
  - $\leq 1/3$ number of source drivers
Colour break-up

Smooth pursuit eye-tracking

Moving target

Saccade

Static target

Slide courtesy of Toni Järvenpää, Nokia Research Centre, Tampere
Colour breakup by smooth pursuit eye tracking

- Origin same as sample-and-hold blur: Measurable by VESA MBM etc
- Blur -> edge colorisation
Colour break-up reduction by black field

No black field insertion

Black field insertion

Width of colorised edge decreased but contrast unchanged
Colour break-up reduction by black subfield

No black field insertion

Black subfield insertion

Width of colorised edge unchanged but contrast decreased
Colour break-up reduction by higher field rate

No black field insertion

3x field rate

1 frame

Gaze vector

1x < Input frame rate < 3x display rate: asynchronous driving –
temporal smoothing -> reduced colour break-up visibility
Saccadic colour break-up

<table>
<thead>
<tr>
<th>Size</th>
<th>Max speed</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1°</td>
<td>80° / s</td>
<td>25 ms</td>
</tr>
<tr>
<td>10°</td>
<td>300° / s</td>
<td>40 ms</td>
</tr>
<tr>
<td>30°</td>
<td>800° / s</td>
<td>80 ms</td>
</tr>
</tbody>
</table>

Slide courtesy of Toni Järvenpää, Nokia Research Centre, Tampere
Measurement of saccadic colour break-up

**FIGURE 4** — Target virtual display, the two-axis tilting mirror, and the 90° deflecting C-mount optics.

**FIGURE 6** — Photodiode installed in front of the target display.

Figures courtesy of Toni Järvenpää, Nokia Research Centre, Tampere
**Measurement of saccadic colour break-up**

**FIGURE 10** — Test target image and the path of the 10° saccade. Initial and end views are marked with the dashed rectangles.

**FIGURE 12** — Enhanced red, green, and blue sub-frame images.

**FIGURE 13** — Combined sub-frame images.

Figures courtesy of Toni Järvenpää, Nokia Research Centre, Tampere
Measurement of saccadic colour break-up

**FIGURE 11** — The brightness variations of the display and the captured and enhanced sub-frame images during the 10° saccade.

Figures courtesy of Toni Järvenpää, Nokia Research Centre, Tampere
Measurement of saccadic colour break-up

**FIGURE 9** — (a) Position curve and (b) speed curve of the saccade.

**FIGURE 14** — The configurable FSC “display.”

Figures courtesy of Toni Järvenpää, Nokia Research Centre, Tampere
Reduction of saccadic colour break-up

• Depends on contrast, brightness, field-of-view
  • Dynamic contrast and brightness reduction
• Multi-receptor stimulation
  • RGB -> CMY
  • RGB -> RGBxy
Spatio-temporal flashes – multiplexed displays

Conventional field-sequential colour

\[ \Delta T = \text{field period} \]

Display image

Temporally fused colours

\( T \quad T + \Delta T \quad T + 2\Delta T \quad \text{Time} \)

B

G

R

\( \Delta T = \text{field period} \)
Superposition of primary colours

\[ \Delta T = \text{field period} \]

**Display image**

**LCD**

Temporally fused colours
Adaptive gamut – trading of gamut for luminance

\[ X_i' = X_i + d \Sigma X_{i \neq j} \]
\[ Y_i' = Y_i + d \Sigma Y_{i \neq j} \]
\[ Z_i' = Z_i + d \Sigma Z_{i \neq j} \]

Desaturation factor:
\[ d = 1 - \frac{d_{G1}}{d_{G0}} \]

Example of gamut trading (1)

- 0.40 desaturation
- +80% luminance
  - Better outdoor contrast
- Or luminance preservation
  - Lower power
  - Better moving image quality
Flexible primary composition

• RGB => CMY (BG, RB, RG)
  • Increased luminance
  • Decreased colour breakup

• RGB => RGBW
  • *Local* luminance boost
  • Large aperture vs RGBW subpixels

• RGB => monochrome
  • Add grey levels by PWM
  • Arbitrary colour
  • #primary trading for depth
Dynamic false contours

- Any subfield modulated display
- Plasma Display Panels (PDP)
- Reduction by subfield reordering

Combined artefacts

- Edge blur + ringing + resolution reduction
- Judder + Edge blur
- Ghosting + ringing
- Edge blur + chromatic and grey-scale aberration

Metrics
- Reference-based, e.g. PSNR
- Dynamic contrast
- Moving picture resolution
- Resolution visible (MTF)
Image quality metric categories

Full Reference metric

Reduced-Reference metric

Case of display device evaluation:
- Compression/transmission system \(\Leftrightarrow\) device-induced motion artifacts

Non-Reference metric

Slide courtesy of Jean-Luc Olives, Nokia Technology Platforms, Helsinki
Bit-based metrics

- Mean square error (MSE)/peak signal-to-noise ratio (PSNR)
  - Difference to reference image/video
  - Pixel-based, content independent
  - Mediocre quality predictor
  - Difficult to implement in device evaluation (full reference metric)

\[
MSE = \frac{1}{XYT} \sum_{t=1}^{T} \sum_{y=1}^{Y} \sum_{x=1}^{X} (i(x, y, t) - r(x, y, t))^2, \text{ where}
\]
\[
i(x, y, t) = \text{original signal}, \ r(x, y, t) = \text{reconstructed signal}
\]

\[
PSNR = 10 \log_{10} \frac{255^2}{MSE}
\]

- Network QoS
  - Bit error rate, packet loss ratio, etc...
  - Bit packet-based, content independent
  - Meaningless without perception

Slide courtesy of Jean-Luc Olives, Nokia Technology Platforms, Helsinki
Vision-based metric

- Multi channel models (~1993): Visible Difference Predictor from S. Daly (Kodak)

Slide courtesy of Jean-Luc Olives, Nokia Technology Platforms, Helsinki
Dynamic contrast

Arbitrary still image

Window of analysis:
Shape and size depend on artifact under study

Same image scrolled at a predefined angular speed
Area-averaged dynamic contrast

\[ C_{stat} = \frac{S_{max} - S_{min}}{S_{max} + S_{min}} \]  
(Michelson contrast)

\[ C_{dyn} = \frac{1}{NM} \sum_{i=1}^{M} \sum_{j=1}^{N} 1 - \frac{|M_{ij} - S_{ij}|}{M_{ij} + S_{ij}} \]

\[ S = \text{Luminance of still image} \]
\[ S_{ij}(M_{ij}): \text{Luminance of element } ij \text{ of still (moving) image} \]
Static and dynamic contrast

\[ C_{stat} = \frac{S_{max} - S_{min}}{S_{max} + S_{min}} \]

Value between 0 and 1

\[ C_{dyn} = \frac{1}{NM} \sum_{i=1}^{M} \sum_{j=1}^{N} 1 - \frac{|M_{ij} - S_{ij}|}{M_{ij} + S_{ij}} \]

- Value between 0 and 1
- Value between 0 and 1
- 0: No distinguishable features
- 1: Same as static contrast
Advantages of dynamic contrast

• Independent of display device and its size
• Includes blur, edge enhancement, false contours
• Averaging window can be tuned to artifact of interest
• Works for any display contents
• Analogous to Michelson contrast which is standard in vision
Artifact metrics

- Algorithm is dedicated to detect one type of artifact
- Works well for device evaluation (non-reference metric)
- Blur detection
  - Reduction of high frequencies (edges)
  - Average spread of significant edges
- Blockiness
  - Block structure, block boundaries
  - Average 1D power spectra of horizontal & vertical differences
- Jerkiness
  - Frame rate reduction
- Mean Opinion Score prediction: Combination of artifact metrics

Slide courtesy of Jean-Luc Olives, Nokia Technology Platforms, Helsinki
Blur and overshoot metric (1)

\[
\text{edge blur} = \frac{\sum_{\text{blur region}} |\text{Error}|}{\text{Step Size}}
\]

\[
\text{Ringing} = \frac{\sum_{\text{ringing region}} |\text{Error}|}{\text{Step Size}}
\]

Figure 2. Ringing and edge blur at an edge of a one-dimensional signal.

From G.A.D Punchihewa, D. G. Bailey and R. M. Hodgson, “Objective Quality Assessment of Coded Images: The development of New Quality Metrics” Institute of Information Sciences & Technology, Massey University, Palmerston North, New Zealand, g.a.punchihewa@massey.ac.nz
Moving picture resolution

- Linearly moving pattern and camera
- Fixed scroll speed
- Based on subjective pair-wise comparison
- Metric: # TV lines
- 3x3 grey levels (3 contrast levels)
- Contrast-averaged resolution

http://www.advanced-pdp.jp/
## Scroll speed by content

<table>
<thead>
<tr>
<th>Content</th>
<th>Speed (PPF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panning background in a movie</td>
<td>2-4</td>
</tr>
<tr>
<td>Slow panning in a drama</td>
<td>4-8</td>
</tr>
<tr>
<td>Sports broadcast</td>
<td>8-11</td>
</tr>
<tr>
<td>Scrolling text (stock price ticker etc)</td>
<td>11-12</td>
</tr>
<tr>
<td>Average (used in measurements)</td>
<td>5-6</td>
</tr>
</tbody>
</table>

* Pixels per frame, 1920 horizontal pixels, 60 Hz

[http://www.advanced-pdp.jp/](http://www.advanced-pdp.jp/)
## Scroll speed by content in vision units

<table>
<thead>
<tr>
<th>Content</th>
<th>Speed °/s @ 30 cpd</th>
</tr>
</thead>
<tbody>
<tr>
<td>1920 px 32° FOV</td>
<td></td>
</tr>
<tr>
<td>Panning background in a movie</td>
<td>2-4</td>
</tr>
<tr>
<td>Slow panning in a drama</td>
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</tr>
<tr>
<td>Average (used in measurements)</td>
<td>5.3-6.4</td>
</tr>
</tbody>
</table>

http://www.advanced-pdp.jp/
Moving picture resolution (TV lines)

900 lines resolvable

300 lines resolvable

http://www.advanced-pdp.jp/
Moving picture resolution - test pattern

http://www.advanced-pdp.jp/
Moving picture resolution - reporting

Display A: Analyzed Results by Resolution
Background Level = [Medium], Contrast = [Medium]

[TV lines]
[Resolution]: 300  350  400  450  500  550  600  650  700  750  800  850  900  950  1000  1080
>> judgment:  OK  OK  OK  OK  OK  OK  OK  OK  NG  NG

Display B: Analyzed Results by Resolution
Background Level = [Medium], Contrast = [Medium]

[TV lines]
[Resolution]: 300  350  400  450  500  550  600  650  700  750  800  850  900  950  1000  1080
>> judgment:  OK  NG  NG  NG  NG  NG  NG  NG  NG  NG  NG  NG  NG  NG  NG

Measured Results: Display A

<table>
<thead>
<tr>
<th>High Contrast</th>
<th>Medium Contrast</th>
<th>Low Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>850</td>
<td>850</td>
</tr>
<tr>
<td>850</td>
<td>900</td>
<td>1080</td>
</tr>
<tr>
<td>1080</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

> AVERAGED RESOLUTION = 926.66 [TV lines]

Measured Results: Display B

<table>
<thead>
<tr>
<th>High Contrast</th>
<th>Medium Contrast</th>
<th>Low Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>300</td>
<td>350</td>
</tr>
<tr>
<td>300</td>
<td>300</td>
<td>350</td>
</tr>
<tr>
<td>350</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

> AVERAGED RESOLUTION = 322.22 [TV lines]

http://www.advanced-pdp.jp/
Moving picture resolution - problems

• Contrast sensitivity function depends on scroll-speed
  • Subjective validation at a single speed not sufficient
• Does 5-6 deg/s represent real content?
• Eye-movement amplitude much smaller on mobile displays; 4” @ 400 mm => 761x428 @ 30 cpd
• Are 3x3 grey levels sufficient and on what grounds are they chosen?
Campbell-Robson Chart
Contrast sensitivity function (CSF)

Shows the minimum perceivable contrast as a function of image detail.

Yields:

• Contrast necessary to display an image of given detail

or

• Maximum perceivable detail at a given lightness contrast
Motion and resolution

- Images have lower contrast and spatial frequency content compared to text
- Motion-dependence of contrast sensitivity function (CSF)


Johan Bergquist - Resolution and contrast in mobile displays
Example: Mobile Display

- Assumptions:
  - Viewing distance: 400 mm
  - 3” display: FOV=9.5°
  - Object motion speed: 2° s⁻¹
  - Maximum contrast limit of CSF

- Static CSF: 30 cycles/degree
  (437 PPI @ 400 mm)

- For motion at 2 deg/s, the max resolution becomes 10 cycles/degree
  (146 PPI @ 400 mm)

- Conclusion: >150 PPI is not necessary for video

Motion-dependent CSF model
0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64, 128 ° s⁻¹
Conclusions

- Motion blur most pronounced display-induced artefact
- Blur-reduction could lead to ringing
- Temporal subfield modulation causes spatio-temporal artefacts
- Field-sequential colour attractive but colour break-up is a challenge for large FOV displays
- Correlation between objective and subjective measurements good for blur
- Verification of metrics by subjective experiments are lacking
- Video-only mobile displays do not need more than 150-160 PPI