— *Solution notes* —

COMPUTER SCIENCE TRIPOS Part II – 2021/2022 – Paper 10

1 Advanced Graphics and Image Processing (rkm38)

Answer ALL questions below.

Tone mapping

(*a*) You are asked to design a custom tone mapping for an outdoor mini-LED display. You can control the peak luminance of the display in the range from 100 cd/m^2 to 1000 cd/m^2. The LEDs do not emit any light when set to 0 intensity. The reflectivity of the display is k=1%. The display is equipped with a light sensor measuring ambient illuminance E in the units of lux.

(*i*) Write a formula for controlling the peak luminance of the display as the function of ambient illuminance E so that the display shows at least 8 stops of the effective dynamic range or it operates at it is maximum peak luminance. Note that the reflected luminance can be approximated by $L_{\text{refl}} = k\frac{E}{\pi}$. [8 marks]

Answer: The dynamic range of the display in stops can be computed as:

$$r = \log_2\left(\frac{L_p}{k\frac{E}{\pi}}\right), \tag{1}$$

where L_p is the peak luminance of the display and $k = 0.01$. Hence,

$$\hat{L}_p(E) = 2^8\, k\, \frac{E}{\pi} \tag{2}$$

for the display with the unrestricted luminance range and

$$L_p(E) = \min\left\{1000, \max\{100, \hat{L}_p(E)\}\right\} \tag{3}$$

for the given display.

(*ii*) Suggest an algorithm for computing the tone curve for the display and justify your choice. You do not need to explain the algorithm in detail or give the formula, but you need to briefly analyze its strength and weaknesses. [7 marks]

Answer: The answer could suggest either CLAHE or a sigmoidal tone curve. For CLAHE:

Strengths: Can adapt to image content; can enhance contrast without boosting it too much, low computational cost.

Weaknesses: requires computing image histogram (reduction operation may be problematic if hardware implementation is needed); the tone curve can change rapidly between the frames, which will result in flicker. To avoid flicker, the tone curve will need to be filtered over time.

(*iii*) The tone-curve from the previous question is expressed with the function $L_{\text{out}}(x, y) = t(L_{\text{in}}(x, y), r_{\text{dst}})$, where r_{dst} is the target dynamic range in stops, $L_{\text{in}}(x,y)$ and $L_{\text{out}}(x,y)$ are the input and output colour values in the linear space, both normalized so that the maximum value is 1.

Write the formula for the final, display-encoded pixel value, which compensates for the ambient light reflection. Assume that the display expects gamma-encoded values with $\gamma = 2.2$. [7 marks]

Answer:

$$L'(x,y) = \left(t(L_{\text{in}}(x,y), r_{\text{dst}}) - \frac{L_{\text{refl}}}{L_p(E)} \right)^{1/\gamma} \tag{4}$$

where $L_{\text{refl}} = k \, \frac{E}{\pi}$ and $L_p(E)$ was provided in the first answer.

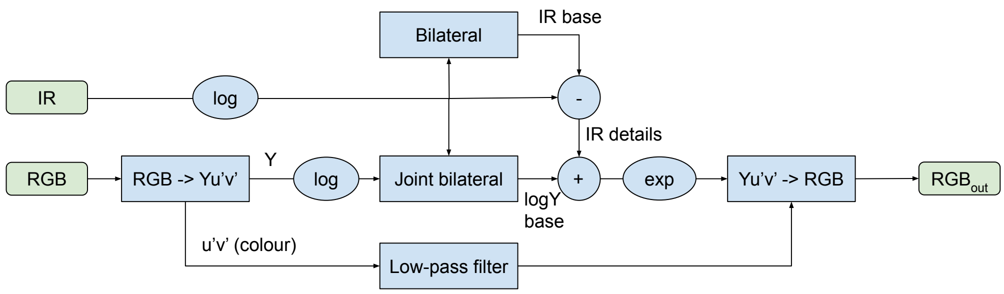
Advanced image processing

(*b*) You are building a new type of camera that captures at the same time RGB colour channels and an infrared (IR) channel. The camera is meant to capture the video of scenes that are dimly lit with visible light but well illuminated with IR light. Such a camera could be used, for example, to capture live performance in the evening on a scene that is illuminated with (dark) IR light. Propose a method for fusing RGB and IR colour channels so that the resulting image has the same appearance as the RGB image but with reduced noise and increased sharpness. The input to your method are RGB and IR images, both in linear colour space. Use advanced image filters for that purpose.

Illustrate your method with a diagram and a concise description of the processing steps. Briefly justify the relevance of each step. There is no need to write the equations for the filters unless they help to clarify the explanation. The frames captured by the camera and the resulting fused frames are in the linear colour space (there is no need for tone mapping and display encoding). [28 marks]

Answer: This is an open-ended question and the answers can vary. This problem is similar to the flash/no-flash photography problem discussed in the Advanced Image Processing lecture and the student should be able to draw an analogy. The points are awarded for well-justified use of the techniques learned in the course, such as joint-bilateral filter, chroma/luma channel decomposition, base-detail decomposition and using the logarithmic space for perceptual uniformity.

One of the solutions may involve processing diagram as shown below:



The RGB image is decomposed into luminance (Y) and chrominance (u'v') channels. Because HVS is not sensitive to the loss of high frequencies in chrominance (HVS lecture), chrominance channels can be low-pass filtered to reduce noise. The luminance and IR channels are transformed to the log domain for improved perceptual uniformity (to account for Weber's law). Then, a joint (cross) bilateral filter is used to filter noisy luminance while avoiding blurring across the edges found in the IR image. This gives us a log-luminance channel that has reduced noise but may lack details. The details are added from the IR image, using the base-detail separation produced with a bilateral filter. The resulting log-luminance channel is converted back to the linear domain (exp) and colours are introduced by the inverse Yu'v' to RGB transform.

The student can also note that the edges found in the IR image may not correspond to the edges in the visible image. Therefore adding details from the IR may introduce the details that are not normally present in the visible spectrum. The edges may also have different characteristics (polarity) than the edges found in the luminance image. This kind of problem is typically solved by renormalizing the IR image using the RGB image (10.1109/TIP.2007.894236) but the technique is out of the scope of this course.

This problem could be also formulated in the gradient domain.

Marking guidelines:

- Use of joint-bilateral filter — 8
- Base-detail decomposition — 8
- Luminance-chroma decomposition and the low-pass on chroma — 4
- Log domain — 4
- The quality of the presentation — 4
- Points halved if the processing step is poorly explained or not justified
- Extra points could be awarded for well justified ideas outside the proposed solution, but the total cannot exceed the full mark for this question.
