Photo Response Non Uniformity (PRNU) of image sensors for camera identification
Summary

• Camera identification in MM-F

• Image sensor imperfections and noise

• Photo Response Non Uniformity (PRNU)

• PRNU estimation

• PRNU for applications
Before taking a digital content as evidence, its **trustworthiness** should be verified!

Any acquisition and processing step leaves some traces on the digital data, detectable although imperceptible.
Source identification

Like a gun on the bullet, the acquisition devices leave distinctive traces on the acquired content.

Analyzing the digital footprints left by the acquisition process, it is possible to:

• distinguish if the content is real or computer generated
• distinguish between different devices (camera, scanner, etc.)
• distinguish which camera captured the image: Camera identification
Source identification

What kind of footprints?

- **Statistical and physical properties**: statistical and geometrical features, color distribution, edge, textures…

- **Color Filter Arrays and Interpolation**: *scanners* detect all three colors at each pixel, *cameras* only detect one color at each pixel and the remaining 2 colors are estimated using interpolation algorithms

- **Sensor Noise**: inherent in any electronic device
Camera identification

We look at the footprints left by the **imaging sensor** (Sensor Noise)
**Image acquisition cycle**

Scene light is focused by the lenses on a 2D array of CCD/CMOS sensors.

Photons hitting CCD/CMOS are converted into voltage signals and then sampled by an A/D converter.
Charged Couple Device (CCD) image sensor

Typically, a digital camera has a 2D array of **several million CCDs**, each of which is responsible for the acquisition of a single pixel.

A CDD is often exemplified as a **bucket collecting rain** (photons) until a certain level (the pixel value) is reached.
CCD sensor imperfections

- **Ideally**, when uniform light falls on a camera sensor, each pixel should output exactly the same value......

- **Practically**, small variations in cell size and substrate material result in slightly different output values

- Thus, some noise is introduced into the image. Such noise has 2 components:
  - Fixed Pattern Noise (FPN)
  - Photo Response Non Uniformity (PRNU)
Sensor imperfections: FPN

- The FPN is the pixel to pixel difference **when sensor is not exposed to light**
- In most digital cameras this difference is **equalized by subtracting a dark frame** (mask) from the picture
Sensor imperfections: PRNU

- PRNU is caused by the different sensitivity of the sensors to light
- Due to the manufacturing process
  - Does not depend on temperature and time

If we capture this noise pattern, we can create a distinctive link between a camera and its photos.
**PRNU fingerprint model**

A digital image $I$ taken from camera $C$ can be modeled as

$$I = I^{(0)} + I^{(0)}K + \Theta$$

Where:

- $I^{(0)}$ is the sensor output in the absence of noise
- $K$ is the **PRNU fingerprint** of camera $C$
- $\Theta$ represents all the other noise terms (shot, readout, etc.)

**OSS:** The PRNU pattern noise is a **multiplicative noise**
PRNU fingerprint estimation (1/3)

For any digital image $I$ and a denosing filter $F$, we get the denoised image

$$\hat{I}^{(0)} = F(I)$$

- $\hat{I}^{(0)} = I^{(0)}$ means ideal denoising:

- The **noise residual** of $I$ is defined as:

$$W_I = I - \hat{I}^{(0)}$$

$$= IK + I^{(0)} - \hat{I}^{(0)} + (I^{(0)} - I)K + \Theta$$

$$= IK + \sum$$

Where $\sum$ are noise contributions independent of $K I$
PRNU fingerprint estimation (2/3)

Let $I_1, I_2, \ldots, I_N$ be a set of images acquired by a same camera $C$

Let $W^{(1)}, W^{(2)}, \ldots, W^{(N)}$ be their noise residuals (from a certain filter $F$)

When $\sum^{(i)}$ is modeled as an i.i.d. Gaussian, the maximum likelihood estimator of the PRNU fingerprint of $C$ has the form:

$$\hat{K} = \frac{\sum_{i=1}^{N} W^{(i)} I^{(i)}}{\sum_{i=1}^{N} (I^{(i)})^2}$$
PRNU fingerprint estimation (3/3)

For getting a **good** estimate $\hat{K}$ of the PRNU fingerprint $K$

- the estimation is done on **flat-field images** (uniform content, low variance)
- The luminance of the images should be as high as possible but not saturated ($I^{(i)}(k) \approx 255$)
- About 20 **flat field** (**bright**) images suffice to have a good estimate of $K$

Now that we have an estimate of the PRNU fingerprint for camera C we can use it for testing purposes……
PRNU fingerprint detection

Let $J$ be an input image (from the same camera $C$ or another one).

The presence of $K$ in $J$ can be determined by means of the correlation detector

$$\rho = \text{corr}(W_J, \hat{K}J)$$

where:

$$\text{corr}(X, Y) = \frac{(X - \overline{X}) \cdot (Y - \overline{Y})}{||X - \overline{X}|| \ ||Y - \overline{Y}||}$$

$$X \cdot Y = \sum_{i,j} X[i,j]Y[i,j]$$

$$||X|| = \sqrt{X \cdot X}$$

High when $J$ was acquired by camera $C$ with PRNU fingerprint $K$, low otherwise.
PRNU correlation test

From which camera the test image comes from?

The PRNU of the tested image is correlated with each camera’s reference PRNU pattern. The camera with the highest correlation is the one that acquired the image.
Application: camera identification (device)

PRNU can be used to identify the type of the device that acquired an image

- Which device?
Application: camera identification (brand)

PRNU can be used to distinguish between devices of the same brand

- Which iPhone?
Applications: camera identification (model)

It is possible to distinguish even among identical models!

- Which iPhone 4?
Olympus C3030 vs other models (JPEG)
Canon G2 vs other models (uncompressed)
Applications: video camera identification

Extension to video device identification is straightforward

- Videos are sequences of images (frames), usually 24/30/50/60 per second
- PRNU can be estimated on flat-field video sequences (e.g. blank walls)
Computing image residuals: old filters

\[ W_I = I - F(I) \]

• Gaussian smoothing, 2D-Wiener …

• Advantages
  o Simple implementation
  o Very fast

• Disadvantages
  o Image content left behind in the pattern alters the correlation between reference PRNU and the residual of the image under analysis
Computing image residuals: new filters

\[ W_I = I - F(I) \]

- **Wavelet based denoising**

- **Advantages**
  - Significantly more accurate
  - Better PRNU fingerprint estimation

- **Disadvantages**
  - Slower
  - Higher complexity
Other application: tampering detection (1/3)

*Cut & Paste* is a common way to alter the semantic meaning of an image

- A portion of a different image is selected and copied on the to-be-modifed image
- Used to remove or add content to an image
Other application: tampering detection (2/3)

The source PRNU “behind” the visual content is also copied and pasted on the tampered image

- By looking for local *statistical inconsistencies* of the PRNU of the tampered image, it is possible to reveal the manipulation.
Applications: tampering detection (3/3)

Cut & paste detection in a nutshell

- The image is divided into blocks (overlapping or not) that are analysed separately
- Each block is labelled as “tampered” or “original”, leading to a tampering map

Tampered image

Tampering map