Invisible Geo-Location Signature in a Single Image

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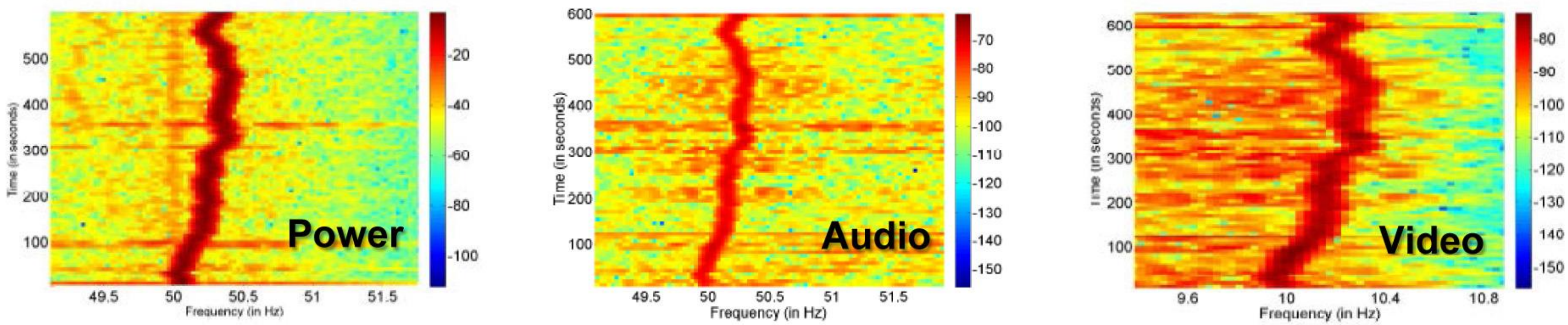
Importance of Geo-Tagging

- U.S. & U.N. estimate in every year
  - over 300,000 U.S. children are sexually exploited, and
  - about a million children are forced into prostitution worldwide.
- Geo-tagging of multimedia data is important to law enforcement, national security, journalism, etc.
- Location information such as GPS stored as metadata can be easily tampered.
- Visible terrains, landmark based visual clues (FINDER program of IARPA): may not suit for indoor images.

Environmental Signature by Power Network

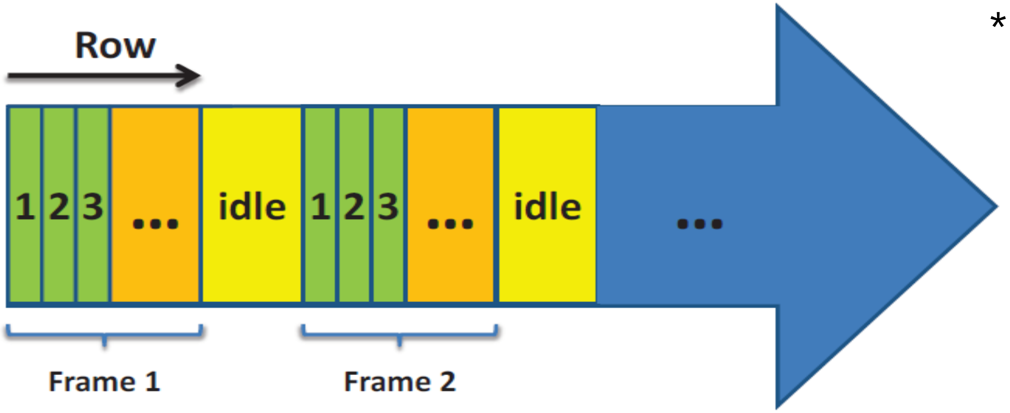
- The power supply frequency has a nominal value of 60 Hz (most of Americas), or 50 Hz (rest of the world).
- Instantaneous frequency fluctuates due to supply-demand changes. This change over time is defined as the ***Electric Network Frequency (ENF) signal***.
- Inherently recorded in a sensing stream: audio and video. Variations tend to be very similar at different points in the same grid. Good for time-location identification.



R. Garg, A. L. Varna, and M. Wu. ‘Seeing’ ENF: Natural time stamp for digital video via optical sensing and signal processing. In Proceedings of the ACM International Conference on Multimedia, pages 23–32, 2011.

Image as a Temporal Signal

- Geo-tagging using ENF signal thus far requires hosting signal to be temporal in nature: audio or video.
- ENF signals can be embedded in images via ***rolling-shutter mechanism***



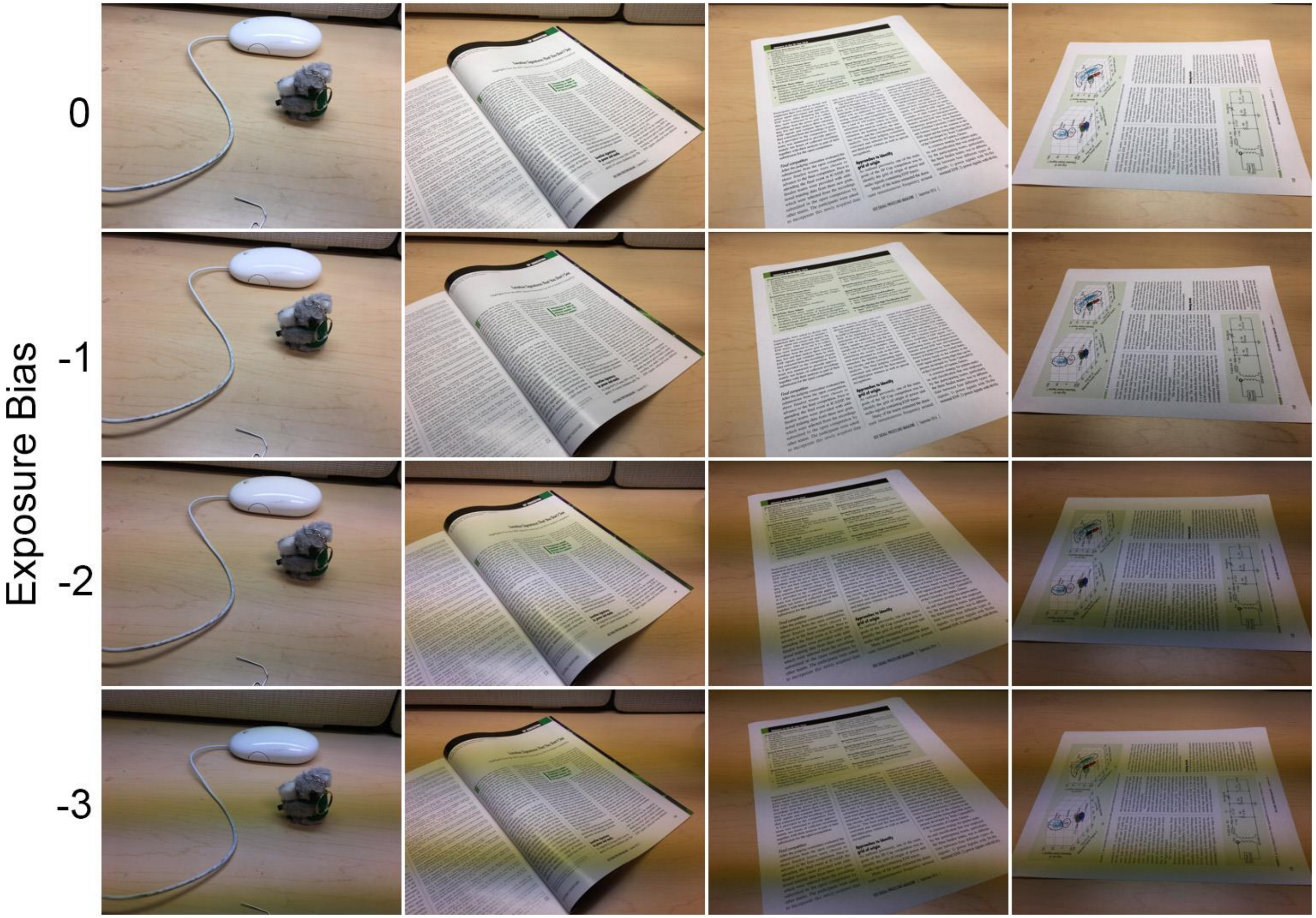
Each row are ***sequentially*** sampled/exposed, followed by an idle period before proceeding to the next frame.

* H. Su, A. Hajj-Ahmad, R. Garg, and M. Wu, "Exploiting rolling shutter for ENF signal extraction from video," in IEEE International Conference on Image Processing, Oct. 2014, pp. 5367–5371.

Challenge of Geo-Tagging Using ENF From Images

- Research questions:
  - Can ENF signals be detected in single still images?
  - Can we differentiate images captured at a 50 Hz or 60 Hz region?
  - Can we locate further within the region?
- Our proposed method exploits:
  - The parametric form of ENF signal.
  - A predictable increase in a statistic of the image before and after ENF embedding.
- Model ENF-containing images as visual content + ENF signal:

$$m[i,j] = m_0[i,j] + e[j]$$

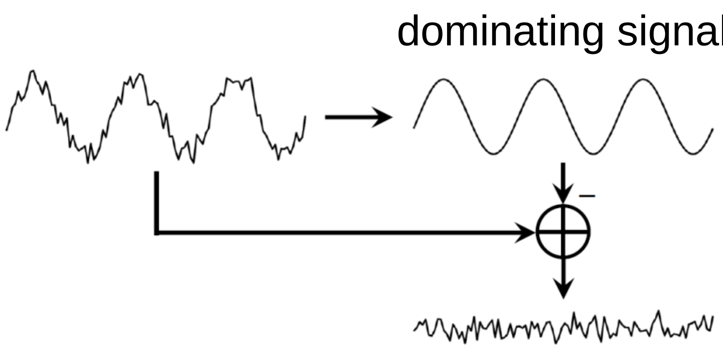


Time-domain ENF signal variation along the row index i :

$$e[i] = \cos\left(2\pi f_{\text{ENF}} \cdot (iT_{\text{row}}) + \phi_0\right)$$
$$= \cos\left(2\pi \frac{f_{\text{ENF}}}{f_{\text{row}}} \cdot i + \phi_0\right), \quad f_{\text{ENF}} \in \{100, 120\}\ \text{Hz}$$

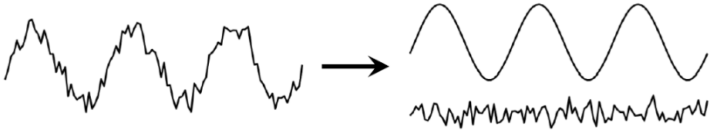
Micro Signal Extraction Strategies

- **Residue based:**
  - ENF from video [Su *et al.,* 2014]
  - Heart rate from video [Zhu *et al*., 2017]
  - Unique surface for authentication [Wong et al., 2015]



- **Property based:**
  - ENF from audio [Garg *et al*., 2011]
  - ENF from image (this work)

- **Statistical source separation:**
  - Heart rate from video, rest case [Poh *et al*., 2010]
  - ENF from image (limited performance, discussed in the next slide)



Statistical Signal Separation

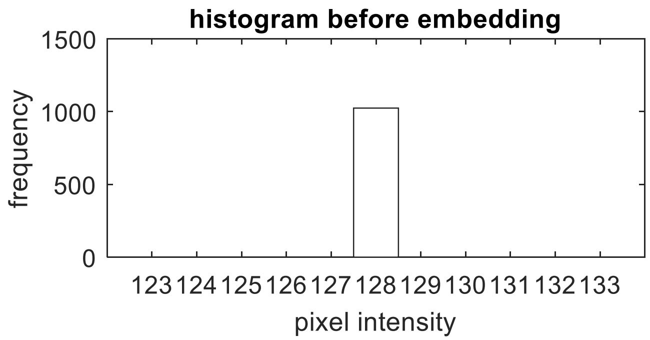
- Intuitive approach using *independent component analysis (ICA)*:

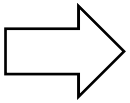
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} x_{\text{img\_content}} \\ x_{\text{ENF}} \\ x_{\text{other}} \end{bmatrix}$$

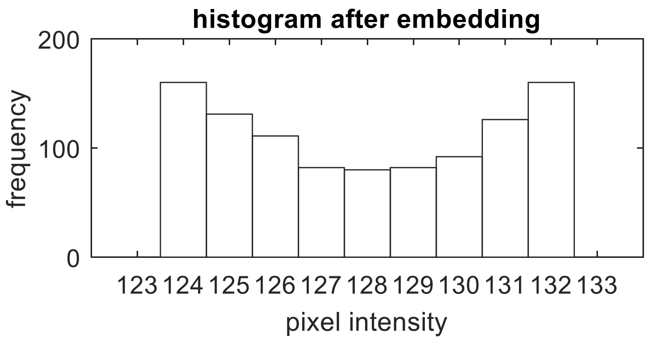
- Drawbacks (all in modeling assumptions):
  - Ignored the parametric form of ENF signal (sinusoid-like).
  - Treated time-series data points as i.i.d. observations.
  - Assumed simple probabilistic sources, but image content and ENF component are hierarchically random.

Entropy Impact by ENF Embedding

- Intuition: constant signals corrupted by sinusoid signals, histograms become more spread → entropy increased.

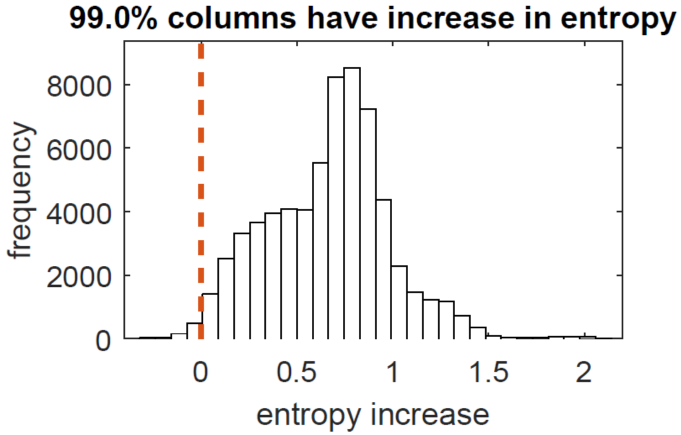






- Can prove for image columns with linear change in intensity values, similar statistical behavior exists.

- Simulation on real image data:

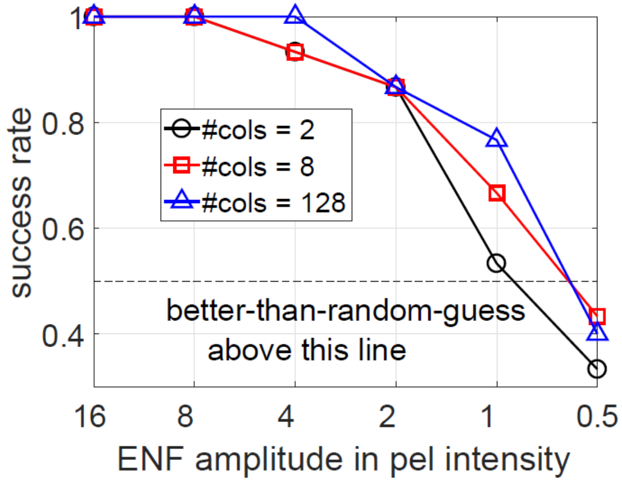


Proposed Method Using Entropy Minimization

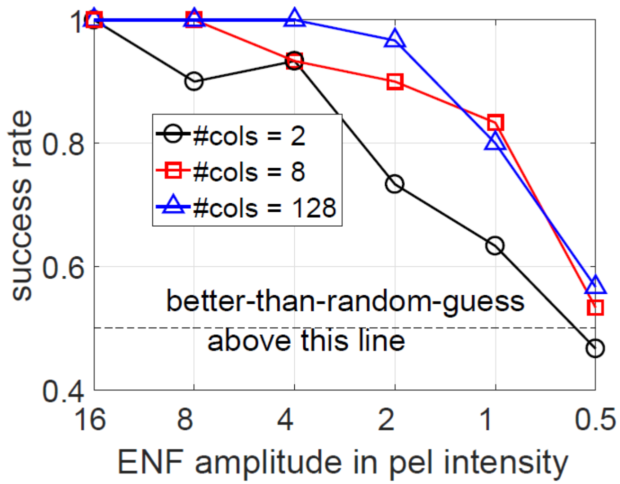
- Images contain a lot of near-constant intensity regions.
- Strategy: find a parametric surface that minimize the total entropy of independent image columns.
- Proposed *Entropy Minimization* method:
  - Cost function: total entropy of histograms of K selected columns of a residue image.
  - Residue image is obtained by subtracting an ENF surface parametrized by (A, f, ϕ_0) from ENF-containing image.
  - Decide between f = 50 Hz & 60 Hz by the one leads to lower entropy. Need to search for the best nuisance parameters (A, ϕ_0). The cost function with f fixed is empirically convex over (A, ϕ_0).

Results with Simulated ENF Signals

60 Hz



50 Hz



Success rates for deciding images with 60 Hz and 50 Hz ENF as a function of the ENF strength and the number of columns, *K,* used in the cost function.

Exp. Conditions: Test images generated by adding sinusoid signals with random initial phases to native images.

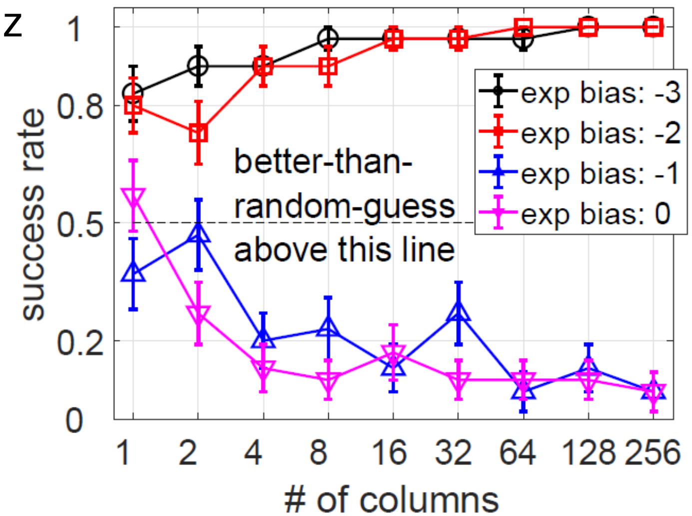
Differentiating images captured in 50 vs 60 Hz regions: ENF signal strength ↑ → Performance ↑

When ENF amplitude drops to 0.5 and 1 (out of 256 shades of gray) → detection reduced to random guess.

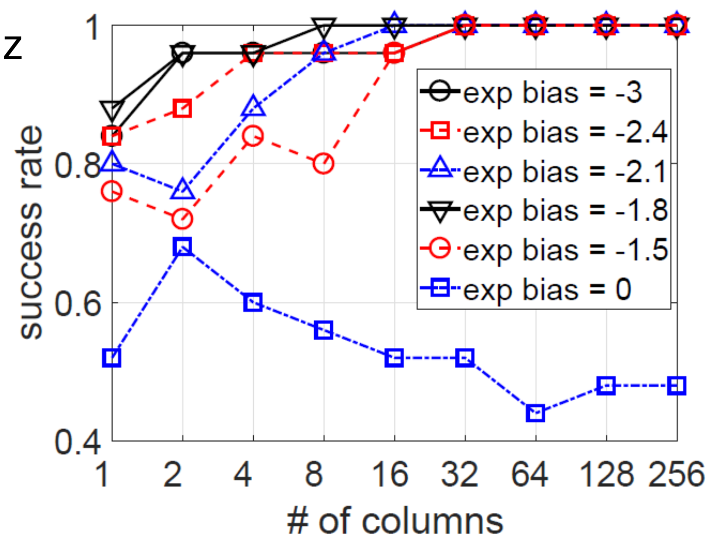
Effectiveness of the proposed algorithm confirmed by simulated data.

Results on Real Rolling Shutter Images

60 Hz



50 Hz



Exp. Conditions:

- Real-world images captured indoor by smartphone cameras.
- Exposure bias controls the amplitude of embedding ENF signal.

8+ columns needed for robust detection. Start to fail when bias reduces to −1 or ENF amplitude reduces to 10.

Gap needs to be closed between results on simulated and real images.

Multiplicative model is good when no global intensity bias per our theoretical analysis. Experimental results show additive model performs better.

Conclusions

- Explored an invisible power signature in rolling shutter images for geo-tagging purposes.
- Addressed a challenging question of identifying embedded ENF signals in images. Proposed the entropy minimization method.
- The proposed method is able to make accurate decisions for images with synthetically added ENF signals.
- Demonstrated invisible power traces can help narrow down the capturing geographic region of an image.