



#### Journée industrielle du LabEx PRIMES

# SINGLE-PIXEL CAMERA

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> > September 13th, 2017





#### **OPTICAL SETUP**



- Spatial light modulator: spatial filtering of the image
- Measurements: projections of the image on the SLM patterns

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# CONCEPT



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Single-pixel camera	Possible applications 00	Conclusic O
CONCEPT		
	P <sub>1</sub> . Pattern design	

- P<sub>2</sub>. Image restoration
- Problem *P*<sub>1</sub>: how to choose the SLM patterns?
- Problem P<sub>2</sub>: how to restore the image from the measurements?

Compressive sensing paradigm<sup>1,2</sup>

- P<sub>1</sub>. Few random patterns (i.e., measures) ©
- P<sub>2</sub>. Slow  $\ell_1$ -minimization  $\odot$



Example of a random pattern

<sup>1</sup> Donoho, IEEE Transactions on Information Theory, 52, 2006 <sup>2</sup> Duarte et al., IEEE Signal Processing Magazine, 25, 2008

Compressive sensing paradigm<sup>1,2</sup>

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- P<sub>2</sub>. Slow ℓ<sub>1</sub>-minimization ☺

Adaptive basis scan in the wavelet domain<sup>3,4</sup>

- P1. Few wavelet patterns ©
- P2. Fast inverse wavelet transform ©



Example of a random pattern



Example of a wavelet pattern

<sup>&</sup>lt;sup>1</sup> Donoho, IEEE Transactions on Information Theory, 52, 2006

<sup>&</sup>lt;sup>2</sup>Duarte et al., IEEE Signal Processing Magazine, 25, 2008

<sup>&</sup>lt;sup>3</sup>Dai et al., Applied Optics, 53, 2014

<sup>&</sup>lt;sup>4</sup>Rousset et al., IEEE Transactions on Computational Imaging, 3, 2017

Experimental limitations in single-pixel imaging

- Impossible implementation of patterns with negative elements
- Biased measurement due to dark current at the detector

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- Impossible implementation of patterns with negative elements
- Biased measurement due to dark current at the detector
- $\rightarrow$  Pattern generalization technique<sup>5,6</sup>



<sup>5</sup>Rousset et al., FR Patent 1751515, filed the 02.24.17

<sup>6</sup>Rousset et al., IEEE Transactions on Computational Imaging, submitted

#### ULTRAVIOLET AND INFRARED IMAGING

Single-pixel detectors vs array of sensors (CCD/CMOS)

- Better efficiency
- Low cost outside the visible domain

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- Low cost outside the visible domain

 $\rightarrow$  Ultraviolet and infrared imaging (e.g. gas leak detection^7) possible with high quality single sensors



Object with amount of gas trapped inside each cell (left) and its SPC recovered image<sup>7</sup> (right)

<sup>&</sup>lt;sup>7</sup>Gibson et al., Optics Express, 25, 2017

#### MULTI-DIMENSIONAL IMAGING

Single-pixel detector can be changed for

- $\bullet$  A photon counting board  $\rightarrow$  temporal information
- A spectrometer  $\rightarrow$  spectral information

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- A photon counting board  $\rightarrow$  temporal information
- A spectrometer  $\rightarrow$  spectral information

 $\rightarrow$  Low-cost multispectral/hyperspectral and time-resolved systems (e.g. fluorescence lifetime sensing^8)



Stack of time images<sup>8</sup> (left) and spectral images (right, Wikipedia)

<sup>&</sup>lt;sup>8</sup>Rousset et al., Proceedings of SPIE, 10070, 2017

### SINGLE-PIXEL IMAGING

Active topic in the last years

- Many patents: Rice University<sup>9</sup>, Xerox<sup>10</sup>, Google<sup>11</sup>
- Increasing number of publications/research groups

<sup>&</sup>lt;sup>9</sup>US Patent 8199244, Rice University, 2010

<sup>&</sup>lt;sup>10</sup>US Patent 9188785 and 9253420, Xerox Corp., 2013

<sup>&</sup>lt;sup>11</sup>US Patent 9071739, Google Inc., 2014

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Possible improvements/future work

- Speed of acquisition (hardware and software)
- Video imaging
- High resolution imaging
- Machine learning

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### REMOTE IMAGING

Acquisition on a single pixel = hardware compression

- Small storage unit
- Low electricity consumption

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- Small storage unit
- Low electricity consumption

 $\rightarrow$  Remote imaging (e.g. aerospace remote imaging^{12}) for which the data transmission rate is low



Original image (left) and SPC recovered image with 25% of measurements<sup>12</sup> (right)

<sup>&</sup>lt;sup>12</sup>Ma et al., IEEE Geoscience and Remote Sensing Letters, 6, 2009