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Time-resolved wavelet-based acquisitions using a single pixel camera

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Overview

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4 – State of the art

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1 – Experimental setup
2 – Wavelet decomposition
3 – ABS-WP strategy
4 – Extension to TR measurements

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1 – Temporal resolution
2 – Application to FLIM
3 – Multispectral TR measurements

Conclusion
Introduction > 1 – Single pixel camera

- **Spatial modulator**: SLM, LCD, **DMD** (Digital Micro-mirror Device)

- **DMD**: array mirrors that can *independently* be tilted in two states

**Single-pixel camera (SPC)  Two mirrors of 13.7 µm (Texas Instruments)**

![Image of Digital micro-mirror device (DMD)](image-url)
Multi-dimensional acquisitions $\rightarrow$ management of huge datasets

Single pixel camera (SPC) $\rightarrow$ partial compression at the hardware level
- Infrared or multispectral imaging [Edgar et al., Scientific Reports, 5, 2015]
- Low cost time-resolved system [Pian et al., Biomedical Optics, 2016]

COUPLE COMPRESSION TECHNIQUES (SOFTWARE LEVEL) WITH THE SPC (HARDWARE LEVEL)
Introduction > 3 – Problem

Image of size $N \times N$: $f$

$I$ patterns of size $N \times N$: $p_i$

$\Rightarrow I$ measurements: $m_i = f^T p_i$

- Sequential measurements $m_i$ for different patterns $p_i$

- **Problems**
  
  - P1 – Choice / design of the patterns $p_i$
  
  - P2 – Restoration of the image $f$ from the measures $m_i$ knowing $p_i$
Compressive sensing \cite{Duarte2008}

- P1 – Random ±1 Bernoulli variables
- P2 – Restoration by $l_1$-minimization

Random pattern
Introduction > 4 – State of the art

➢ Compressive sensing [Duarte et al., IEEE SPM, 25, 2008]
  • P1 – Random ±1 Bernoulli variables 😊
  • P2 – Restoration by $l_1$-minimization 😞

➢ Basis scan [Zhang et al., Nature Comm., 6, 2015]
  • P1 – $N^2$ patterns in a basis (Hadamard, Fourier, etc.) 😞
  • P2 – Chosen basis inverse transform 😊
Compressive sensing \cite{Duarte et al., IEEE SPM, 25, 2008}

- P1 – Random ±1 Bernoulli variables 😊
- P2 – Restoration by $l_1$-minimization 😞

Basis scan \cite{Zhang et al., Nature Comm., 6, 2015}

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Adaptive basis scan \cite{Dai et al., Applied Optics, 53 (29), 2014}

- P1 – $I << N^2$ patterns in a chosen basis 😊
- P2 – Chosen basis inverse transform 😊

→ Prediction of the $I$ patterns based on previous measures
Compressive sensing [Duarte et al., IEEE SPM, 25, 2008]
- P1 – Random ±1 Bernoulli variables ☹
- P2 – Restoration by $l_1$-minimization ☹

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Materials and methods > 1 – Experimental setup

Photon counting board (SPC-630, Becker & Hickl GmbH)

PMT

Fluorophores absorbing light at $\lambda_{\text{abs}}$ and emitting at $\lambda_{\text{em}}$

Supercontinuum pulsed white laser (SuperK Extreme EXW-12, NKT Photonics)

Tunable wavelength filter (SuperK Select)

HPM-100-50, Becker & Hickl GmbH

$T = 4096$ time channels

$m_{i,t} \quad t \in [1, T]$

$I$ patterns $p_i$

1024×768 DMD (DLP7000-V7001, Vialux)
Adaptive approach in the wavelet domain

One wavelet coefficient: \[ c = f^T p \] \iff one SPC measurement

Non-linear approximation: retains a percentage of the strongest wavelet coefficients and shows excellent image recovery [Mallat, Academic Press, 2008]

Ground truth 512 x 512 image

4-level wavelet decomposition 512 x 512
Materials and methods > 2 – Wavelet decomposition

- **Adaptive** approach in the wavelet domain

- One wavelet coefficient: \( c = f^T p \) ↔ one SPC measurement

- **Non-linear approximation**: retains a percentage of the strongest wavelet coefficients and shows excellent image recovery [Mallat, Academic Press, 2008]

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*Ground truth 512 x 512 image*

*10% of the strongest coefficients*
Materials and methods > 2 – Wavelet decomposition

- **Adaptive** approach in the wavelet domain

- One wavelet coefficient: \[ c = f^T p \] \( \iff \) one SPC measurement

- **Non-linear approximation**: retains a percentage of the **strongest wavelet coefficients** and shows excellent image recovery [Mallat, Academic Press, 2008]

![Ground truth 512 x 512 image](image1)

![Restored image with 10% of the coefficients](image2)
Materials and methods > 3 – ABS-WP strategy

- **ABS-WP**: Adaptive Basis Scan by Wavelet Prediction [Rousset et al., IEEE TCI, in press, 2017]

- **Multiresolution** approach: non-linear approximation idea applied on each of the \( j = 1 \ldots J \) scales of the \( J \)-level wavelet decomposition

- **Steps**: example for a 128 x 128 pixel image for \( J = 1 \)
ABS-WP: Adaptive Basis Scan by Wavelet Prediction [Rousset et al., IEEE TCI, in press, 2017]

Multiresolution approach: non-linear approximation idea applied on each of the $j = 1 \ldots J$ scales of the $J$-level wavelet decomposition

Steps: example for a 128 x 128 pixel image for $J = 1$

1 – Approximation image acquisition
Materials and methods > 3 – ABS-WP strategy

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- **Steps**: example for a 128 x 128 pixel image for \(J = 1\)
  1. Approximation image acquisition
  2. Over-sampling by a factor 2 by a bi-cubic interpolation
**Materials and methods > 3 – ABS-WP strategy**

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1 – Approximation image acquisition
2 – Over-sampling by a factor 2 by a bi-cubic interpolation
3 – 1-level wavelet transform
4 – A percentage $p_j$ of the strongest detail wavelet coefficients is retained
5 – The “predicted” significant coefficients are experimentally acquired
**Materials and methods > 3 – ABS-WP strategy**

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  4. A percentage \( p_j \) of the strongest detail wavelet coefficients is retained
  5. The “predicted” significant coefficients are experimentally acquired

- Set of percentages \( \mathcal{P} = \{p_J, ..., p_1\} \) to control the compression rate (CR)
Materials and methods > 4 – Extension to TR measurements

- N×N single image $f \rightarrow$ 2D+t stack of $T$ images $f_1, \ldots, f_T$ of size N×N

- Vector of time measurements directly obtained by the TR-SPC

$$m_i^\top = p_i^\top F_{1\ldots T}$$

- Prediction performed on the continuous-wave (CW) measures

$$m_i = \sum_{t=1}^{T} m_{i,t}$$
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Results > 1 – Temporal resolution

- Cuvettes with different solutions of dyes (Coumarin 540A or DCM) in ethanol
  - Laser
  - C540A
  - DCM
  - Mirror
  - 8.5 cm
  - 2 cm
  - 1.2 cm
  - 4 cm

- Illumination: wavelengths ranging from 455 to 485 nm with a 5 nm step
  - \( \lambda_{\text{abs}} = 422 \text{ nm} \)
  - \( \lambda_{\text{em}} = 532 \text{ nm} \)
  - \( \lambda_{\text{abs}} = 468 \text{ nm} \)
  - \( \lambda_{\text{em}} = 624 \text{ nm} \)

- Detection: long-pass filter at 500 nm (FEL0500, ThorLabs)
High temporal resolution with a minimum of 3.05 ps per time channel

In practice → binning of the time channels to reduce the noise influence

Acquisition of the cuvettes with a binning of 10 (30.05 ps per time channel):

\[ t \approx 10 \text{ (frames)} \times 30.05 \text{ ps} \]

\[ \Rightarrow d = c \times t \approx 9 \text{ cm} \]

Ability to detect the laser beam travelling at the speed of light
Results > 2 – Application to FLIM

- Phantom with different fluorophores

Red autofluorescent plastic slide (CHROMA):
  \( \lambda_{\text{abs}} = 520 \text{ nm} \)
  \( \lambda_{\text{em}} = 625 \text{ nm} \)

Solution of DCM in ethanol:
  \( \lambda_{\text{abs}} = 468 \text{ nm} \)
  \( \lambda_{\text{em}} = 624 \text{ nm} \)

Green autofluorescent plastic slide (CHROMA):
  \( \lambda_{\text{abs}} = 464 \text{ nm} \)
  \( \lambda_{\text{em}} = 525 \text{ nm} \)

- Illumination: 455 to 485 nm with a 5 nm step

- Detection: long-pass filter at 500 nm (FEL0500, ThorLabs)

- \( T = 72 \) time channels: 0 to 21.66 ns (0.305 ns time step)
Results > 2 – Application to FLIM

- Total of 72 images of size 64×64 acquired and restored with ABS-WP using Daubechies wavelet (Db5) with a CR of 93%:

- Fluorescence decay

\[ I(t) = Ae^{-\frac{t}{\tau}} \]

Time curves

- SPC recovered stack
- Fluorescence decay

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Results > 2 – Application to FLIM

- $I(t) = Ae^{-\frac{t}{\tau}}$ depicted by experimental curves $\hat{I}(t)$ for each pixel of the image

- Fitting of the model for each pixel $\rightarrow$ amplitude and lifetime maps

$$(A^*, \tau^*) = \arg\min ||\hat{I}(t) - Ae^{-\frac{t}{\tau}}||^2_2$$

Amplitude (photons)  Lifetime (ns)
Results > 3 – Multispectral TR measurements

- New experimental setup: addition of a grating with $\Lambda = 16$ parallel detectors (PML-16-1, Becker & Hickl GmbH) $\rightarrow$ possibility to obtain $\Lambda \times T$ images

- Images obtained with ABS-WP with the same parameters:

- Ability to discern the 3 fluorophores using the time and spectral information

$CW$ image for $\lambda = 525$ nm

$CW$ image for $\lambda = 625$ nm
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Conclusion

- Proposed system to acquire $2D + t + \lambda$ images by a SPC:
  - Adaptive technique
  - Wavelet patterns
  - Bi-cubic interpolation prediction
  - Multiresolution approach

- Faster than CS for equivalent image quality [Rousset et al., IEEE TCI, in press, 2017]

- Efficient yet low cost (multispectral) time-resolved system, transposable on a microscope

- Perspectives
  - Investigate prediction based only in certain time channels
  - Method to divide the acquisition time by 2
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Wavelet pattern creation

- We note $W$ an orthonormal operator so that one wavelet pattern $p$ can be obtained as

$$p = W^{-1}e$$

$W \in \mathbb{R}^{P \times P}$

with $e$ a unit vector chosen from the canonic basis:

- Obtained patterns have real positive and negative values. The DMD can only receive $b$-bits patterns

  $\rightarrow$ uniform quantization of the patterns and positive/negative separation:

$$q_f = \frac{\max(|p|)}{2^b - 1}$$

$$\hat{p} = \left[\frac{1}{q_f} p\right]$$

$$c \approx q_f f^\top \hat{p} = q_f (f^\top \hat{p}^+ - f^\top \hat{p}^-)$$
Average computation times (acquisition time excluded), includes TV-minimization for CS and the prediction step + restoration for ABS-WP

<table>
<thead>
<tr>
<th>Image size</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CS</td>
</tr>
<tr>
<td>128 x 128</td>
<td>13.18</td>
</tr>
<tr>
<td>256 x 256</td>
<td>213.62</td>
</tr>
</tbody>
</table>

TV-minimization demands expensive computations, time increases quickly with the number of measures and the image size.

For ABS-WP, bi-cubic interpolation and the wavelet transform are optimized and fast operations.

Real time possible for our technique.