Agile Single Pixel Imager *
- A Review

By
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* In passive imaging, “Single Pixel” in the literature commonly refers to using a Single Detector, i.e., a Point Photo-Detector, to design the Imager.

Note: Common Imaging Systems are called Cameras, Imagers, Scanners, Profilers, Sensors
Conventional Passive and Active Single Pixel Imaging Around for a Long Time (50+ years)
Passive versus Active

**Passive**
- **Object illuminated by ambient light** is imaged onto X-Y scan mirror which sequentially directs the shifted image irradiance onto a point detector.
- Pixel basis irradiance sampling is enabled by the point photo-detector that forms the sampling pin-hole (pixel).
- Image reconstruction is sequential (pixel by pixel).

**Active**
- **Object illuminated by custom light source or object itself is generating light, e.g., Television Display**
- Imaging operations same as Passive Imager.

* Alternative Design replaces X-Y scan Mirror & Lens by object X-Y motion stage

- Use of **single pixel** for imaging by **F. O. Huck** \(^1\)-\(^2\) in **1969**. Also used by the USSR in **1968** \(^3\).

Application:
NASA Planetary Lander Imager

- Robust Optomechanical Design for Spacecraft Platform giving Spectral Flexibility

**Single Pixel Imager called a facsimile camera** \(^2\)

Moving Digital Mask Coding of Spatially Dispersed Optical Radiation Detected By One Point Photo-Detector has been Around for a Long Time (50+ years)

For Making Spectrometers – M. Golay 1949

Moving Digital Mask Coding of Spatially Dispersed Optical Radiation Detected By One Photo-Detector has been Around for a Long Time (50+ years)

For Television Display – P. Gottlieb 1968

Example Active Single Pixel Imaging
The Fiber-Coupled Scanning Mirror-based Single Pixel Imager

- Use of single pixel for active imaging by Kino Lab\textsuperscript{1} in 1998.

Application:
Confocal Microscopy

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Imagers are also Called Scanners, Profilers, Mappers in Industry & Technical Literature

1998 –Riza

Single Pixel Active 3-D Imager using the PMOS

P-MOS: Polarization Multiplexed Optical Scanner

Polarization Switching System (Bits - 1 through N)

Linearly Polarized Light

Expander Optics

1

N

BIT 1 Module

3-D Optical Beam Scanning Field

x: x-direction

y: y-direction

z: z-direction

PMOS-Single Pixel Active 3-D Imager [1]

1999 – Riza
Introducing the Concept of an Agile Pixel
Single Pixel (Detector) Active 3-D Imager

-- Agile Pixel here Refers to:
Shape of Each Sampling Pixel
is Unique & Programmable By SLM

-- Single Pixel here and Consistent with Prior-Art
Refers to:
Using Single Point Detector


This Fast Optical 3-D Scanner/Imager using Wavelength Coding where each Programmable BFE/SLM creates a Unique Agile Pixel to Sample the 3-D Object

1999 – Riza

Single Pixel Active 3-D Imager using the CMOS
C-MOS: Code Multiplexed Optical Scanner

This Fast Optical 3-D Scanner/Imager using Spatial Coding
where the Programmable SLM creates a Unique Agile Pixel to Sample the 3-D Object

SLM: Spatial Light Modulator

Agile Pixel:
Shape and Location
of Each Active
Sampling Pixel
is Unique &
Programmable
By SLM via
CDMA code

Fig. 2 The proposed CDMA Scanner concept using a
holographic storage material.

2001 – Riza
SLM-based Single Pixel Passive 2-D Imager using Agile Pixel

- Digital Micromirror Device (DMD) SLM deployed for single pixel-imaging, first proposed and demonstrated by Riza¹ in 2001 for image reconstruction using an agile pixel.

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2003 – Riza

SLM-based Dual Pixel (i.e. Dual Point Detector) 2-D Imager with Agile Pixel

--- Accurate Even when Input Optical Power Fluctuates during Pixel to pixel scanning operation implemented in DMD

Super Resolution Irradiance Mapper --- Resolution ~ Pixel/N
- Use Data Interpolation Image Processing Algorithms

• **Takhar et al. at Rice University (USA)** implemented Compressive Sensing on Riza’s basic design **single pixel imager**.

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In 2008, Shapiro demonstrated Ghost Imaging using a single pixel detector.

Experimental setup in [1] uses a single pixel photodiode

Conventional vs Compressive vs Ghost

X-Y Mirror-1969-F. O. Huck
Code SLM-(active) 1999-N. A. Riza
SLM (passive)-2001-N. A. Riza
SLM (active +passive ) 2010 - Riza

Ambient Light

Imaging Lens

Object

Single Pixel Detector

- Passive, Active and Passive+Active Imaging

- Object is imaged onto Spatial Light Modulator (SLM) or X-Y scan mirror which sequentially directs the image irradiance onto a point detector.

- Image reconstruction is sequential (pixel by pixel) using non-random and smart (agile pixel) SLM/ Mirror control.

R. G. Baraniuk-2006
Implemented Compressive Sensing on Riza’s SLM Imager

Random 2-D Spatial Pattern on SLM

Ambient Light

Imaging Lens

Single Pixel Detector

- Passive Imaging

- Object is imaged onto SLM, programmed with random sparse patterns, which directs the image irradiance onto a single pixel detector. Iterative processing between SLM coded patterns and corresponding detector values allows image reconstruction.

- Image reconstruction is not sequential (pixel by pixel). It is iterative.

J. H. Shapiro-2008
Ghost

Custom Light Source

Random 2-D Spatial Pattern on SLM

Lens

Object

- Active Imaging

- Object illuminating random SLM coded light is collected by a single pixel detector. Iterative processing between SLM coded patterns and corresponding detector values allows image reconstruction.

- Image reconstruction is not sequential (pixel by pixel). It is iterative.
CS: Compressive Sensing (or Compressed Sensing) based Image Reconstruction Principles via Agile Pixel Camera

Image Estimation Using:
- Measurement of N photo-detected Signals via Point Detector (PD) in Camera
- N Spatial Pattern Masks used for the N PD Measurements
- Compressed Sensing Reconstruction Algorithm via Numerical Optimization deployed on PD measurements and Spatial Mask Information to Estimate Image
- Change Image Processing Optimization Criteria and Repeat Image Acquisition and CS Processing Steps to Improve Image Quality
Random Pattern-based Image Reconstruction

\[ \text{Image Reconstruction} = \sum_{i=1}^{M} \left( \text{Point PD detected intensity } I_i \times \text{SLM programmed random pattern } P_i \right) \]

\( M \): number of Random 2-D patterns

Sum over \( M \) measurements

\( i^{th} \) weight

\( i^{th} \) measurement
Random Pattern-based Image Reconstruction
(Linear Reconstruction used in Tera Hertz Sensing Imaging)

Fig. 1. Schematic depicting multiplex imaging process where the spatial modulation of a formed image allows for the reconstruction using a single pixel detector. Example $7 \times 9$ binary masks taken from rows of the $63 \times 63$ S-matrix are shown.

Random Pattern-based Image reconstruction (used in TeraHertz Imaging)

DMD-based broadband optical image sensor for robust imaging[1]

τ: Time delay of 1 pixel.
2012 – Riza
SLM-based Passive Parallel-Serial Scan 3-D Imager

- DMD-based Single Pixel Imaging using Electronic Lens for 3-D Multi-Spectral Light Irradiance Capture (Passive) using both Point Detector (Serial Scan) and CCD/CMOS/2-D Detector Array (Parallel Scan of Image Irradiance)
2014 – Riza
Coded Access Optical Sensor (CAOS) Imager

- Active and Passive Illumination Designs
- Paradigm Shift from 2-D Spatial Domain Mask-type Coding (e.g., random masks for compressive imaging) to RF Wireless Communication Style Non-Random Time-Frequency Domain encoding/decoding (e.g., CDMA, FDMA, TDMA and hybrid versions) of many programmed agile pixels
- Can deploy optical/electrical coherent detection.

And Embedded single pixel imaging system demonstrated by **Riza in 2015** for image reconstruction.

![Embedded single pixel imaging system](image)

2003
Riza’s SLM based dual agile pixel Passive 2-D Imager

2005
Riza’s SLM-based Single Agile Pixel 2-D Super Resolution Imager using Hybrid Analog-Digital SLM Control

2006
Baraniuk’s group implemented Compressive Sensing on Riza’s SLM-based Passive Single Pixel 2-D Imager

2008
Shapiro’s SLM-based Active Single Pixel Ghost 2-D Computational Imager

2008
Silberberg implements Compressive Sensing on Shapiro’s Ghost Imager

2010
Riza’s SLM-based Active and Passive Single Agile Pixel 3-D Imager

2012
Riza’s SLM-based Hybrid Parallel-Serial Scan Passive Single Agile Pixel 3-D Imager (Point PD with Array PD)

2014
Riza’s CAOS Imager