Medical Image Processing for Diagnostic Applications

Flat Panel Detectors

Online Course – Unit 14
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Topics

Flat Panel Image Receptors ...

- ... replace image intensifier technology and film.
- ... implied profound changes in radiology.
- ... are well established in
  - digital radiography,
  - cardiology, and
  - mammography.

Killer Applications of Flat Panel Detectors

With the introduction of flat panel detector technology, standard radiography systems could **increase patient throughput**, and they experienced a **significant simplification of image archiving and image exchange** with other hospitals and physicians.

Figure 1: Radiography system using flat panel detectors (image courtesy of Siemens Healthcare)

Killer Applications of Flatpanel Detectors I

- **Cardiology:** In cardiology, flat panel detectors were introduced in 2002.
- **Neuroradiology:** Biplane flat panel detector C-arm systems are available on the market since 2006.

Figure 2: Cardiac system using a flat panel detector (left), biplane neuroradiology system (right) (image courtesy of Siemens Healthcare)

Killer Applications of Flatpanel Detectors II

Flat panel detectors allow for 3-D reconstruction of static, low contrast objects using C-arm systems.
The following images show examples of the contrast resolution achieved by today's C-arm CT devices and algorithms.

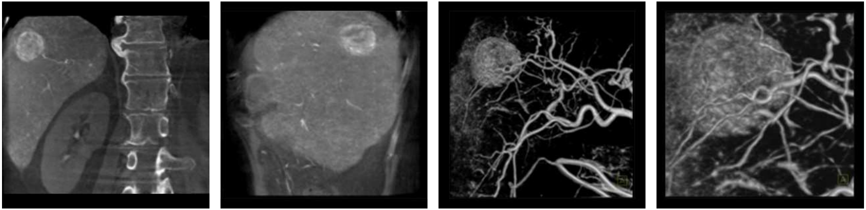

Figure 3: 3-D low contrast C-arm reconstruction of hepatocellular carcinoma (image courtesy of Siemens Healthcare)

Killer Applications of Flatpanel Detectors III

In **magnetic navigation systems** the catheter is directed by a magnetic field. The manual control of its orientation is based on X-ray images.
Obviously it is impossible to operate an image intensifier in a magnetic field, thus flat panel technology is mandatory.

Figure 4: Niobe system for magnetic navigation (image courtesy of Siemens Healthcare)

Advantages of Flat Panel Detectors

- Simple assembly and readout
- Higher contrast resolution (high dynamic range)
- Not sensitive to magnetic fields (no magnetic distortion)
- More robust with respect to under- and overexposure
- Reduced space requirements (do not underestimate this advantage!)
- Optimization of the clinical workflow
- Mechanically rugged

Disadvantages of Flat Panel Detectors

- Relatively slow readout
- Still an expensive technology (will change over time)
- High rejection rate in production
- Elimination of defects with digital image processing

Contrast Resolution

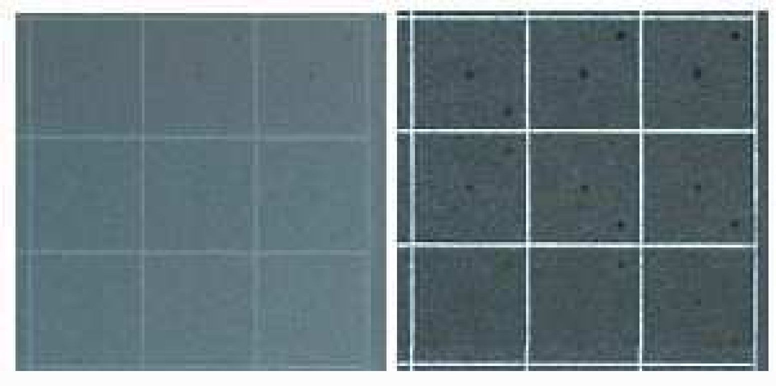

Figure 5: Higher contrast resolution using flat panel detectors: left image acquired on film, right image acquired with a digital detector (image courtesy of General Electrics)

Goals of Flat Panel Design

- Digital imaging in all areas of radiology (replace film & image intensifiers)
- Cost reduction in health care (elimination of film!)
- Improved image quality
- Waste minimum amount of incoming X-ray (fill factor $\sim$40 %)
- Detection area sizes more than 40 cm $\times$ 40 cm
- Spatial resolution of pixels 50 µm to 150 µm

Flat Panel Detectors

Typical image data of a Pixium 4600:

- area: 43 cm × 43 cm,
- resolution: 3001 × 3001,
- pixel size: 143 µm,
- quantization: 14 bit (2 byte).

Figure 6: Pixium 4600

Flat Panel Detectors

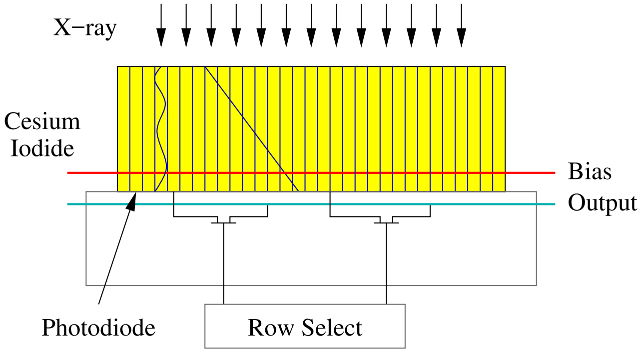

Figure 7: Scheme of a CsI based detector

Flat Panel Detectors

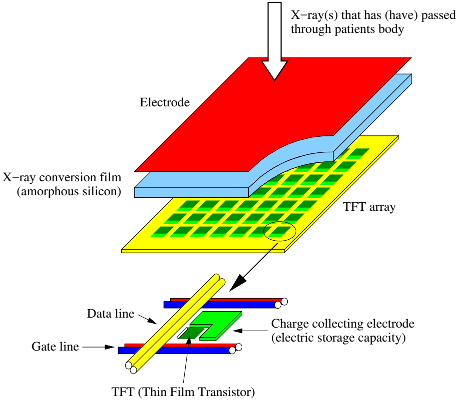

Figure 8: Direct conversion using amorphous silicon

Topics

Take Home Messages

- Flat panel detectors are the modern detector technology in digital X-ray systems.
- There exist different principles to realize a flat panel image receptor.
- Applications for flat panel detectors are manifold, and the technology has a lot of advantages including a higher contrast resolution compared with film.
- However, digital image processing is necessary to compensate for manufacturing flaws.

Further Readings

- One starting point for more information on flat panel detectors could be vendor webpages like, e.g., from Varian, or Trixell.
- The method presented for defect pixel interpolation in the frequency domain was published by Til Aach and Volker Metzler in 2001:

  Til Aach and Volker Metzler. "Defect Interpolation in Digital Radiography: How Object-Oriented Transform Coding Helps". In: *Proc. SPIE 4322, Medical Imaging 2001: Image Processing*. Vol. 4322. San Diego, CA: SPIE, Feb. 2001, pp. 824–835. DOI: 10.1117/12.431161

- A recent article about defect pixel interpolation with respect to image quality issues can be found here:

  Jan Kuttig et al. "Effects of Defect Pixel Correction Algorithms for X-ray Detectors on Image Quality in Planar Projection and Volumetric CT Data Sets". In: *Measurement Science and Technology* 26.9 (Aug. 2015), 095406 (14pp). DOI: 10.1088/0957-0233/26/9/095406

Medical Image Processing for Diagnostic Applications

Artifacts and Preprocessing Problems

Online Course – Unit 15

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Topics

Acquisition Artifacts

Defect Pixel Interpolation

Summary
- Take Home Messages
- Further Readings

Artifacts of flat panel detectors

- Large detectors composed of four detectors $\rightarrow$ butting cross
- Offset in intensities
- Inactive pixels:
  - Single pixels
  - Pixel clusters
  - Image columns
  - Image rows

Typical Preprocessing Problems

- Offset and gain correction
- Defect interpolation
- Butting cross correction

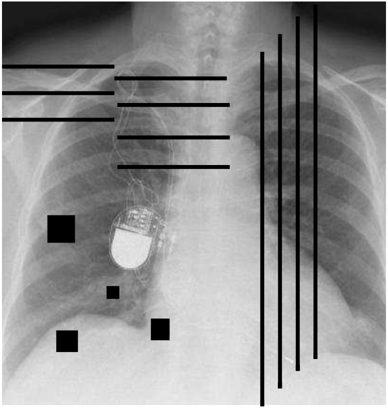

Figure 1: Thorax image with defect pixels

Butting Cross Artifact

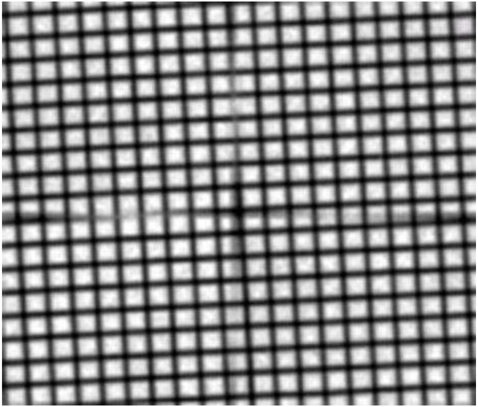

Figure 2: Artifacts appearing after butting cross correction

Butting Cross Artifact

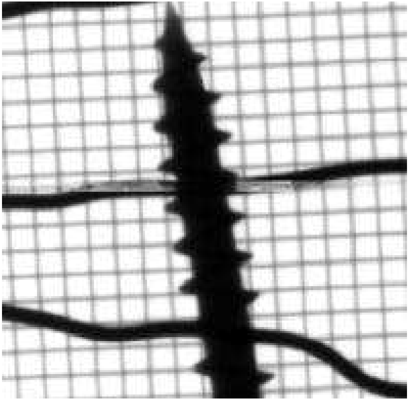

Figure 3: Artifacts caused by an improper correction method

Topics

Defect Pixel Interpolation

There are two general approaches for defect pixel interpolation:

1. **interpolation in spatial domain:**
   - non-adaptive linear filtering,
   - non-linear filtering (like median),
   - suitable for small defect areas,
   - unnatural appearance (amplified by post-processing);
2. **interpolation in frequency domain:**
   - enforce bandlimitation by bandpass filtering,
   - defect interpolation corresponds to the deconvolution of defect and ideal image,
   - binary defect image is computed in a calibration step,
   - ideal image is multiplied with the binary defect image.

In this course, we are introducing the second type.

Mathematical Modeling of Pixel Defects

Defect pixels are caused by defect detector cells. The mathematical model for defect generation is just the multiplication of the original image with a defect mask:

- Let $f_{i,j}$ denote the intensity value at grid point (i, j) of the **ideal image** f that has no defect pixels.
- Let $w_{i,j}$ denote the indicator value at (i, j) where w is the **mask image** that indicates defect and uncorrupted pixels:

$$w_{i,j} = \begin{cases} 0, & \text{if pixel is defect,} \\ 1, & \text{otherwise.} \end{cases}$$

- Let $g_{i,j}$ denote the intensity value at (i, j) of the **observed image** g that is acquired with the flat panel detector and has defect pixels.

Mathematical Modeling of Pixel Defects

By pixelwise multiplication of the ideal image with the mask image, we get the observed image computing

$$f_{i,j} \cdot w_{i,j} = g_{i,j}$$

for a pixel at (i, j), and likewise for all pixels.

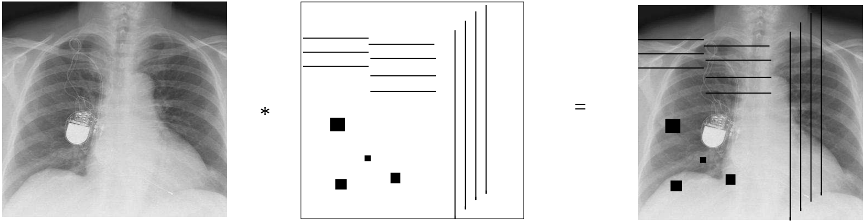

Figure 4: The ideal image (left) is multiplied with the defect mask (middle) which results in the output defect image (right).

Defect Pixel Interpolation in Frequency Domain

In the frequency based algorithms for defect pixel interpolation, three important properties of or related to the Fourier transform are applied:

- the Nyquist-Shannon sampling theorem,
- the convolution theorem, and
- the symmetry property of the Fourier transform of real signals.

We recommend to refresh your memory regarding these topics before going to the next unit.

Topics

Acquisition Artifacts

Defect Pixel Interpolation

Summary

- Take Home Messages
- Further Readings

Take Home Messages

- An image acquired with a flat panel detector can contain certain types of artifacts.
- Defect pixel interpolation can be done in spatial and frequency domain.
- The pixel defects can be modeled by multiplication of a defect mask and the ideal image.

Further Readings

- The method presented for defect pixel interpolation in the frequency domain was published by Til Aach and Volker Metzler in 2001:

  Til Aach and Volker Metzler. “Defect Interpolation in Digital Radiography: How Object-Oriented Transform Coding Helps”. In: *Proc. SPIE 4322, Medical Imaging 2001: Image Processing*. Vol. 4322. San Diego, CA: SPIE, Feb. 2001, pp. 824–835. DOI: 10.1117/12.431161

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Medical Image Processing for Diagnostic Applications

Defect Pixel Interpolation

Online Course – Unit 16

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Topics

Defect Interpolation by Bandlimitation

Summary

- Take Home Messages
- Further Readings

Defect Interpolation by Bandlimitation

The initial idea for defect pixel interpolation using frequency domain methods is based on a fundamental result of signal theory:

- According to the sampling theorem, the ideal signal $f(n)$ is required to be bandlimited regarding to a certain band frequency ξ.
- Defect detector elements bring intensities of corresponding pixels down to zero.
- Defect pixels cause high differences in intensities of neighboring pixels and thus imply higher frequencies in the 2-D image function. These higher frequencies cause a violation of the required bandlimitation.

Idea for defect interpolation: Replace defect pixels iteratively by enforcing bandlimitation.

Remark: Discrete signals are inherently bandlimited, consider this as a conceptual approach in the first place.

Defect Interpolation by Bandlimitation

compute FT of input signal $g(n)$

- set $G(\xi) = 0$ for $\xi < B_{\mathrm{lower}}$ or $\xi > B_{\mathrm{upper}}$
- compute inverse FT of corrected $G(\xi)$
- replace defect samples in $g(n)$ with values of the bandlimited signal

UNTIL changes are below a threshold

Figure 1: Interpolation by enforcing a bandlimited signal in a frequency range of $[B_{\mathrm{lower}}, B_{\mathrm{upper}}]$

Drawbacks of Bandlimitation

The proposed method is quite simple and intuitive, but there exist a few serious practical issues:

- The bandlimitation $B_{\text{lower}}, B_{\text{upper}}$ must be known.
- The interpolation scheme is computationally expensive, because each iteration requires the Fourier transform of the signal twice. This prohibits its straightforward practical use.
- The proposed interpolation algorithm is not optimal w. r. t. the minimum number of non-zero frequencies.
- Extrapolations decay outside the observation interval.
- The application of adaptive thresholding during interpolation is advantageous.

Topics

Defect Interpolation by Bandlimitation

Summary

- Take Home Messages
- Further Readings

Take Home Messages

- Bandlimitation can iteratively be applied to a defect pixel image.
- Be careful when applying defect pixel interpolation.

Further Readings

- The method presented for defect pixel interpolation in the frequency domain was published by Til Aach and Volker Metzler in 2001:

  Til Aach and Volker Metzler. "Defect Interpolation in Digital Radiography: How Object-Oriented Transform Coding Helps". In: *Proc. SPIE 4322, Medical Imaging 2001: Image Processing*. Vol. 4322. San Diego, CA: SPIE, Feb. 2001, pp. 824–835. DOI: 10.1117/12.431161

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Medical Image Processing for Diagnostic Applications

Defect Pixel Interpolation – Utilizing Symmetry

Online Course – Unit 17

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Topics

Defect Pixel Interpolation using Symmetry Properties

Interpolation Algorithm

Summary

- Take Home Messages
- Further Readings

Notation

For simplicity and without loss of generality we limit the following discussion to 1-D signals of length N, and use the following notation:

- discrete ideal signal: $f(n)$,
- binary mask image: $w(n)$,
- observed signal: $g(n)$.

The respective Fourier transforms are denoted $F(\xi)$, $W(\xi)$, $G(\xi)$.

Frequency Domain Defect Pixel Interpolation

Observations:

- We consider real valued signals $f(n)$, $g(n)$, $w(n)$.
- They satisfy the following relationship:

$$g(n) = f(n) \cdot w(n) \quad \Leftrightarrow \quad G(\xi) = F(\xi) * W(\xi).$$

- For the ideal, the mask, and the defect image, the Fourier transform satisfies the symmetry property:

$$F(\xi) = \overline{F}(N-\xi),$$
$$G(\xi) = \overline{G}(N-\xi),$$
$$W(\xi) = \overline{W}(N-\xi),$$

where the bar symbol in $\overline{z}$ denotes the complex conjugate of z.

Frequency Domain Defect Pixel Interpolation

Now we make explicit use of the symmetry property of the Fourier transform to derive an interpolation algorithm:

- Select a pair $G(s)$ and $G(N-s)$ of the Fourier transform of the corrupted image showing pixels defects.
- Select a pair $F(s)$ and $F(N-s)$ of the Fourier transform of the ideal image.

Frequency Domain Defect Pixel Interpolation

- Let us assume that the Fourier transform of the ideal image $F(\xi)$ consists only of two lines at s and $N-s$, where $s \neq 0$.
- We can then rewrite the Fourier transform of $f(n)$ using Dirac's δ-function:

$$F(\xi) = \widehat{F}(s)\delta(\xi - s) + \widehat{F}(N-s)\delta(\xi - N + s),$$

where $\widehat{F}$ denotes an estimate of F, and the δ-function is defined by

$$\delta(k) = \begin{cases} 1, & \text{if } n = 0, \\ 0, & \text{otherwise.} \end{cases}$$

Frequency Domain Defect Pixel Interpolation

The convolution of F and the Fourier transform W of the given mask image leads to the Fourier transform of the observed corrupted image:

$$G(s) = \frac{1}{N}\left(\widehat{F}(s)W(0) + \overline{\widehat{F}}(s)W(2s)\right).$$

This can be shown as follows:

$$G(s) = F(s) * W(s) = \frac{1}{N}\sum_{k=0}^{N-1} F(k) * W(s-k).$$

Due to our assumption, we know that $F \neq 0$ only at $k = s$ or $k = N - s$, hence:

$$\begin{aligned} G(s) &= \frac{1}{N}\left(\widehat{F}(s)W(0) + \widehat{F}(N-s)W(s-N+s)\right) \\ &= \frac{1}{N}\left(\widehat{F}(s)W(0) + \overline{\widehat{F}}(s)W(2s)\right). \end{aligned}$$

Frequency Domain Defect Pixel Interpolation

- For the conjugate complex Fourier transform of the observed image we get:

$$\overline{G}(s) = \frac{1}{N}\left(\overline{\widehat{F}}(s)\overline{W}(0) + \widehat{F}(s)\overline{W}(2s)\right).$$

- Since W is known, we get two equations linear in $\widehat{F}(s)$ and $\overline{\widehat{F}}(s)$.
- Hence, the final estimator for the Fourier transform of the ideal image is:

$$\widehat{F}(s) = N\frac{G(s)\overline{W}(0) - \overline{G}(s)W(2s)}{|W(0)|^2 - |W(2s)|^2}, \qquad \text{(FT-EST)}$$

where $|.|$ denotes the absolute value of the complex number.

Error Spectrum

- An objective function to measure the quality of the interpolated image results from the least square error:

$$\Delta_\varepsilon = \frac{1}{N}\sum_{n=0}^{N-1}\left(g(n) - w(n)\widehat{f}(n)\right)^2 .$$

- The spectrum of the error in the i-th iteration step is given by:

$$G^{(i)}(\xi) = G^{(i-1)}(\xi) - \frac{1}{N}\left(\widehat{F}^{(i)}(s)\delta(\xi - s) + \overline{\widehat{F}}^{(i)}(s)\delta(\xi - N + s)\right) * W(\xi).$$

Topics

Interpolation Algorithm

compute FT of input signal $g(n)$

initialize $\widehat{F}^{(0)}(k) = 0$, $G^{(0)}(k) = G(k)$, $i = 1$

randomly select a line pair $G^{(i-1)}(s)$, $G^{(i-1)}(N-s)$ for $s \neq 0$

estimate $\widehat{F}^{(i)}(s)$, $\widehat{F}^{(i)}(N-s)$ using (FT-EST)

update spectrum $\widehat{F}^{(i)}(k)$, compute error Δ_ε

error Δ_ε above a threshold?

`true`	`false`
Compute error spectrum $G^{(i)}(k)$, increment i	GOTO END

UNTIL error is below a threshold

END: Compute inverse FT of $\widehat{F}^{(i)}(k)$

Figure 1: Interpolation algorithm according to Aach and Metzler

Topics

Defect Pixel Interpolation using Symmetry Properties

Interpolation Algorithm

Summary

- Take Home Messages
- Further Readings

Take Home Messages

- Assuming the spectrum of a signal/function consists of two non-zero lines, then we find an estimate for the Fourier transform.
- The symmetry property of the Fourier transform w. r. t. real valued functions can be used to build a defect interpolation algorithm.

Further Readings

- The method presented for defect pixel interpolation in the frequency domain was published by Til Aach and Volker Metzler in 2001:

  Til Aach and Volker Metzler. "Defect Interpolation in Digital Radiography: How Object-Oriented Transform Coding Helps". In: *Proc. SPIE 4322, Medical Imaging 2001: Image Processing*. Vol. 4322. San Diego, CA: SPIE, Feb. 2001, pp. 824–835. DOI: 10.1117/12.431161

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Medical Image Processing for Diagnostic Applications

Defect Pixel Interpolation – Examples

Online Course – Unit 18
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- Take Home Messages
- Further Readings

Interpolation Results

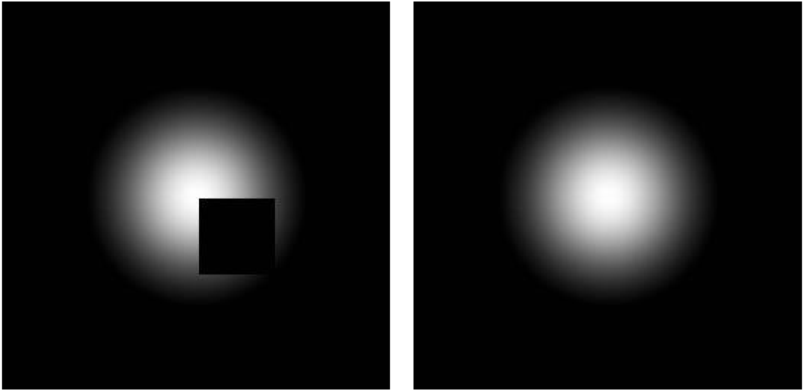

Figure 1: Synthetic image with a square artifact (left) and the result after 100 iterations (right)

Interpolation Results

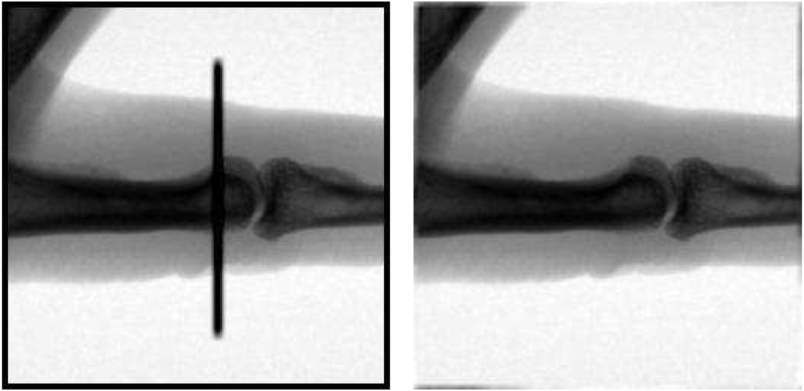

Figure 2: Original image including defects (left) and the result after 500 iterations (right)

Interpolation Results

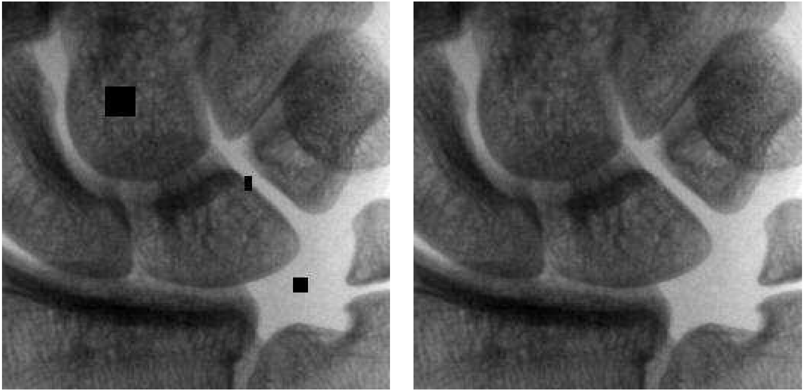

Figure 3: X-ray image with defects (left) and the result of interpolation after 500 iterations (right)

Interpolation Results

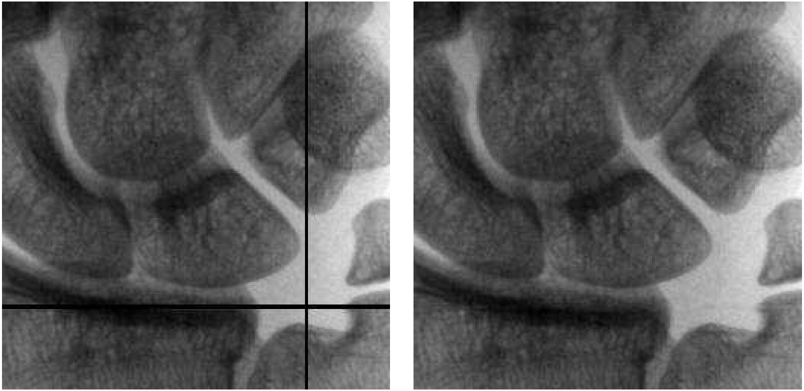

Figure 4: X-ray image with defects (left) and the result of interpolation after 1000 iterations (right)

Interpolation Results

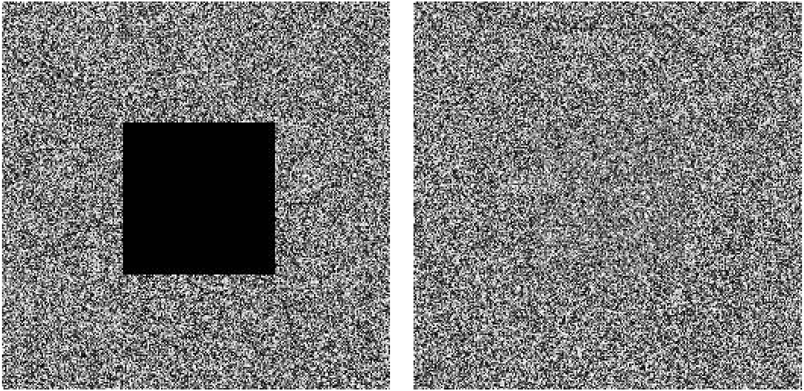

Figure 5: Artificial noise image with defect pixels (left) and the result of interpolation after 1000 iterations (right)

Interpolation Results

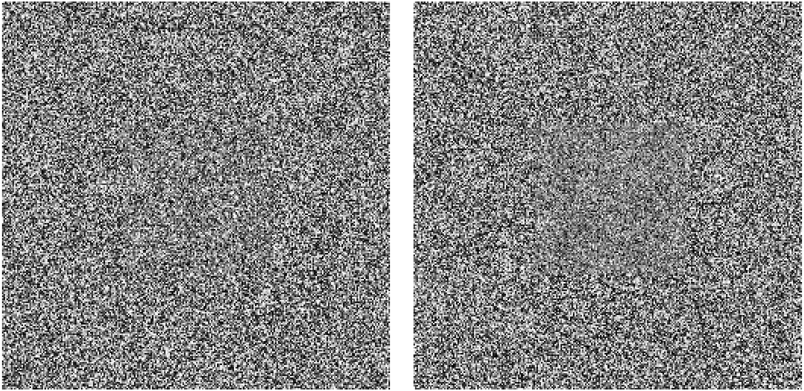

Figure 6: Result of interpolation after 1000 (left) and 5000 iterations (right)

Topics

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Further Readings

Application to Endoscopy

- Endoscopy: wet surfaces lead to specular reflections
- Segmentation of highlighted areas
- Apply defect interpolation

Figure 7: Endoscopy image with reflections, segmentation result, and result of interpolation (image courtesy of Xie Weiguo)

Application to Ophthalmology

Color images in Ophthalmology

- In Ophthalmology the early diagnosis of diseases is done on the basis of retina images.
- For the diagnosis of Glaucoma disease, sometimes vessel structures are less important and misleading.

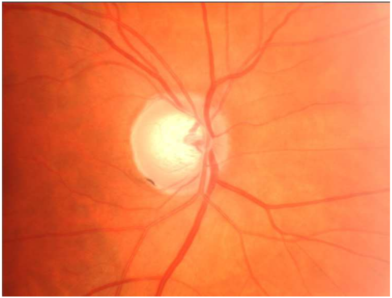

Figure 8: Color image of retina showing also the papilla, veins and arteries

Application to Ophthalmology

Eliminate vessel structures:

- Perform a segmentation of vessels, i. e., identify all image points that belong to a vessel.
- Consider pixels of vessels as defects.
- Run a defect pixel interpolation algorithm on images with defects.

Figure 9: Segmented image (left) and image after defect pixel interpolation (right)

Application to CT Angiography

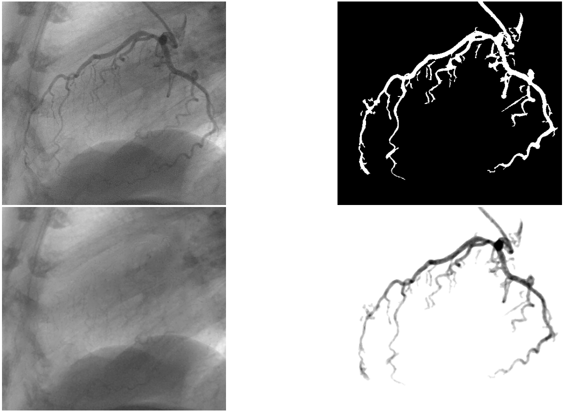

Figure 10: CT image showing heart scan (top left), segmentation (top right), inpainting (bottom left) and DSA (bottom right) (Mathias Unberath, Pattern Recognition Lab, FAU)

Topics

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Summary

Take Home Messages

Further Readings

Take Home Messages

- You have seen results of defect pixel interpolation.
- The methods from defect pixel interpolation are applied to many other problems in medical image processing.

Further Readings

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