Simulation and Image Reconstruction for a Low-Cost PET Detector Concept

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What is PET?

- Positron Emission Tomography (PET) is one of the most **sensitive** imaging techniques available.
- It allows physicians to monitor **metabolic activity**, localise tumours and assess treatment efficacy.
- Patients are injected with a small amount of **radiotracer**, which is absorbed by metabolically active or diseased cells, making them **visible** to the scanner.

The Need for Low-Cost PET

- The World Health Organisation (WHO) has recommended a PET scanner ratio of **two scanners per million people** to meet population needs.
- South Africa currently only has **18** PET scanners for a population of nearly **60 million people.**

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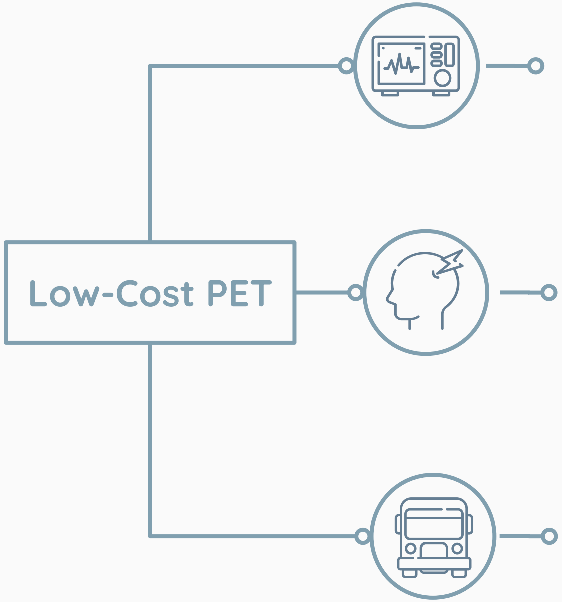


Advanced medical imaging more widely accessible

Reduce downstream healthcare costs by enabling accurate and early diagnosis

Logistical obstacles

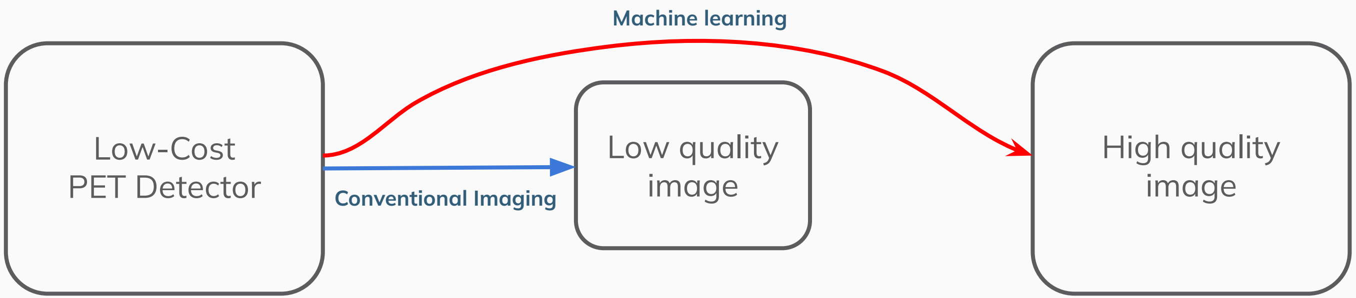
Project Goals

- The main goal of my project is to create a **digital workbench** through simulation to evaluate different low-cost detector designs

- At the end of this workflow, you should be able to make a suitable decision whether a low-cost detector design is **clinically usable**.

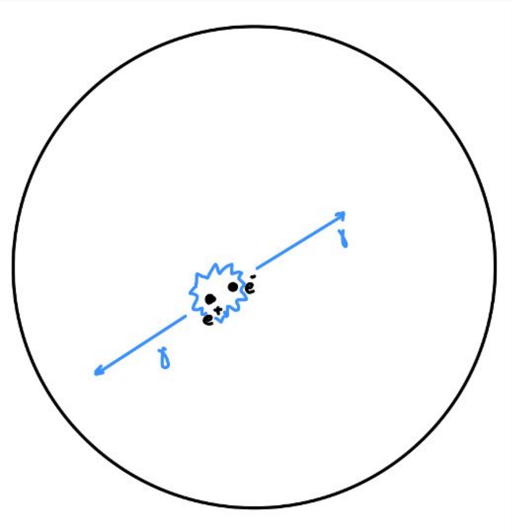
Project Goals

- If we have a **simpler** design, the images that are produced will never be of the same quality as a standard PET detector
- Can we use **machine learning** to **bridge this gap** and denoise our images to get high quality, clinically usable images?

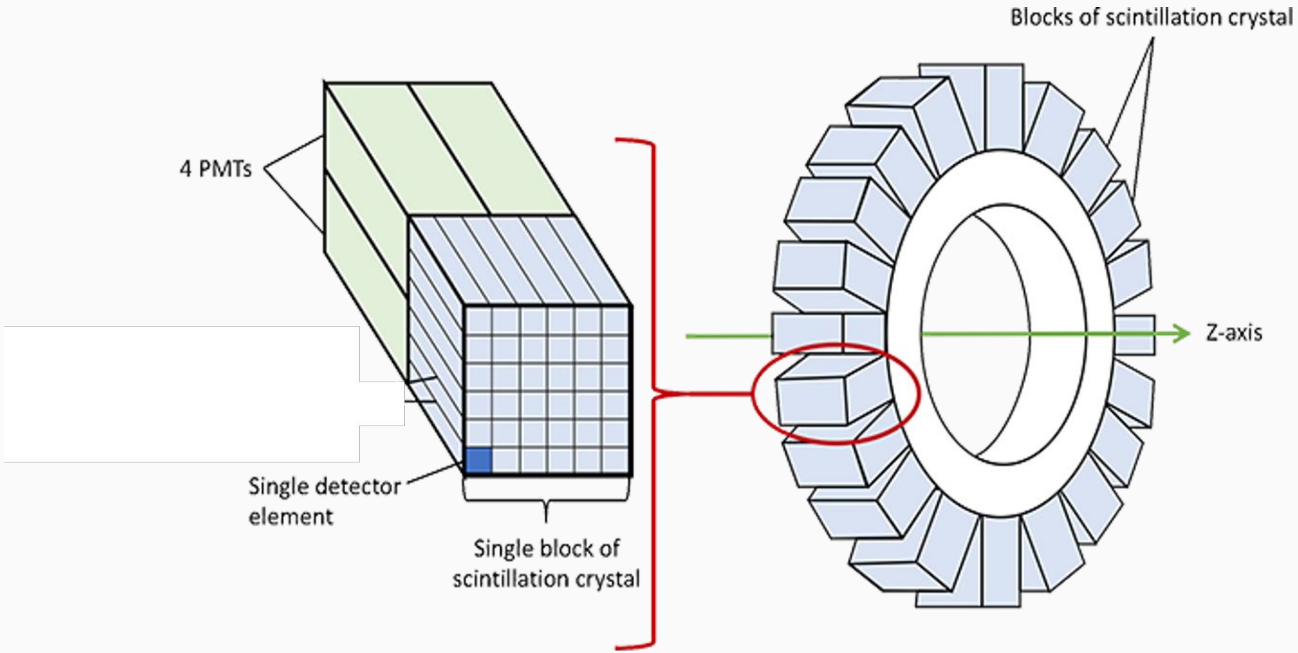


How PET Works: Annihilation

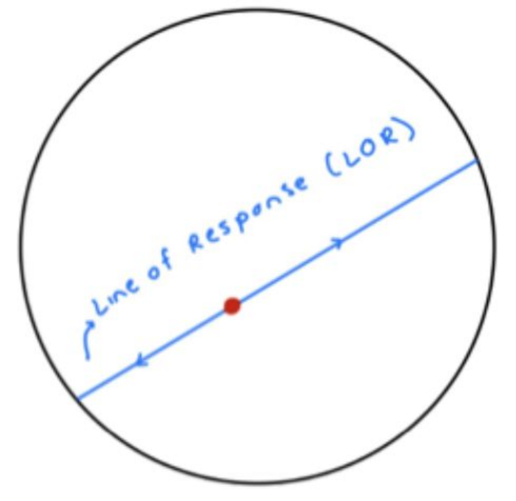
- The radiotracer that patients are injected with contain a **positron emitting isotope**
- These isotopes are **radioactive** and **unstable** and will undergo beta plus decay, **releasing a positron**, to become more stable
- When the positron encounters an electron in nearby tissue, they will undergo an **annihilation reaction**
- This reaction produces **two 511 keV photons** which move to **opposite sides** of the detector



How PET Works: Detection



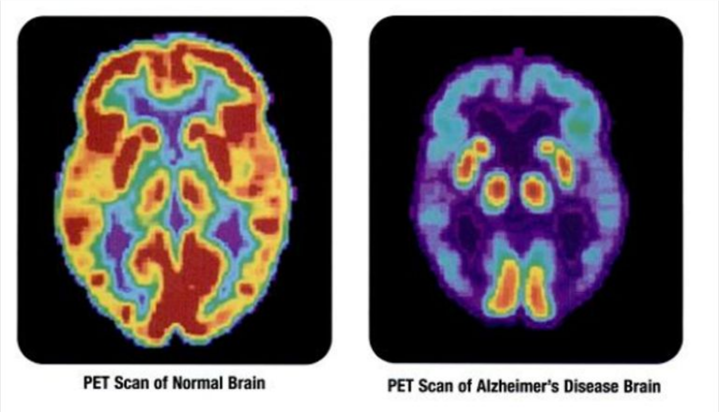
How PET Works: Detection



- The LOR only constrains the annihilation event to lie somewhere along that line; **it does not indicate the exact location of the event**.

How PET Works: Image Reconstruction

- The primary task of an image reconstruction algorithm for a PET detector is to take the data collected and **transform it into an accurate image**



From Design to Decision: Design

Detector Design

- The first preliminary design that has been tested is a compact PET system with **simplified modules** and **smaller geometry**

- This will be compared with a **commercial Philips Vereos Digital PET system**

	Philips Vereos	Low-Cost
Radius	500 mm	160 mm
Module Dimensions	19 mm x 131.4 mm x 164 mm	15 mm x 24 mm x 24 mm
Pixels per module	1280	64

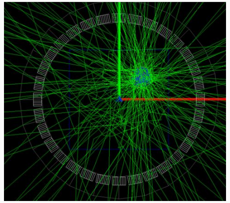
**A module is an array of scintillators*

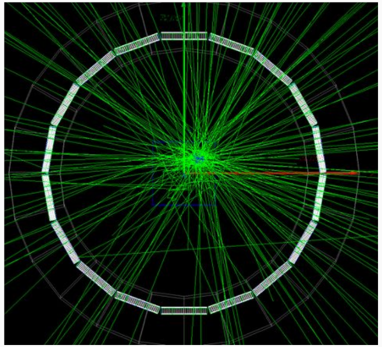
From Design to Decision: Simulation

The Simulation

- The simulations in this project were performed using **GATE** (Geant4 Application for Tomographic Emission)
- GATE builds on the Geant4 Monte Carlo toolkit and provides a dedicated interface for **medical imaging simulations**

Visualisation of the compact low-cost PET scanner in GATE

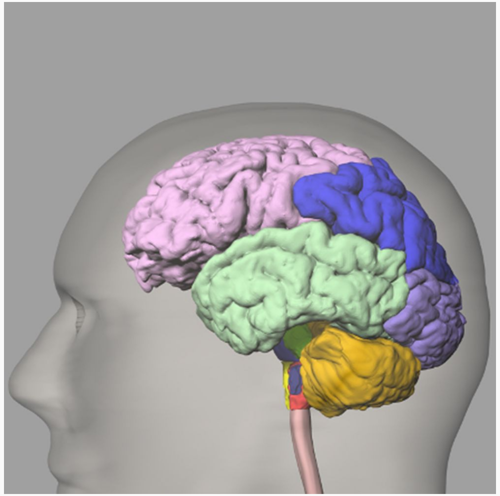




Visualisation of the Philips Vereos PET scanner in GATE

Phantoms

- Phantoms are objects that are used to **mimic human tissue** to validate detector performance
- GATE provides the flexibility to **define various phantoms** with controlled activity distributions
- Realistic brain phantoms can be created by **voxelising public CT scan datasets** into anatomical regions



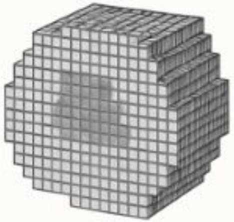
Example of a voxel-based brain phantom segmenting ~100 structures generated from CT/MRI data and voxelised for use in GATE.

What does it Mean to Voxelise Something?

- **Voxelisation**: The process of converting a 3D object into a grid of voxels

A single 2D example of a CT brain scan

Stacking the slices



Each voxel stores local tissue information

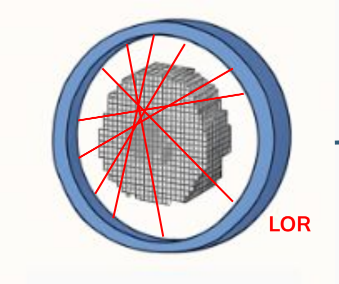
Voxelised phantoms used in PET simulation

From Design to Decision: Image Reconstruction

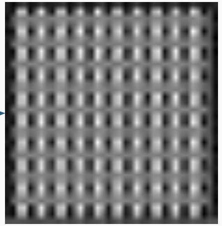
Image Reconstruction Using MLEM

- We use the **Maximum Likelihood Expectation Minimisation (MLEM)** algorithm for image reconstruction
- MLEM is the **most widely used** method in PET imaging
- MLEM tries to find the **most likely image** that would have been produced the data that we measured

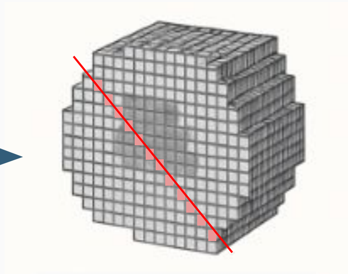
Image Reconstruction Using MLEM



Collecting the data



Start with a guess



Forward project: Simulate the detectors view

$$L\,(D|P(I))$$

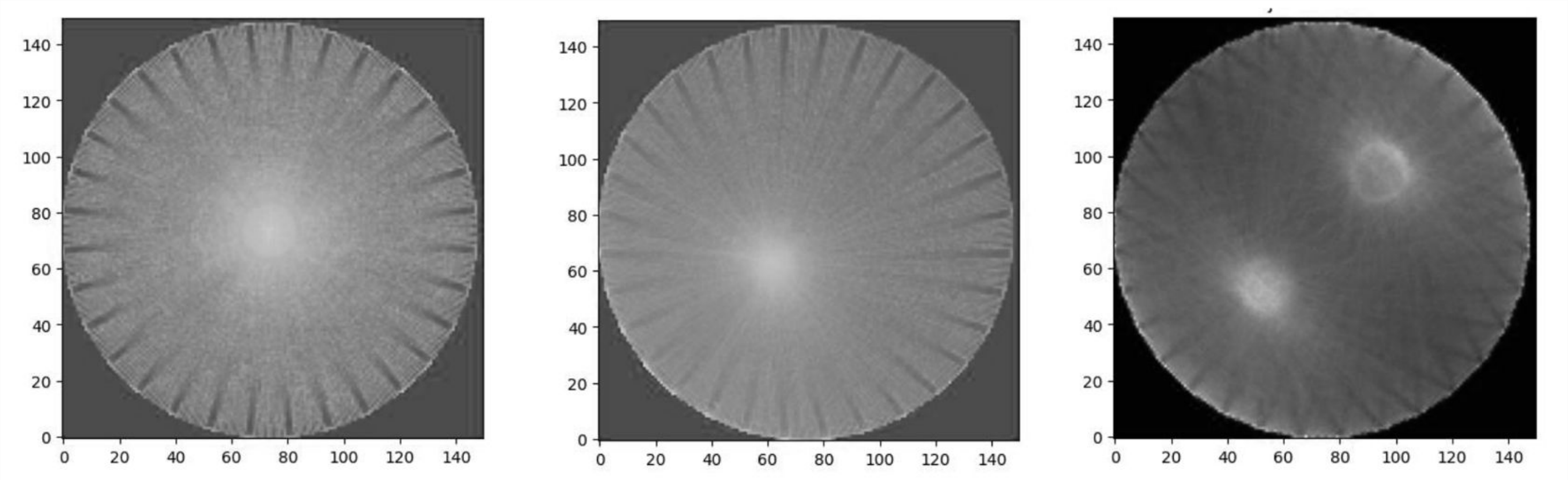
D: Measured Data

P(I): Forward projection of image estimate I

We evaluate the likelihood of the measured data given our current guess

Correct and improve image

Image Reconstruction Using MLEM



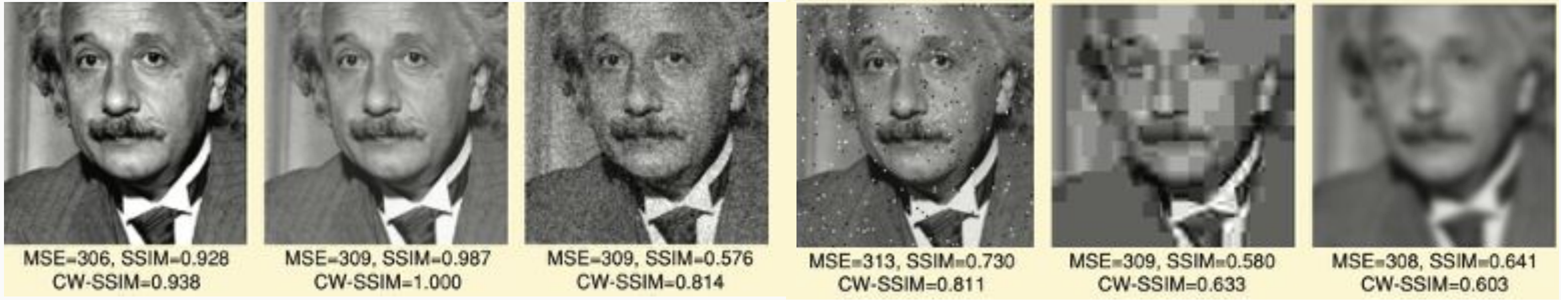
Reconstructed images of spherical sources using MLEM

From Design to Decision: Comparison Metrics

Image Comparison Metrics

- We need a metric that is able to quantify how **similar** the images produced by the detectors are

- **Mean squared error (MSE)** has been shown to report nearly **identical values** for images that appear very **different** to the human eye

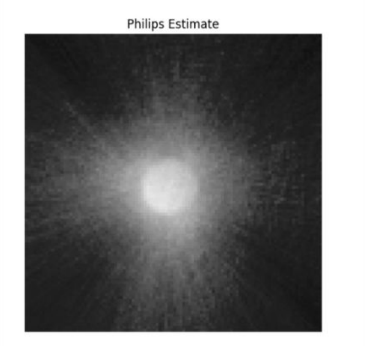


The Structural Similarity Index (SSIM)

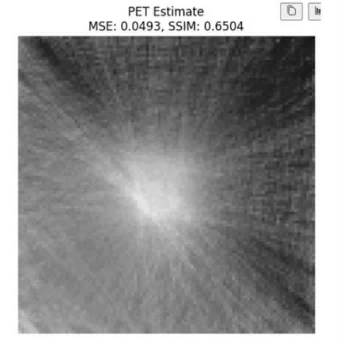
- The core idea behind the SSIM is that the human visual system is highly sensitive to structural changes, and therefore the **image quality should be assessed based on the preservation of structural information**

- The SSIM evaluates the similarity between two images based on three components: **luminance, contrast and structure**

- The SSIM score ranges from -1 to 1 where a value of **1** indicates perfect structural similarity



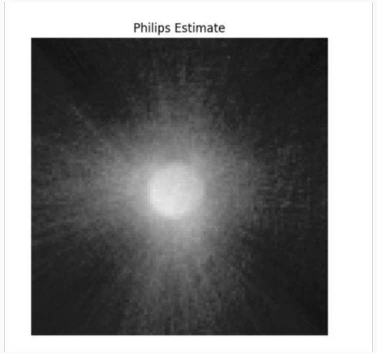
Reconstructed Image using Vereos Detector

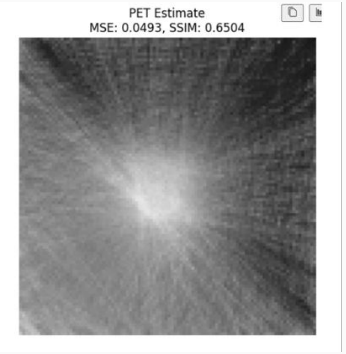


Reconstructed Image using low-cost detector, with the relevant SSIM score

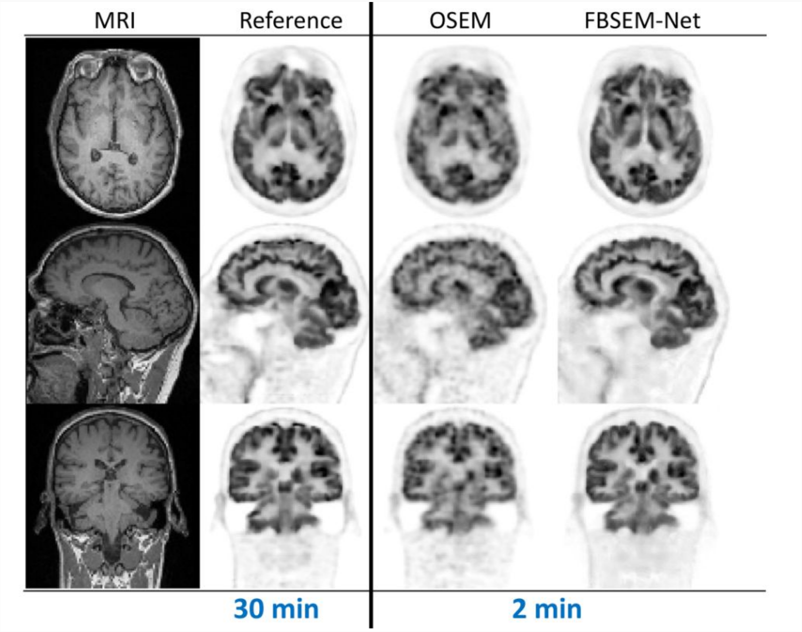
Using ML to Bridge the Image Quality Gap

- The simplified modules and reduced resolution of our design lead to inherently **noisier, lower quality images**
- We are implementing ML denoising methods to **enhance image quality**, aiming to approach the performance of high-end PET systems.
- These include autoencoders trained on high-resolution data to **learn structural priors** for image upsampling and denoising.





Using ML to Bridge the Image Quality Gap



Machine learning enhances low-count PET scans: A deep learning model (FBSEM-Net) reconstructs high-quality images from 2-minute scans, recovering structural detail comparable to a 30-minute reference.

Scaling Up the Simulation

	Current Simulation	Real PET Brain Scan
Scan time	0.1 s	20 minutes
Photon pairs detected	~500 000	~10^{11}
% of full data	0.0005%	100%

- To simulate realistic scan duration and photon statistics we need to **optimise our workflow**

Making the Final Decision

- By running each design through this pipeline, we can make an informed decision about:
  - ***Is the design producing clinically relevant images?***
  - ***Is the performance good enough to replace high-cost systems?***

Thank you!

Do you have any questions?

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The MLEM Update Equation

Image estimate at iteration k

Back projection process

Measured projection data

$$x^{k+1} = \frac{x^k}{A^T 1} A^T \left(\frac{m}{Ax^k + b} \right)$$

System matrix responsible for forward projection

Additive term representing background events such as random coincidences or scatter

The SSIM

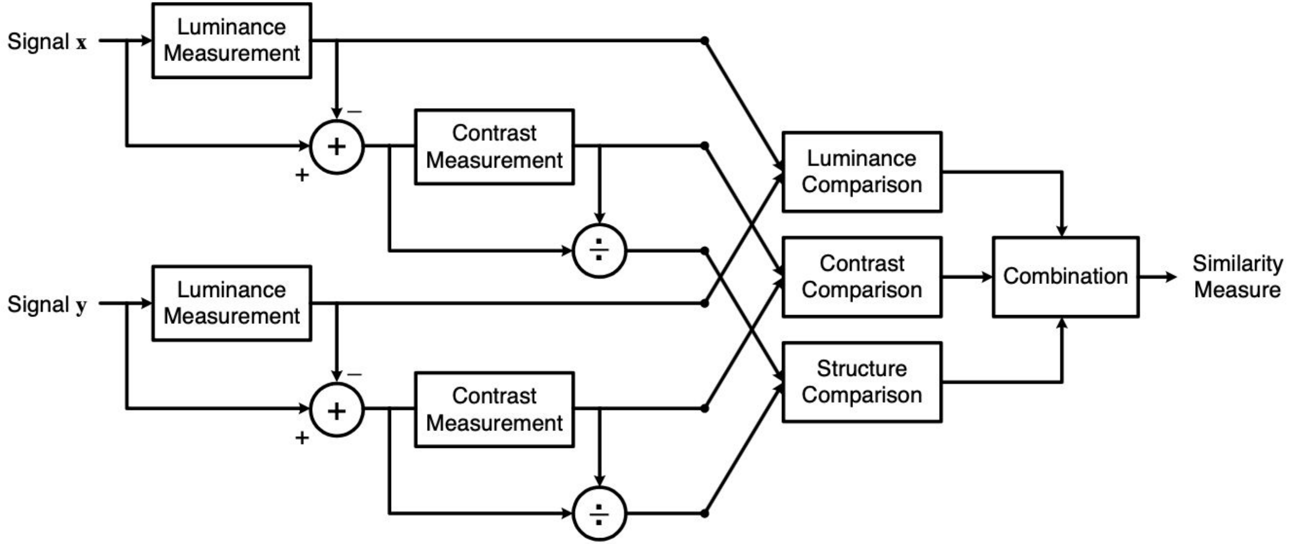

Fig. 3. Diagram of the structural similarity (SSIM) measurement system.