Project Title: Tomographic Medical Image Reconstruction using federated learning

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# 1. Introduction

## 1.1 Purpose

This document defines the functional, interface, performance, and security requirements for a federated learning system that reconstructs 3D SPECT images. Building upon prior work in tomographic image reconstruction using deep learning, the current project integrates a comprehensive data generation pipeline—including detailed augmentation strategies—to produce synthetic datasets that are subsequently used for training a robust neural network in a federated learning environment. The aim is to enhance reconstruction quality and generalizability while maintaining patient privacy.

## 1.2 Scope

The system shall:

- Data Generation: Produce detailed synthetic datasets using XCAT-based phantom generation, enhanced to XCAT+s by applying statistical tracer distributions (for healthy and, later, diseased patients). The pipeline is detailed in the Dataset Augmentation Plan.

- Augmentation: Apply a multi-stage augmentation process (sinogram squashing, Gaussian blurring, Z-axis shifting, and backprojection-shift-forward projection) to increase dataset diversity by up to 275× per XCAT+.

- Federated Learning: Enable secure, privacy-preserving model training through:

1. An Orchestrator Application that manages and aggregates the global model.
2. A Contributor Application that conducts local training on real SPECT data without exposing raw patient information.

- Data Management: Provide mechanisms to verify simulation outputs (e.g., verifying the OpenGATE sinogram dimensions) and support a centralized data catalogue/repository.

## 1.3 Document Organization

- Section 2: System Overview and Architecture.

- Section 3: Detailed Functional Requirements (including the granular data pipeline and federated learning processes).
- Section 4: Performance Requirements.
- Section 5: Security & Privacy Requirements.
- Section 6: References and Appendices.

## 2. System Overview

2.1 Product Perspective

The system integrates established imaging simulation tools (XCAT/XCAT+, OpenGATE) and deep learning frameworks (PyTorch) with a federated learning platform (e.g., Flower, PySyft, or OpenFL) to achieve rapid, high-quality 3D SPECT reconstruction. The overall pipeline is designed to transition from synthetic data generation to local model training while ensuring that real patient data never leaves the institution.

2.2 Key Components

- Data Generation & Augmentation Module:

1. XCAT Phantom Generation: Generates detailed anatomical models. The system shall support the application of statistical tracer distributions to generate both standard and augmented XCAT+s.
2. OpenGATE Simulation: Simulates SPECT imaging to produce sinograms. The system shall validate the output dimensions (e.g., correcting from 128×128×240 to 128×128×120 where necessary).
3. Augmentation Processes: Multiple techniques (detailed in the Dataset Augmentation Plan) are applied sequentially:
    - Sinogram Squashing: Corrects image splitting artifacts.
    - Gaussian Blurring: Introduces realistic noise characteristics.
    - Z-axis Shifting: Applies random rotations (within ±15°) to simulate acquisition variability.
    - Backprojection-Shift-Forward Projection: Applies spatial shifts and transformation to refine sinogram realism.

- Federated Learning Module:

1. Orchestrator Application: Distributes the global model, initiates training rounds, aggregates parameters, and provides a user interface for learning managers.
2. Contributor Application: Locally trains the model on real data and sends only model updates to the orchestrator.

## 3. Detailed Functional Requirements

3.1 Data Generation and Augmentation
3.1.1 XCAT Phantom and XCAT+ Generation

- REQ-3.1.1.1: The system shall generate XCAT phantoms using a parameter file that includes hundreds of configurable parameters. At a minimum, it shall allow modification of gender, hrt_motion_y, and resp_start_ph_index.

- REQ-3.1.1.2: The system shall support automated randomization of these parameters to increase diversity as described in the Proposed Action section of the Dataset Augmentation Plan.

- REQ-3.1.1.3: The system shall extend XCAT phantoms to XCAT+s by applying statistical tracer concentration distributions (derived from real data) for key regions such as the myocardium, blood pool, and liver.

- REQ-3.1.1.4: The system shall include a configuration option for introducing lesions into the heart, enabling modeling of diseased patients. This functionality will be enabled once the appropriate tracer distributions for lesions are defined.

3.1.2 OpenGATE Simulation Requirements

- REQ-3.1.2.1: The system shall simulate SPECT imaging using OpenGATE and produce sinograms from the generated XCAT+s.

- REQ-3.1.2.2: The system shall validate that the output sinogram dimensions conform to a 128×128×120 format. If discrepancies are detected (e.g., the 128×128×240 artifact), the system shall automatically squash the output to the correct dimensions.

- REQ-3.1.2.3: The simulation shall support output to user-specified directories and file formats (e.g., DICOM for sinograms).

3.1.3 Data Augmentation Procedures

- REQ-3.1.3.1: The system shall apply sinogram squashing to correct for the output artifact observed in OpenGATE simulations.

- REQ-3.1.3.2: The system shall apply a Gaussian blur filter to both input (sinograms) and output images to mimic realistic noise. The parameters (kernel size, sigma) shall be configurable.

- REQ-3.1.3.3: The system shall perform Z-axis shifting by applying random rotations within a specified range (default: ±15°) to each sinogram, with a minimum of 5 rotations per input-output pair.

- REQ-3.1.3.4: The system shall execute a backprojection-shift-forward projection sequence:

1. REQ-3.1.3.4.1: Perform filtered backprojection (inverse Radon transform) on each sinogram.
2. REQ-3.1.3.4.2: Apply a configurable number of random shifts in the XY plane (default: 10 shifts, including the original position).
3. REQ-3.1.3.4.3: Re-apply forward projection (Radon transform) to regenerate the sinograms.

- REQ-3.1.3.5: The overall augmentation factor per XCAT+ should be configurable, with an expected default factor of up to 275×, as detailed in the Dataset Augmentation Plan .

- REQ-3.1.3.6: The system shall eliminate redundant data transpositions and duplicate storage to optimize performance during augmentation, as recommended in the Proposed Action section.

3.1.4 Data Repository and Synchronization

- REQ-3.1.4.1: The system shall support a centralized data catalogue/repository to store and synchronize generated data across multiple devices.

- REQ-3.1.4.2: The repository solution shall allow automated synchronization between up to four networked computers, ensuring consistency of the dataset.

3.2 Federated Learning Framework

3.2.1 Orchestrator Application

- REQ-3.2.1.1: The Orchestrator Application shall maintain the global model and manage the federated learning cycle.

- REQ-3.2.1.2: The system shall distribute the current global model to all registered Contributor Applications at the start of each training round.

- REQ-3.2.1.3: The system shall aggregate only anonymized model updates from Contributor Applications, ensuring no raw patient data is transmitted.

- REQ-3.2.1.4: The Orchestrator Application shall provide a graphical interface for learning managers to:

1. Monitor training progress.
2. Define trusted contributors.
3. Initiate or pause training rounds.

- REQ-3.2.1.5: The system shall include logging and error handling mechanisms to manage communication failures or data inconsistencies.

3.2.2 Contributor Application

- REQ-3.2.2.1: The Contributor Application shall securely receive the global model from the Orchestrator.

- REQ-3.2.2.2: The system shall perform local training using real SPECT data and preprocessed synthetic data as required.

- REQ-3.2.2.3: Only model parameter updates (e.g., weights and biases) shall be transmitted back to the Orchestrator.

- REQ-3.2.2.4: The Contributor Application shall include robust error handling to continue processing even when encountering corrupted or non-DICOM files.

- REQ-3.2.2.5: The system shall log training progress and any exceptions, including file-specific error messages.

3.3 Additional Granular Requirements from Proposed Actions

Drawing on the Proposed Action section of the Dataset Augmentation Plan:

- REQ-3.3.1: The system shall include a mechanism for parameter randomization in the XCAT generation stage to enhance anatomical diversity.

- REQ-3.3.2: The system shall provide options to toggle between models for healthy patients and those incorporating lesion simulation for diseased patients.

- REQ-3.3.3: The system shall implement diagnostic checks for OpenGATE output dimensionality and, if necessary, flag discrepancies for review.

- REQ-3.3.4: The system shall include a module for experimental evaluation that compares augmented synthetic data with real patient data, enabling iterative refinement of the augmentation parameters.

## 4. Performance Requirements

4.1 Image Reconstruction

- PR-4.1.1: The neural network shall reconstruct a 3D SPECT image from a given sinogram in under 5 seconds per instance.

- PR-4.1.2: Reconstruction performance shall be validated against a representative set of both synthetic and real sinograms.

4.2 Federated Learning Cycle

- PR-4.2.1: The system shall support efficient communication between up to 50 concurrent Contributor Applications.

- PR-4.2.2: Although the overall duration of a federated learning cycle is not strictly bounded, the system shall ensure that network overhead and parameter aggregation do not delay subsequent training rounds more than necessary.

- PR-4.2.3: The system shall log communication latencies and model update times to facilitate performance tuning.

4.3 Data Augmentation

- PR-4.3.1: The augmentation pipeline shall process each XCAT+ instance within a time frame that does not become a bottleneck for the overall dataset generation.

- PR-4.3.2: Optimizations (such as removal of unnecessary data transpositions) shall ensure that augmentation remains scalable as dataset size increases. Also cropping out unnecessary components during XCAT phase should significantly decrease the time to produce a sinogram (ie.. cropping out the entire anatomy of a human except required organs)

## 5. Security & Privacy Requirements

5.1 Data Privacy

- SEC-5.1.1: The system shall comply with HIPAA and other relevant privacy regulations by ensuring that no raw patient data leaves the local environment.
- SEC-5.1.2: All data transfers between Contributor Applications and the Orchestrator shall be encrypted using industry-standard protocols.

5.2 Access Control

- SEC-5.2.1: The system shall include role-based access controls to restrict the management interface to authorized learning managers.
- SEC-5.2.2: Contributor Applications shall authenticate with the Orchestrator using secure credentials before receiving model updates.

5.3 Audit and Logging

- SEC-5.3.1: All access, training transactions, and data transfers shall be logged for audit purposes.
- SEC-5.3.2: The system shall support periodic reviews of logs to detect any unauthorized access or anomalies in data handling.

## 6. References and Appendices

6.1 References


- [1] Bruyant, Philippe P. “Analytic and iterative reconstruction algorithms in SPECT.” Journal of Nuclear Medicine 43, no. 10 (2002): 1343–1358.
- [2] Chang, Haoran, Valerie Kobzarenko, and Debasis Mitra. “Inverse radon transform with deep learning: an application in cardiac motion correction.” Physics in Medicine & Biology 69, no. 3 (2024): 035010.
- [3] Additional references are provided in the prior requirements document and the Dataset Augmentation Plan .


6.2 Appendices

Data Augmentation Techniques:

- Sinogram Squashing:
  Fixes OpenGATE artifact (128×128×240 → 128×128×120) by merging duplicate slices.
- Gaussian Blurring:
  Applies a 5×5 Gaussian kernel ($\sigma$=1.0) to sinograms and reconstructions, simulating realistic noise.

- Z-Axis Rotation:
  Introduces ±15° rotations (5× per sinogram) to mimic misalignment.
- Backprojection-Shift-Forward Projection:
  Reconstructs sinograms (via FBP), applies random XY shifts, then forward projects them (11× per sinogram).
- Total Augmentation:
  Combined factor of 275× per XCAT+ phantom.

Proposed Actions:

- Parameter Randomization:
  Randomize XCAT phantom parameters (e.g., gender, heart motion, respiratory phase) for anatomical diversity.
- Diseased XCAT+s:
  Simulate heart disease by modifying lesions and tracer levels based on real SPECT data.
- Investigate OpenGATE Discrepancies:
  Analyze and correct the sinogram output issue across different configurations.
- Process Optimization:
  Streamline operations by removing redundant transpositions and duplicate storage.
- Model Evaluation:
  Compare augmented and real SPECT scans (using RMSE, SSIM, FSIM) to refine augmentation parameters.
- Centralized Repository:
  Implement a unified data storage solution (e.g., Git LFS, Google Drive, NAS) for consistent access.
- Dataset Expansion:
  Increase simulation volume to ensure balanced healthy and diseased datasets.