NeuroX Hybrid: Advanced Brain Analysis Platform

Review I – Problem Identification, Domain Analysis & Feasibility Study

Project ID/Code: BCSE498J

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Project Abstract

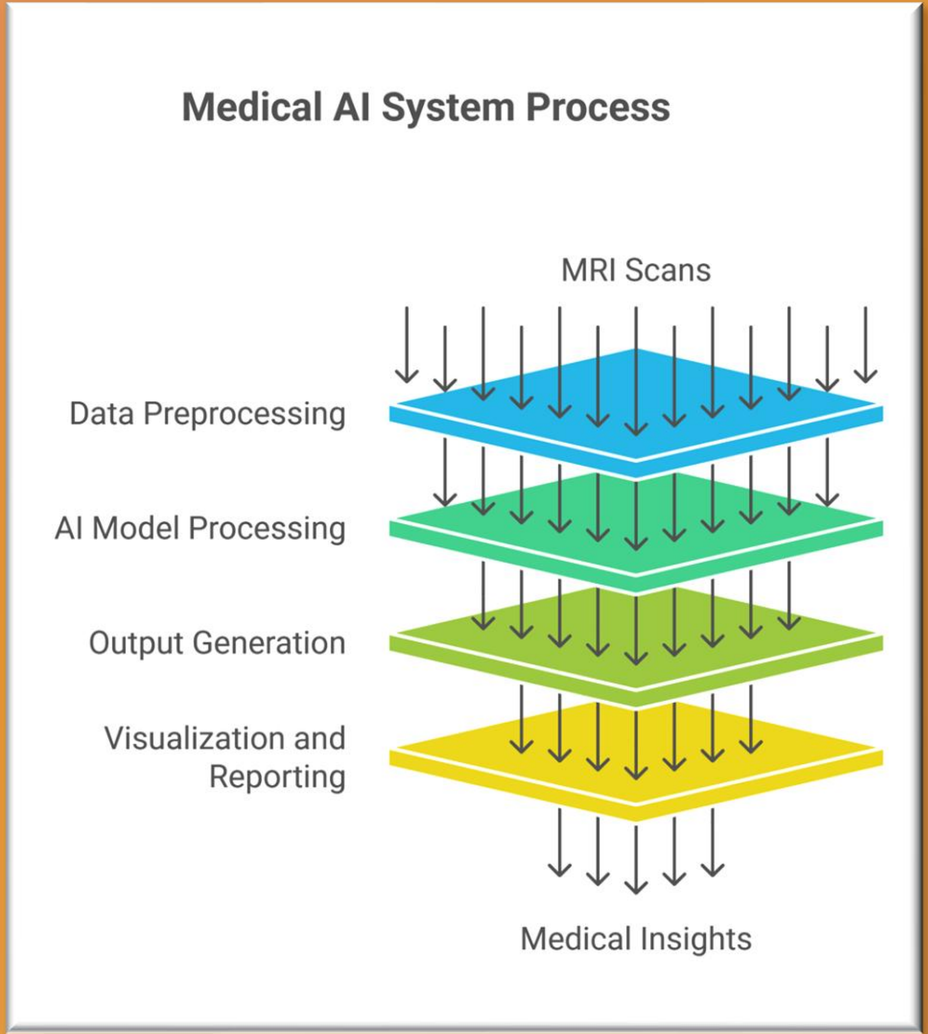
- **The Goal:** To design an automated "Hybrid" Deep Learning system for the simultaneous segmentation and classification of brain tumors from 3D MRI scans.
- **The Problem:** Manual MRI analysis is slow (1-3 hours/patient) and prone to human error. Standard AI models often fail to capture the "global context" of the brain.
- **The Solution:** A unified framework combining 3D ResNets (for detail) and Swin Transformers (for context).
- **Outcome:** A web-based dashboard delivering 3D interactive visualizations and AI-generated clinical reports.

High-Level System Concept

- **Input:** Raw Multi-Modal MRI data (NIfTI format).
- **Processing Layers:**

  The image demonstrates our layered approach:

  Data Preprocessing → AI Model Inference → Output Generation.
- **Output:** The system transforms raw pixels into "Medical Insights" (Reports & 3D Models).



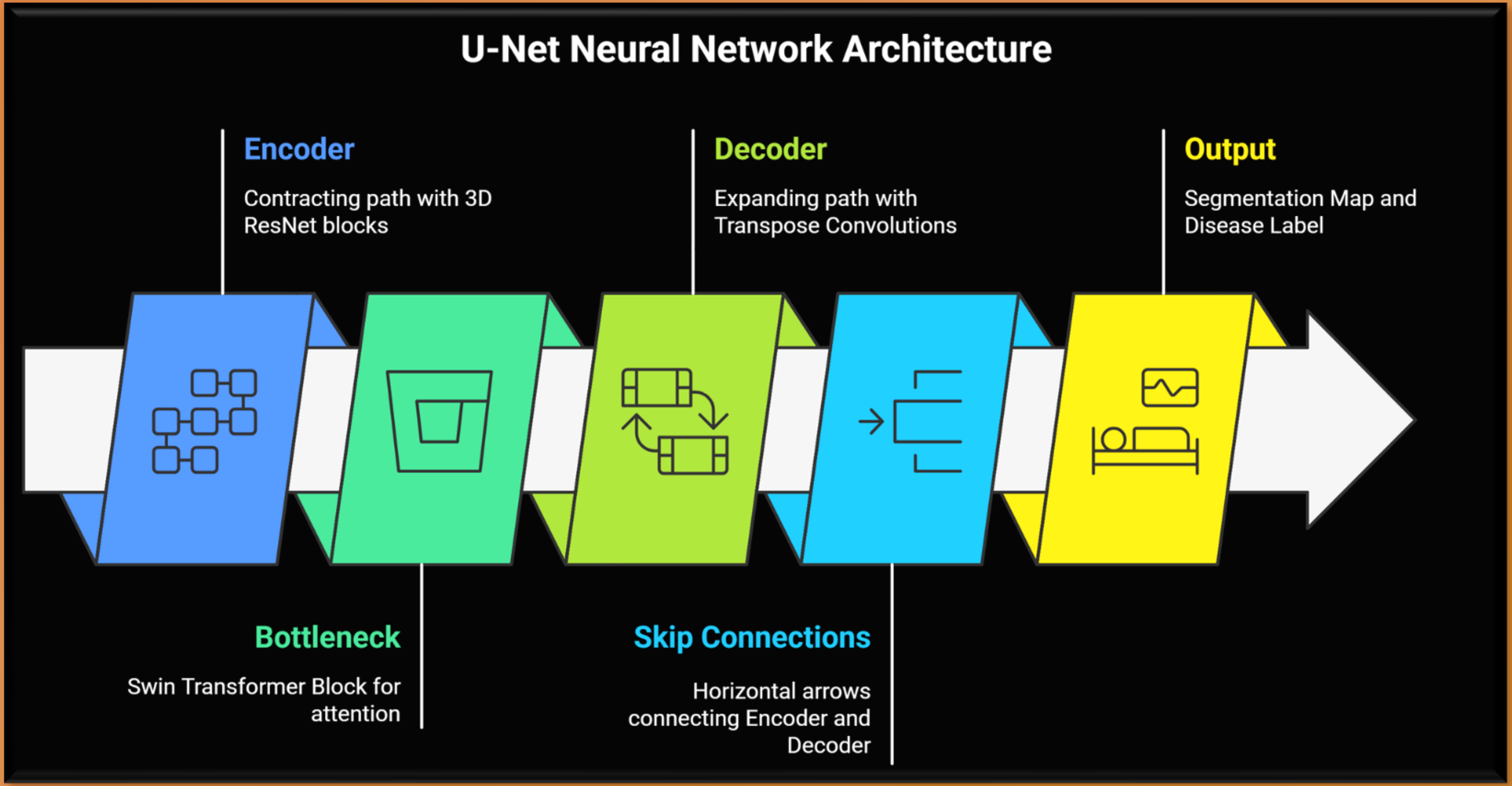
Domain Identification (Rubric: Domain)

- **Primary Domain:** Medical Computer Vision.
- **Sub-Domain:** Volumetric (3D) Image Segmentation.
- **Clinical Context:**
  - **Neuroradiology:** We are addressing the diagnosis of Gliomas and Meningiomas.
  - **Multi-Modal Data:** The domain requires analyzing 4 MRI sequences (T1, T1ce, T2, FLAIR) simultaneously to distinguish edema from the tumor core.
- **Relevance:** Accurate segmentation is critical for radiotherapy planning and tracking tumor growth.

Problem Identification (Rubric: Problem ID)

- **Bottleneck:** Radiologists face "Reader Fatigue." Manual segmentation is subjective; two doctors may trace the same tumor differently.
- **The "Context" Problem:**
  - Tumors have irregular shapes and fuzzy boundaries.
  - **Class Imbalance:** Healthy brain tissue vastly outnumbers tumor pixels, making it hard for standard models to find small lesions.
- **Technical Gap:** Existing tools are either fast but inaccurate (2D slices) or accurate but computationally impossible (Pure 3D Transformers).

Background – The Standard Approach



- This image shows the U-Net architecture, the current industry standard.
- **Strengths:** Good at local feature extraction (edges/textures) using the "Encoder-Decoder" structure.
- **Weakness:** It lacks "Global Attention." It sees the tumor's edge but struggles to understand where the tumor is relative to the rest of the brain structure.

Motivation for "Hybrid" Architecture

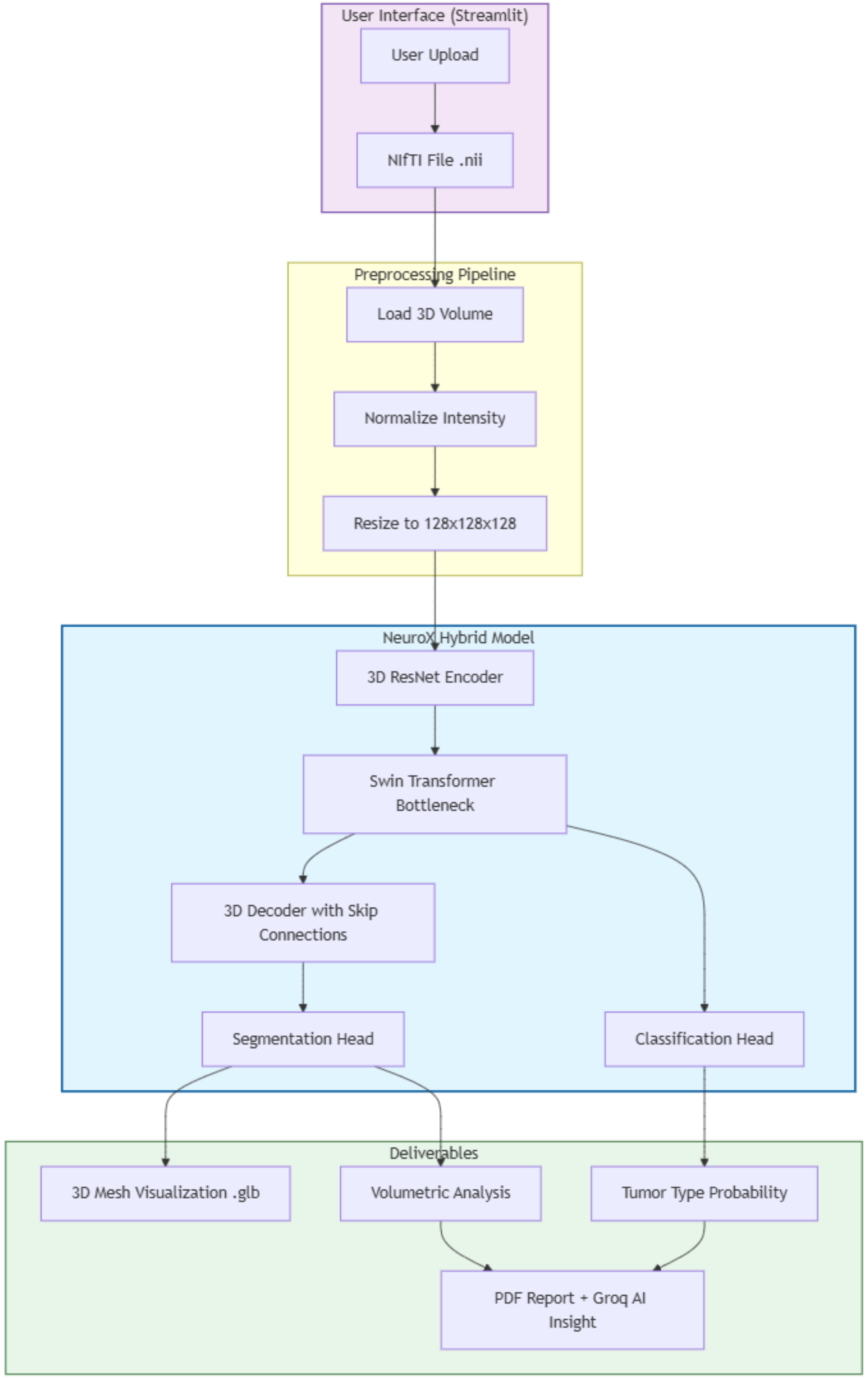
- **Why Hybrid?** We propose combining the best of two worlds:
  1. **CNN (ResNet):** Excellent at capturing high-frequency details (boundaries, texture).
  2. **Transformer (Swin):** Excellent at capturing long-range dependencies (relationships between distant pixels).
- **The Synergy:** The CNN handles the "what" (tumor texture), and the Transformer handles the "where" (spatial location).

Problem Statement

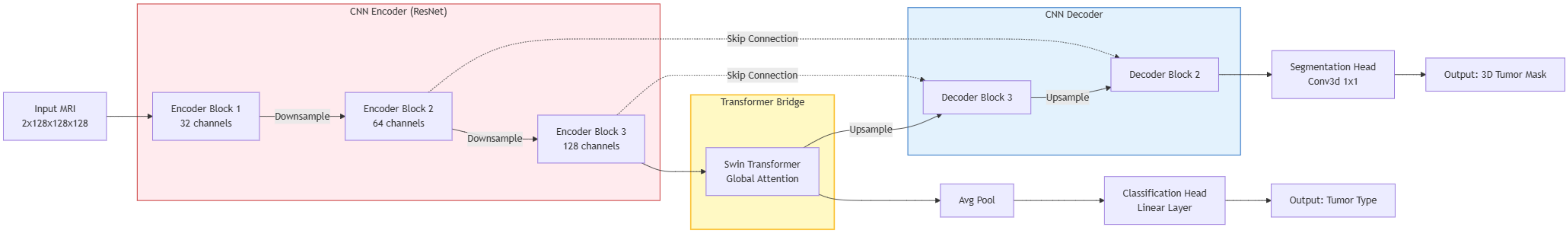
- **Statement:**
  - "To design and develop a Hybrid Deep Learning Framework that integrates 3D Residual Networks and Swin Transformers to automate the segmentation of brain tumor sub-regions and the classification of tumor types (Glioma, Meningioma, Pituitary) from multi-modal MRI scans.“
- **Success Criteria:**
  - Dice Coefficient > 0.85 for Whole Tumor.
  - Inference time < 60 seconds per patient.

System Workflow

- **Workflow Steps:**
  1. **User Input:** Upload .nii or .nii.gz file via Streamlit UI.
  2. **Preprocessing:**
     - Load 3D Volume.
     - Normalize Intensity (0-1 scale).
     - Resize to ROI (128, 128, 128).
  3. **NeuroX Inference:** The Hybrid model processes the data.
  4. **Deliverables:** 3D GLB Mesh generation + PDF Report creation.



Proposed Architecture (Technical Core)



Encoder (Pink): Uses ResBlock3D to downsample features.
Transformer Bridge (Yellow): The key innovation. A SwinBlock3D processes the latent features with self-attention.
Dual Heads (Purple):
- **Segmentation:** Outputting a 3D mask.
- **Classification:** Outputting disease probability.

Feasibility – The Encoder

- **Component:** ResBlock3D (Residual Block).
- **Function:** Extracts features using 3D Convolutions (nn.Conv3d) and Group Normalization (nn.GroupNorm).
- **Feasibility Check:** We limit the channel depth to 32 → 64 → 128 filters. This ensures the model fits within the VRAM of standard GPUs (e.g., T4 or RTX 3060).

Feasibility – The Transformer Bridge

- **Component:** SwinBlock3D.
- **Mechanism:** Uses nn.MultiheadAttention to analyze relationships between features.
- **Optimization:** Instead of standard attention (which is $O(N^2)$), we use window-based attention to reduce computational complexity, making 3D processing feasible.

Assumptions & Constraints

- **Assumptions:**
  - **Input Format:** Data must be in NIfTI format (standard for medical research).
  - **Modality:** Scans must contain at least two channels (e.g., FLAIR + T1ce) for accurate feature extraction.
- **Constraints:**
  - **Resolution:** Input is strictly cropped/resized to (128, 128, 128) to prevent Memory OOM errors.
  - **Scope:** Model detects only Glioma, Meningioma, and Pituitary tumors; it is not a general-purpose brain anomaly detector.

Implementation Plan

Datasets

BraTS 2023 for Glioma segmentation, ISLES 2022 for stroke lesion robustness, and ADNI 3 for structural reference.

Visualization

Trimesh is used for 3D Mesh export.

Reporting

ReportLab for PDF generation and Groq API for AI interpretation.

Framework

PyTorch and MONAI are used as the framework.

Conclusion & Future Work

- **Summary:** NeuroX Hybrid addresses the limitations of standard CNNs by integrating Transformers for better context.
- **Status:** Architecture is defined, datasets are identified, and the feasibility of 3D processing is confirmed via the 128^3 constraint.
- **Next Phase:** We will proceed to training the Encoder-Decoder on the BraTS dataset and developing the Streamlit frontend.