Methods and Experiments

Genetic Algorithm Enhanced Multimodal Brain Tumor Segmentation

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1 Methods

1.1 Architecture

We adopt a YOLO-style encoder-decoder with a segmentation head tailored for multimodal inputs. Two modality-specific streams (CT and MRI) process inputs in parallel, and their features are fused via a cross-modal attention (CMA) module at multiple scales.

Cross-Modal Attention Given CT and MRI features F_c and F_m, CMA computes queries, keys, and values per stream and exchanges information:

$$A = \text{softmax}\left(\frac{Q_c K_m^\top}{\tau}\right) V_m, \quad A' = \text{softmax}\left(\frac{Q_m K_c^\top}{\tau}\right) V_c,$$

with residual gating and LayerNorm for stability. The fused features feed into the decoder and segmentation head.

1.2 Multi-Objective Genetic Tuning

We jointly optimize accuracy (Dice), efficiency (FLOPs/latency), and predictive uncertainty under constraints. The gene space includes width/depth, kernel sizes, attention on/off, thresholds, and augmentation policies. We employ tournament selection, simulated binary crossover, Gaussian mutation, and elitism with early stopping.

1.3 Uncertainty and Postprocessing

We estimate voxel-wise variance via Monte Carlo Dropout or test-time augmentation. Calibration-aware thresholding and morphological postprocessing (keep largest per class, min component size, closing) are applied.

2 Experiments

2.1 Datasets and Protocol

We follow BRaTS-style settings and synthetic validations. Data are preprocessed with robust normalization and registration. We fix seeds and report mean±std over $\geq$5 runs.

2.2 Baselines and Metrics

Baselines include U-Net, Attention U-Net, nnU-Net, and YOLO-based segmentation. We report Dice (WT/TC/ET), Jaccard, Hausdorff95, sensitivity/specificity, and calibration metrics (ECE).

2.3 Implementation Details

Reproducibility is ensured by global seeding, MLflow logging, and environment metadata. Inference-time efficiency is measured on CPU for portability and on a representative GPU for throughput.

2.4 Statistical Significance

We conduct Welch's t-tests for repeated experiments and report Cohen's d as effect size. Significance is assessed at $p < 0.05$.