AKD-BNN: Adaptive Kernel Dynamic Bayesian Neural Networks for Enhanced Medical Image Segmentation with Uncertainty Estimation

Qianying He, Xuan Liu, Wenjian Liu*

City University of Macau

INTRODUCTION

Medical image segmentation underpins computer-aided diagnosis and therapy planning, yet high spatial heterogeneity, low tissue contrast, and noise make accurate delineation and calibrated uncertainty difficult. Existing BNN–GP methods estimate uncertainty but depend on fixed kernels and weight-space priors that fail to adapt to local anatomical variation, limiting robustness in complex cases. We propose the Adaptive Kernel Dynamic Bayesian Neural Network (AKD-BNN), a dynamic Bayesian framework that learns adaptive GP kernels from local semantic features, fuses multi-scale representations with a Transformer backbone, and optimizes with an uncertainty-weighted loss. AKD-BNN improves boundary modeling, delivers reliable uncertainty maps that highlight high-risk regions, and enhances adaptability to high-dimensional medical tasks—advancing trustworthy segmentation for real-world clinical use.

BACKGROUND

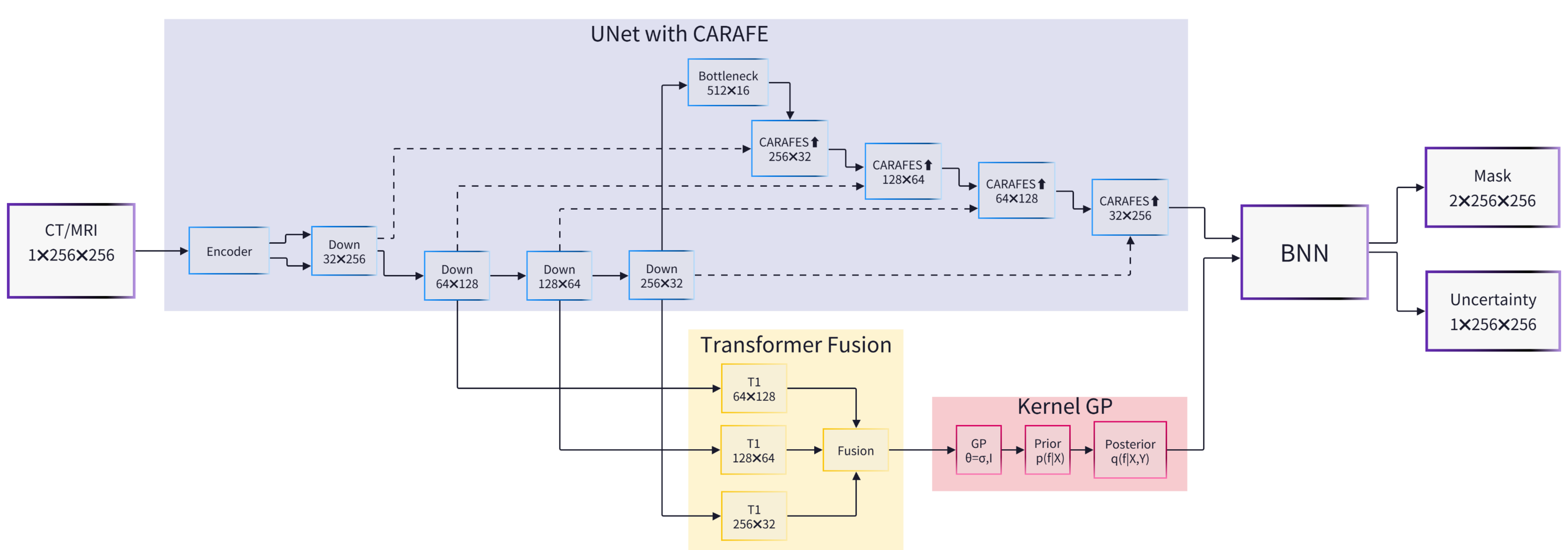
Medical image segmentation has seen significant progress with deep learning advancements, especially through architectures like UNet and DeepLabV3+. UNet, with its encoder-decoder structure and skip connections, excels in multi-scale feature fusion, while DeepLabV3+ enhances boundary detection using atrous convolutions and spatial pyramid pooling. Despite their success, these methods focus on deterministic predictions, lacking uncertainty estimation, which limits their clinical applicability. Traditional Bayesian Neural Networks (BNNs) combined with Gaussian Processes (GPs) offer a promising framework for uncertainty quantification. However, the use of fixed-kernel GPs in medical image segmentation struggles to model local variations, such as tumor boundaries, due to the uniform assumptions of feature correlations. This limitation hinders the accurate assessment of uncertainty, especially in critical regions like lesion boundaries, and remains an open challenge in the field.

CONTRIBUTIONS

✓ We propose AKD-BNN for medical image segmentation, enhancing both segmentation accuracy and uncertainty estimation. The model incorporates dynamic kernel Gaussian processes and a multi-scale feature fusion mechanism to improve adaptability to spatial heterogeneity.

✓ We introduce an uncertainty-guided loss function, which prioritizes high-uncertainty regions in medical images, optimizing segmentation performance while ensuring reliable uncertainty estimation for clinical applications.

METHOD



AKD-BNN is a framework designed to enhance medical image segmentation and provide reliable uncertainty estimation. Built upon the UNet architecture, AKD-BNN retains the CARAFE operator for semantic feature extraction. It introduces two key components: (1) the Adaptive Kernel GP module, which adjusts kernel parameters to better model local image features, and (2) a multi-scale feature fusion mechanism that leverages Transformer-based multi-resolution extraction and dynamic weighting to optimize global and local context representation. The pipeline involves feature extraction, followed by adaptive prior/posterior distribution construction using the Adaptive Kernel GP, and final segmentation and uncertainty map generation through a BNN inference layer.

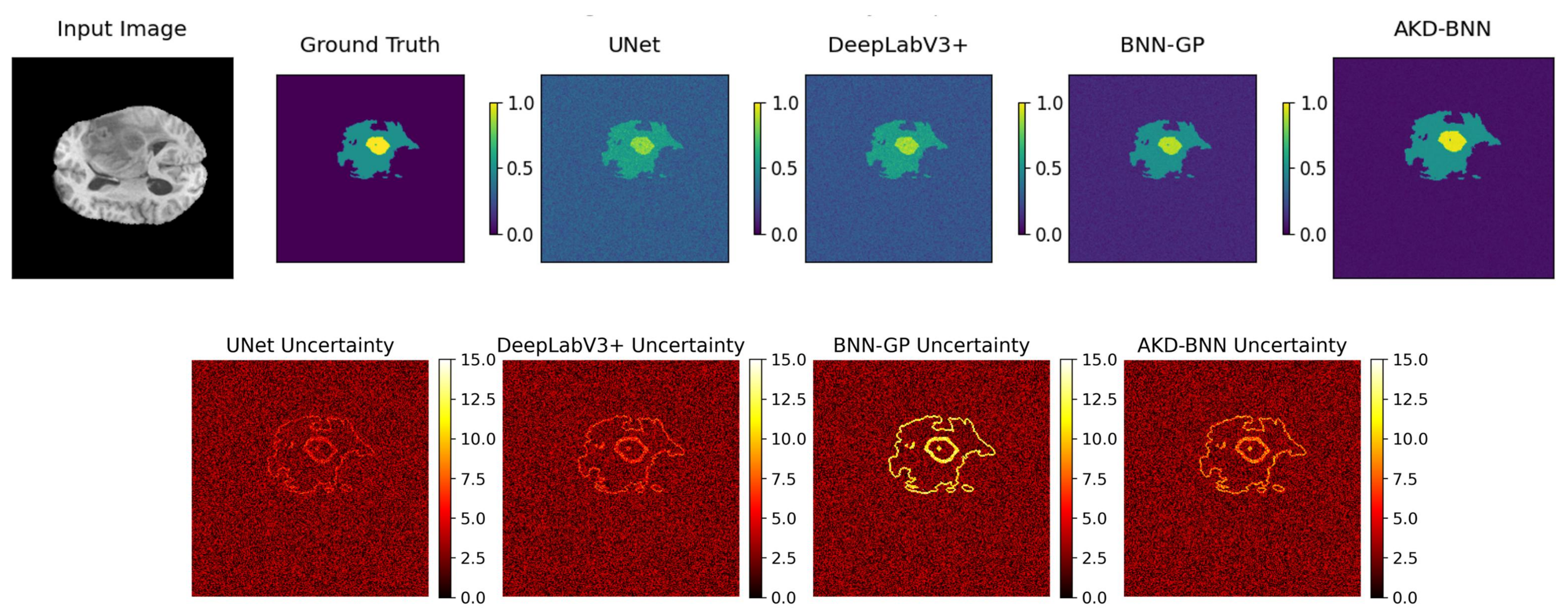
RESULTS

Method	Dataset	Dice	IoU	HD (mm)	ECE
UNet	BraTS	0.87	0.78	4.5	0.15
DeepLabV3+	BraTS	0.89	0.81	4.0	0.12
BNN-GP	BraTS	0.90	0.83	3.8	0.10
AKD-BNN	BraTS	**0.95**	**0.89**	**3.2**	**0.08**
UNet	ACDC	0.88	0.79	4.2	0.14
DeepLabV3+	ACDC	0.90	0.82	3.9	0.11
BNN-GP	ACDC	0.91	0.84	3.7	0.09
AKD-BNN	ACDC	**0.96**	**0.90**	**3.1**	**0.07**
UNet	LIDC-IDRI	0.85	0.76	5.0	0.16
DeepLabV3+	LIDC-IDRI	0.87	0.78	4.7	0.13
BNN-GP	LIDC-IDRI	0.88	0.80	4.5	0.11
AKD-BNN	LIDC-IDRI	**0.93**	**0.86**	**3.9**	**0.09**

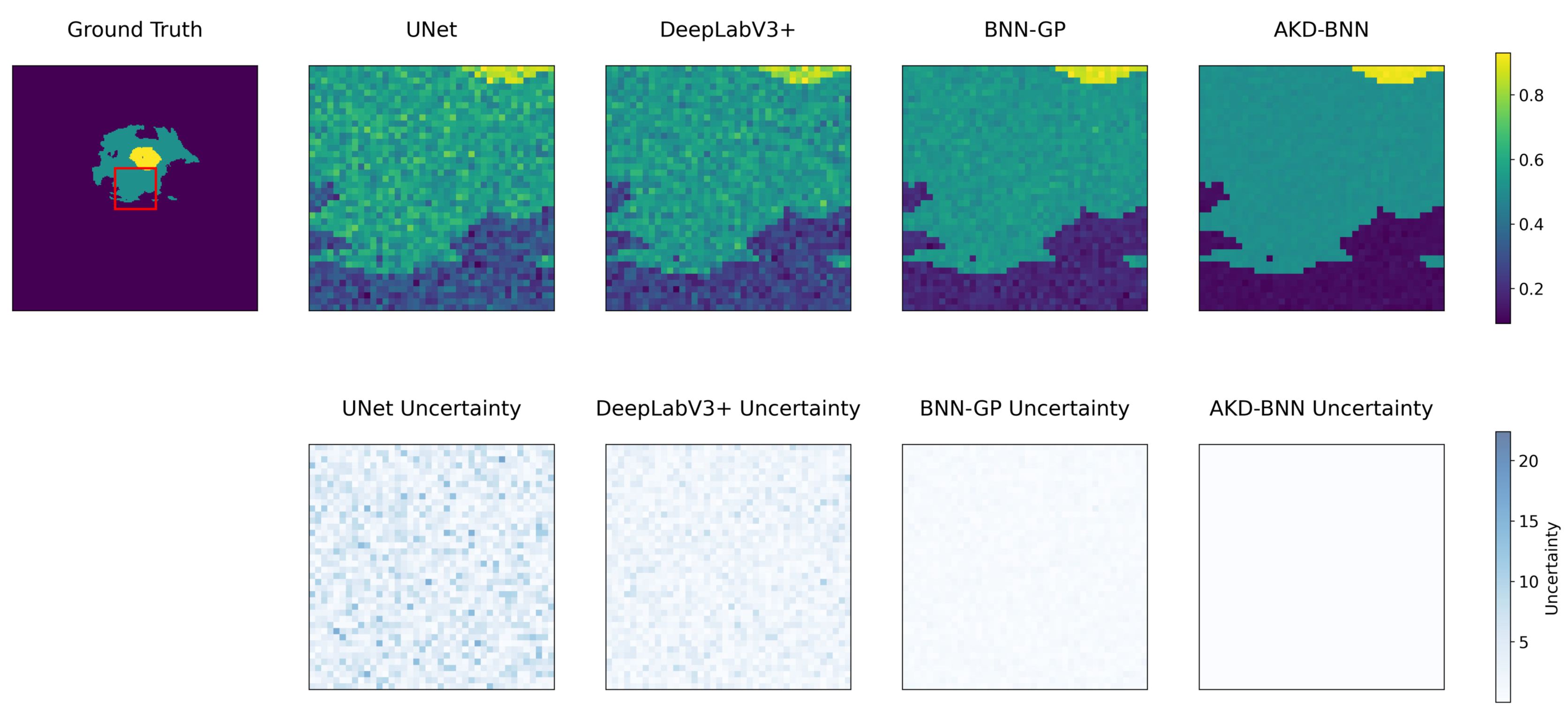
(a)Performance Comparison of AKD-BNN Andbaselines

Configuration	Dice	IoU	HD (mm)	ECE	Coverage
UNet + BNN-GP	0.90	0.83	3.8	0.10	0.88
+ AK-GP	0.92	0.85	3.6	0.09	0.89
+ Multi-Scale	0.94	0.87	3.4	0.085	0.91
+ Uncertainty Loss	**0.95**	**0.89**	**3.2**	**0.08**	**0.92**

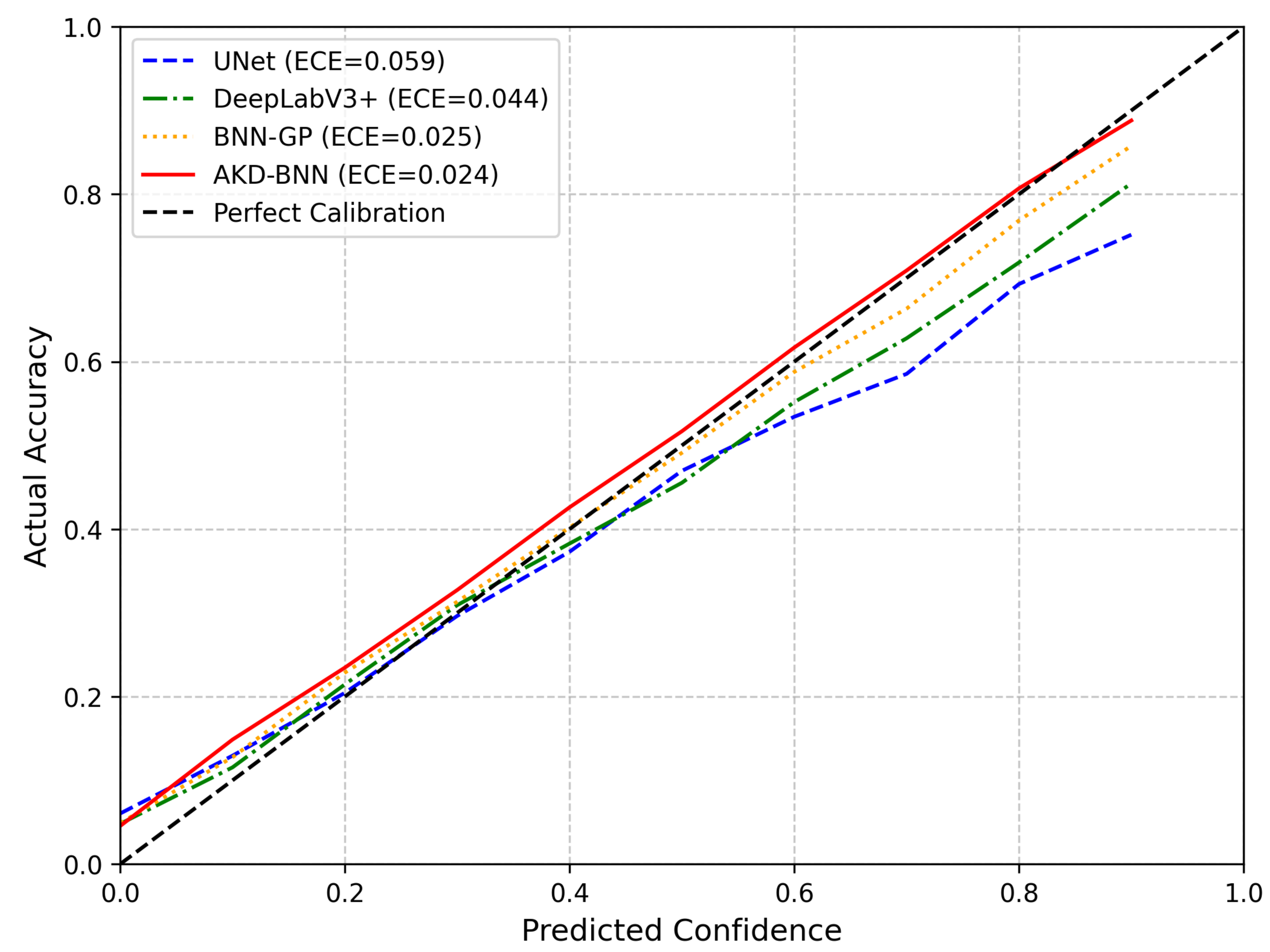
(b) Ablation Study of AKD-BNN on BraTS



(c) Model Predictions and Uncertainty Maps on the BraTS Dataset



(d) Magnified View of Tumor Boundaries on the BraTS Dataset



(e) Uncertainty Calibration Curves on the BraTS Dataset