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Liver Segmentation using Deep learning with Multi-Core Pooling Modules

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Abstract

Accurate liver segmentation in laparoscopic procedures is an important challenge owing to low contrast, non-uniform illumination, occlusion from instruments, and non-uniform organ boundaries. Inaccurate or delayed segmentation may enhance surgical risk, operating time, and recovery time for the patient. Although convolutional neural networks (CNNs) have shown good performance in medical image segmentation, previous approaches either obtain high accuracy at the expense of computational efficiency or obtain lightweight operation with low precision but usually lose fine-grained boundary details. To overcome the above shortcomings, we introduce a new deep learning network for laparoscopic liver segmentation that combines an InceptionV3 backbone with Multi-Core Pooling (MCP) and an enhanced Atrous Spatial Pyramid Pooling (ASPP) module. The proposed hybrid architecture extracts multi-scale contextual information, preserves boundary precision, and is computationally light

enough for future real-time surgery use. The model is tested on the publicly available M2CAI Segmentation dataset and exhibits better performance than state-of-the-art algorithms like U-Net++, nnU-Net, and SwinD-Net. Our findings reveal that the proposed model provides robust, accurate, and efficient liver segmentation, presenting a promising solution for real-time intraoperative guidance.

Introduction

Laparoscopic liver surgery is more prevalent today because it is minimally invasive, but precise intraoperative segmentation and identification of the liver is still a significant problem. The laparoscopic setting adds complications like low contrast, non-uniform illumination, occlusion by instruments, and irregular boundaries of organs, all of which make pixel-level segmentation procedures difficult [13], [9], [8]. Traditional solutions cannot deliver consistent real-time segmentation under these conditions and are therefore confined to ad-hoc use cases in clinical pipelines. Inaccurate or delayed liver segmentation during surgery may result in severe complications, such as misidentification of key structures, increased operative time, and heightened surgical risk [9], [21]. Efficient and computerized segmentation techniques are thus critical for helping surgeons to better perceive the operating field, enhance surgical accuracy, and minimize intraoperative mistakes and patient recovery times [22], [5]. Consistent liver segmentation inevitably facilitates safer outcomes in surgical procedures like tumor resections and living donor liver transplants [8]. Deep learning techniques, especially convolutional neural networks (CNNs), have been proven to have high capability in laparoscopic image analysis [20], [1]. Architectures of U-Net and its extensions (U-Net++ [24], nnU-Net [10], INet [20]) have yielded great success in medical image segmentation, whereas annotation-efficient approaches [18] and light-weight networks such as SwinD-Net [13] have enhanced applicability in resource-constrained

environments. Certain laparoscopic applications involve semantic segmentation of autonomic nerves [9], instrument segmentation [7], and registration of 3D models in real-time [14]. Even with these developments, the majority of methods lack robustness in tough surgical conditions. To overcome these constraints, we introduce a better deep learning algorithm for laparoscopic liver segmentation involving an InceptionV3 backbone [19] combined with Multi-Core Pooling (MCP) and a revised Atrous Spatial Pyramid Pooling (ASPP) module [10]. The suggested method is intended to extract multi-scale contextual information, maintain fine-grained boundary details, and be computationally efficient enough for real-time application in surgery. The model is assessed on the publicly available m2caiSeg dataset [12], [11], which constitutes a challenging benchmark for comparison of performance.

- Proposing a new liver segmentation model integrating InceptionV3, MCP, and ASPP for improved feature extraction and contextual learning. • Conducting a thorough evaluation of the segmentation performance using Dice Score, Jaccard Index, and Intersection-over-Union (IoU) [15, 4, 2].
- Comparing with current state-of-the-art techniques such as U-Net++, nnU-Net, and SwinD-Net, demonstrating improvements both in accuracy and robustness.
- Designing a lightweight architecture suitable for future integration within real-time laparoscopic systems.

Even though CNN-based architectures have shown good performance, existing approaches either emphasize high accuracy but suffer from inefficient computation [24, 10] or focus on lightweight operation with lower accuracy [13]. Moreover, most models do not efficiently preserve fine boundary structures that are essential for surgical navigation, particularly in complicated light conditions. This work bridges these

limitations by introducing an optimized architecture with accurate, robust, and efficient computation, paving the way for real-time clinical use.

2 Literature Review

Deep learning has redefined medical image segmentation from hand-crafted pipelines to end-to-end trainable models. Exhaustive surveys distill essential concepts in CNNs, common encoder–decoder topologies, and real-world challenges including limited labels, class imbalance, and domain shift, and chart application frontiers across healthcare and beyond [1, 5]. Among biomedical segmentation alone, U-Net-based families prevail: nested skip connections within U-Net++ promote multi-scale feature fusion and detailed boundary restoration [24], and nnU-Net further automates preprocessing, architecture, and training to dataset statistics, creating strong baselines on various tasks [6]. INet delves into the design decisions of convolution tailored to biomedical images and demonstrates how architectural priors applied thoughtfully can compete with larger models with fewer parameters [20]. Recent advancements like UNeXt have pushed the boundaries of efficiency by integrating tokenized MLPs for ultra-fast segmentation, proving critical for real-time clinical applications [17]. Together, these lines demonstrate that architectural bias towards multi-scale context, boundary fidelity, and computational efficiency continues to be most critical to performance.

Early work on laparoscopy-specific vision demonstrated feasibility for each of the primary subproblems—organ/tissue parsing, instrument segmentation, and surgical scene understanding—under very tight constraints of smoke, specularities, and rapid motions [7, 16, 21]. More recent research aims higher toward clinical specificity and efficiency. Kojima et al. proved semantic segmentation of autonomic nerves during colorectal surgery, highlighting the requirement for accurate boundary modeling of thin,

low-contrast anatomy [9]. Ouyang et al.'s SwinD-Net enjoys hierarchical transformers while remaining light, proving that token mixing with caution and windowed attention can satisfy laparoscopic runtime requirements without penalizing accuracy [13]. The shift towards transformer-based architectures is further exemplified by models like TransUNet, which combine the visual recognition strength of ViT with the precise localization of U-Net, setting a new standard for accuracy [3]. Collectively, these studies highlight two ongoing demands in the operating room: robustness to occlusion/lit artifacts, as well as deployable latency.

Image quality and geometric coherence are concurrent enablers for subsequent segmentation. Zheng et al. presented a deep learning framework for improving laparoscopic video quality, reducing noise and lighting fluctuation that undermine pixel-wise accuracy [22]. To assure spatial consistency of the endoscopic image and pre/intraoperative models, Padovan et al. have suggested a deep real-time framework for 3D model registration for robot-assisted laparoscopy, emphasizing the importance of small-but-stable temporal features and effective correspondence in the presence of stringent computational budgets [14]. The implications are that segmentation precision is bound up with upstream improvement and geometric registration in real-world pipelines.

Outside of raw architecture, lack of annotation encourages techniques that reduce labeling burden without sacrificing performance. Wang et al. surveyed annotation-efficient medical segmentation learning under weak, semi-, and selfsupervised regimes as well as consistency/uncertainty-based objectives that minimize dependence on dense pixel labels [18]. These methods are most applicable to laparoscopic datasets where expensive and center-variable expert delineation exists and prophesy future

combination with lightweight backbones for clinical use. A prime example of this is the UNet++ model trained with limited annotations, which demonstrates how advanced architectures can maintain high performance even with sparse labeled data, directly addressing the annotation bottleneck [23].

Attention mechanisms and atrous pyramids continue to be central instruments for multi-scale context. RAANet integrates residual Atrous Spatial Pyramid Pooling with attention to capture wide-receptive-field information with retaining detail in high-res aerial imagery—an equivalent requirement in laparoscopy where there is variation of scales and intricate edges in organs [10]. Although RAANet is aimed at remote sensing, its principle of design (dilated multi-scale context + attention + residual refinement) naturally generalizes to operating rooms. Also, Inception-like modules that convolve and diversify kernel sizes have been found effective in efficient multi-scale representation; Wang et al. demonstrated better recognition with an improved Inception V3 variant, highlighting the ongoing utility of heterogenous receptive fields under limited compute [19].

Method development is anchored in datasets and clinical comparatives. The m2caiSeg initiative offers a laparoscopic semantic segmentation benchmark with standardized splits and labels, allowing reproducible testing and cross-paper comparison [12, 11]. From a clinical perspective, Kavur et al. compared semiautomatic software with fully automatic deep models in liver segmentation within living donor evaluation, casting light on expert engagement-trade-offs, reliability, and throughput considerations that are immediately relevant to intraoperative application [8]. These studies and resources set up expectations both for quantitative performance and real-world usability.

Lastly, metric selection and loss architecture influentially impact optimization behavior and reported performance. Jaccard/IoU-optimized surrogates stabilize training for class-imbalanced foregrounds common in organ masks [15], while Boundary-IoU emphasizes contour precision, punishing topological and edge mistakes that surgeons most care about during navigation [4]. Dice and Jaccard optimization analyses elucidate when overlap-based losses match evaluation and how to blend them with pixel-wise terms to ensure stable convergence [2]. When combined with enhancement/registration inputs [22, 14], these metric-aware objectives prompt models that are both statistically robust and clinically useful. As shown in Table 1, different segmentation models demonstrate trade-offs between accuracy, computational cost, and applicability across domains.

Table 1: Comparison of Segmentation Models

Reference	Model / Method	Domain & Dataset	Key Features	Limitations
Zhou et al., 2018	U-Net++ (Nested U-Net)	Medical im-Ages	Multi-scale feature aggregation, improved boundary precision	Computationally heavy, sensitive to tuning
Isensee et al., 2021	nnU-Net (Selfconfiguring U-Net)	Biomedical images	Auto preprocessing, architecture, training setup	High computational cost, not real-time
Ouyang et al., 2024	SwinD-Net (Transformerbased)	Laparoscopic liver images	Lightweight, hierarchical Swin blocks, real-time	Slightly lower accuracy than larger hybrids

Liu et al., 2022	RAANet (Residual ASPP + At-tention)	Remote sensing images	Multi-scale pooling, attention for strong boundaries	Designed for aerial images, needs adaptation
Weng & Zhu, 2021	INet (Efficient CNN)	Biomedical images	Balanced accuracy vs. parameter count	Lacks transformer like global context
Chen et al., 2021	TransUNet (Transformer + U-Net)	Multi-domain medical im-ages	Combines ViT for global context with U-Net for localization	High parameter count, requires large datasets to train effectively
Valanarasu et al., 2022	UNeXt (MLP-based)	Medical im-ages	Extremely fast inference, tokenized MLP architecture	Performance can lag behind larger CNN/Transformer models on complex tasks
Zhou et al., 2019	UNet++ (Limited An-notations)	Medical im-ages	Designed for performance with sparse labeled data	Performance still ultimately dependent on quantity and quality of annotations

3 Methodology

The proposed methodology for liver segmentation integrates advanced deep learning architectures to accurately delineate organ boundaries in laparoscopic images. The pipeline involves dataset acquisition and preprocessing, followed by model training using encoder-decoder networks enhanced with Multi-Core Pooling (MCP) and

Improved Atrous Spatial Pyramid Pooling (ASPP) modules. Finally, the trained model generates segmentation masks on unseen test images, with optional explainability provided through LIME for interpretability of predictions. The complete work flow of methodology discussed in the Fig 1.

3.1 Dataset Acquisition

The M2CAI Segmentation Dataset, which is publicly available, was used for the segmentation of liver images. The dataset, downloaded from Kaggle [11], comprises endoscopic images and their respective ground truth masks. For the purpose of experiments, the dataset was split into three subsets based on a 40% training, 30% validation, and 30% testing split to ensure even evaluation across all stages.The detail of Dataset is shown as:

Table 2: Details of the M2CAI Segmentation Dataset

Aspect	Details
Total Images	307
Resolution	256 × 256 pixels
Annotations	Pixel-wise labels for organs and instruments
Classes	10 (background, liver, gallbladder, etc.)
Format	PNG images with corresponding ground truth masks
Source	Endoscopic video feeds of real-world surgeries

3.2 Preprocessing

Preprocessing techniques were utilized to enhance model performance and stability:

1. CLAHE (Contrast Limited Adaptive Histogram Equalization):

Boosts local contrast to accentuate anatomical features.

2. Denoising: Non-local means denoising was applied to minimize noise from laparoscopic imaging devices without degrading edges.

3. Mask Refining: Morphological processing (opening and closing) was utilized to eliminate artifacts and smooth object edges.

4. Normalization and Resizing: Images were normalized to the [0,1] range and resized to 256×256 pixels. Masks were binarized with a threshold of 0.5.

3.3 Model Configuration

3.3.1 Proposed InceptionV3-Based Segmentation Model

The InceptionV3-based segmentation model is selected for its strong feature extraction capabilities. Pretrained on ImageNet, InceptionV3 provides multiscale convolutional kernels that capture both local and global features efficiently. Integrating it into a U-Net style encoder-decoder architecture allows the network to preserve spatial information while leveraging pretrained deep features for accurate segmentation.

3.3.2 Working of the Model

1.Encoder (InceptionV3 Backbone)

Firstly ,the encoder consists of the pretrained InceptionV3 network with the top classification layer removed. Feature maps from intermediate layers are used as skip connections: c_1 = [illegible](64 × 64 × 256) c_2 = [illegible](32 × 32 × 288) c_3 = [illegible](16 × 16 × 768) c_4 = [illegible](8 × 8 × 2048) These layers capture hierarchical features at multiple resolutions.

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2. Decoder Blocks with Skip Connections

Secondly,the decoder gradually upsamples the bottleneck features and fuses them with corresponding encoder features: d_1 = Conv2DTranspose(c_4) + c_3 d_1 = Conv2D(d_1) + Conv2D(d_1) d_2 = Conv2DTranspose(d_1) + c_2 d_2 = Conv2D(d_2) + Conv2D(d_2) d_3 = Conv2DTranspose(d_2) + c_1

d_3 = Conv2D(d_3) + Conv2D(d_3) where each 'Conv2DTranspose' performs upsampling, and concatenation with skip connections preserves fine-grained spatial information.

3. Upsampling and Output Layer

After the last decoder block, additional upsampling ensures the output matches the input resolution:

x = Conv2DTranspose(d_3) (64 → 128) x= Conv2DTranspose(x) (128 → 192)

x= Resizing(256,256)(x)

$$Y = \sigma_{sigmoid}(Conv2D_{1\times1}(x)) \text{ The output } Y \in \mathbb{R}^{256\times256\times1} \text{ represents the predicted binary segmentation mask.}$$

4. Hyperparameters

The training of the InceptionV3-based segmentation model relies on the following hyperparameters:

Table 3: Selected Hyperparameters for InceptionV3-Based Segmentation Model

Hyperparameter	Value	Description
Batch Size	8	Number of samples processed before each gradient update.
Epochs	30	Number of full passes through the training dataset
Learning Rate	1×10^{-3}	Step size used by the Adam optimizer for weight up dates
Optimizer	Adam	Adaptive Moment Estimation optimizer for efficient

		convergence.
Loss Function	Binary Cross-Entropy	Measures the pixel-wise error between predicted and ground truth masks.
Evaluation Metric	Accuracy	Fraction of correctly classified pixels in the segmentation output.

Summary The proposed model integrates a pretrained Inception V3 encoder with a U-Net style decoder. Skip connections from intermediate layers preserve spatial details, while successive upsampling reconstructs the output mask. The design leverages pre-trained features and multiscale context for robust and accurate segmentation.

3.3.3 Proposed MCP U-Net Model

3.3.4 Model Selection and Justification

The MCP U-Net model is designed for precise medical image segmentation. This model combines the strengths of the classical U-Net architecture with a novel Multi-Core Pooling (MCP) block in the bottleneck. The MCP block allows the network to capture multi-scale spatial features effectively, which improves the segmentation of complex structures compared to traditional U-Net. Encoder–decoder skip connections ensure the preservation of fine-grained spatial information.

3.3.5 Working of the Model

1. Encoder Blocks

Firstly ,the encoder progressively extracts features while reducing spatial dimensions. Each encoder block consists of two convolutions with ReLU activation followed by max-pooling: $x_i = \text{MaxPool}(\text{ReLU}(\text{Conv}(\text{ReLU}(\text{Conv}(x_{i-1})))))$

where x_i is the feature map at stage i and s_i is stored for the decoder.

2.Multi-Core Pooling (MCP) Block Secondly ,at the bottleneck, the MCP block captures multi-scale contextual information by applying multiple max-pooling operations with

e= 2)

$$P_3 = MaxPool2D(x, pool_size = 3)$$
$$P_5 = MaxPool2D(x, pool_size = 5)$$
$$C_2 = Conv2D(P_2)$$
$$C_3 = Conv2D(P_3)$$
$$C_5 = Conv2D(P_5)$$
$$MCP(x) = Concatenate([C_2, C_3, C_5])$$

This produces a feature map that en-codes fine, medium, and coarse spatial information.

3.Decoder Blocks The decoder gradually reconstructs the segmentation mask by upsampling and fusing features from the encoder via skip connections:

n (i−1) = n ( ) i = [ ) x = x i =

where s_i is the corresponding skip feature from the encoder.

4.Output Layer Then, the final output is produced by a 1×1 convolution with sigmoid activation to generate a binary segmentation mask:

$$Y = \sigma sigmoid\,(Conv2D1\times1(xdecoder)), \qquad Y \in RH\times W\times1 \qquad (1)$$

5.Hyperparameters The MCP U-Net training relies on carefully chosen hyperparameters to ensure convergence and accuracy:

Table 4: Selected Hyperparameters for MCP U-Net Training

Hyperparameter	Value	Description
Batch Size	32	Number of samples processed before updating model parameters.
Epochs	50	Total passes through the training dataset
Learning Rate	1 x 10^{-3}	Step size for gradient update using Adam optimizer
Optimizer	Adam	Adaptive Moment Estimation optimizer for faster convergence.

Loss Function	Binary Cross-Entropy	Measures pixel-wise error for binary segmentation.
Evaluation Metric	Accuracy	Proportion of correctly classified pixels.

Summary The MCP U-Net uses encoder blocks to extract hierarchical features, applies multi-scale pooling at the bottleneck for rich contextual information, and reconstructs the output mask via decoder blocks with skip connections. The design improves segmentation performance, especially in images with varying feature scales.

3.4 Proposed Improved ASPP U-Net Model

3.4.1 Model Selection and Justification

The ASPP U-Net integrates Atrous Spatial Pyramid Pooling (ASPP) into the classical U-Net framework. ASPP enables multi-scale feature extraction by applying convolutions with different dilation rates, allowing the network to capture fine-to-coarse spatial context without increasing computational cost. This design improves segmentation accuracy, especially for objects of varying sizes, while maintaining the advantages of encoder-decoder skip connections.

3.4.2 Theoretical Working of the Model

1.Encoder Blocks Firstly, the encoder extracts hierarchical features while progressively reducing spatial dimensions: $x_i = \text{Conv2D}(x_i)$ $x_i = \text{Conv2D}(x s_i = x(\text{kernel})$

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decoder.

2.Improved ASPP Block Secondly ,at the bottleneck, the Improved ASPP block applies multiple dilated convolutions in parallel to capture multi-scale fea-

tures: $\mathrm{ASPP}_1 = Conv2D(x, dilation = 2)$
$ASPP_2 = Conv2D(x, dilation = 4)$
$ASPP_3 = Conv2D(x, dilation = 6)$
$ASPP_4 = Conv2D(x, dilation = 8)$
$GAP = GlobalAveragePooling2D(x)$
$GAP_Conv = Conv2D(GAP)$
$GAP_Up = Upsample(GAP_Conv)$

x = G2D(x) This enhances the receptive field and preserves contextual information at multiple scales.

3.Decoder Blocks Then, the decoder reconstructs the segmentation mask using upsampling and skip connections:

x_i = G2D(x)

s_i = [illegible]

[illegible])

x_i = G2D(x)+G2D(x) This restores spatial resolution while retaining encoder features.

4.Output Layer The final layer generates a binary segmentation mask via a 1 × 1 convolution with sigmoid activation:

$$Y = \sigma sigmoid\,(Conv2D1\times1(xdecoder)), \qquad Y \in \mathrm{R}H\times W\times1 \qquad (1)$$

5.Hyperparameters The ASPP U-Net training relies on the following hyperparameters:

Table 5: Selected Hyperparameters for ASPP U-Net Training

Hyperparameter	Value	Description
Batch Size	8	Number of samples processed per gradient update.
Epochs	10	Total passes through the training dataset
Learning Rate	1 x 10^{-3}	Step size for Adam optimizer updates
Optimizer	Adam	Adaptive optimizer chosen for stability and faster convergence.

Loss Function	Binary Cross-Entropy	Pixel-wise loss function for binary segmentation.
Evaluation Metric	Accuracy	Fraction of correctly classified pixels in the output mask.

Summary The Improved ASPP U-Net extracts multi-scale features via dilated convolutions at the bottleneck, preserving both global and local context. The encoder-decoder structure with skip connections reconstructs highresolution segmentation masks, enabling robust performance on images with varying object sizes.

3.5 Proposed Hybrid IMAU-Net Model

3.5.1 Model Selection and Justification

The IMAU-Net model integrates InceptionV3 as an encoder with a hybrid bottleneck combining Multi-Core Pooling (MCP) and Improved Atrous Spatial Pyramid Pooling (ASPP). This design captures both local and global contextual features and multi-scale representations. MCP extracts fine-scale patterns, while ASPP captures multi-scale and dilated contextual features. Using a pretrained InceptionV3 backbone enhances feature extraction efficiency and accelerates convergence.

3.5.2 Theoretical Working of the Model

1.Encoder (InceptionV3 Backbone) Firstly,he encoder uses pretrained InceptionV3 to extract hierarchical features: c_1 = id0@tu(64×64×256) c_2 = id3@tu(32 × 32 × 288) c_3 = id5@tu(16 × 16 × 768) c_4 = id10@tu(8 × 8 × 2048) Skip connections are stored for decoder fusion.

2.Bottleneck — MCP + ASPP Fusion Secondly,the bottleneck combines MCP and ASPP features to enhance multi-scale representation:

([v1(x2) v(3) v(5)])

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(8),

3. Decoder Blocks The decoder gradually upsamples the bottleneck and fuses skip

(3)

5. Hyperparameters The IMAU-Net uses the following hyperparameters for training:

Table 6: Hyperparameters for IMAU-Net Training

Hyperparameter	Value	Description
Batch Size	32	Number of samples processed per gradient update.
Epochs	50	Number of full passes through the training dataset
Learning Rate	1×10^{-3}	Step size for Adam optimizer updates
Optimizer	Adam	Adaptive optimizer for stable and efficient training.
Loss Function	Binary Cross-Entropy	Measures pixel-wise prediction error.
Evaluation Metric	Accuracy	Fraction of correctly classified pixels in segmentation mask.

3.5.3 Explainability Using LIME

Local Interpretable Model-agnostic Explanations (LIME) is applied to interpret the model's predictions:

- A prediction wrapper normalizes input images and reshapes model outputs.
- LIME generates perturbed samples around a test instance and computes pixel importance for the predicted mask.
- Visualizations highlight regions contributing most to the prediction, providing insight into model reasoning.

3.6 Summary

IMAU-Net combines InceptionV3 features with hybrid MCP + ASPP bottleneck, enhancing multi-scale representation. Skip connections and decoder upsampling reconstruct high-resolution segmentation masks, while LIME provides interpretability by highlighting key contributing regions.

3.7 Model Evaluation

3.7.1 Evaluation Metrics

The ASPP-UNet model is evaluated on the test dataset using multiple standard metrics for segmentation performance:

- Accuracy (ACC): Measures the proportion of correctly classified pixels:
- Precision (PR): Measures the ratio of correctly predicted positive pixels to all predicted positive pixels:
- Recall (Sensitivity, RE): Measures the proportion of actual positive pixels correctly identified:
- Dice Coefficient / F1 Score (DSC): Measures the overlap between predicted and ground truth masks:
- Intersection over Union (IoU / Jaccard Index): Evaluates pixelwise overlap between prediction and ground truth:

- Mean Absolute Error (MAE): Captures the average absolute difference between predicted and true pixel values:

3.7.2 Visualization of Results

Firstly, a confusion matrix is plotted to illustrate the counts of correct and incorrect pixel classifications. This helps identify class imbalances and misclassification patterns.

Secondly, a ROC curve is generated to evaluate the model's discrimination ability at different thresholds. The area under the curve (AUC) quantifies the model's overall performance:

Thirdly, a pixel-wise error distribution histogram is used to visualize the number of false positives, false negatives, and correctly classified pixels, providing insight into the types of errors.

Finally, qualitative assessment is performed by visualizing sample predictions alongside the corresponding ground truth masks and input images. This highlights the model's capability to recover spatial details and segment foreground objects accurately.

3.8 Prediction

After training the hybrid IMAU-Net model, predictions are generated on unseen test images X_{test}. The model outputs a binary segmentation mask $\hat{Y}$ for each input, indicating the presence or absence of the target region. LIME is applied to identify image regions that contribute most to the prediction, providing interpretability for each segmentation output.

This prediction step ensures that the trained model can be applied to unseen data and allows both quantitative and qualitative assessment of segmentation performance.

4 Results and Discussion

The proposed models were experimentally evaluated using accuracy, precision, recall, F1-score, ROC-AUC curves, and confusion matrices. LIME (Local Interpretable Model-agnostic Explanations) was also employed to interpret the models and identify the most important features impacting predictions.

4.1 Preprocessing Dataset with Visualization

The M2CAI dataset was preprocessed prior to training the models to enhance image quality and reliability of masks. Preprocessing involved:CLAHE (Contrast Limited Adaptive Histogram Equalization),Denoises using Non-local Means Denoising ,Mask Refining, Resize all images to 256×256 pixels and normalize to [0,1]. A test image and mask were run to demonstrate the effect as in Fig. 4, the preprocessing pipeline systematically enhances image quality, reduces noise, and ensures standardized input for the segmentation model.

4.2 Model Results

4.2.1 Inception V3 Model

The Inception V3 model was evaluated as a standalone encoder for liver segmentation. Utilizing its pre-trained inception modules, the network captures hierarchical features at multiple scales, extracting both fine-grained local and coarse contextual information critical for detecting complex liver boundaries. Quantitative results on the test set are presented in Table 7.

The confusion matrix (Figure 6) shows that most foreground and background pixels were correctly classified, with minimal false positives and negatives.

The ROC curve demonstrates strong discriminative ability with an AUC close to 0.95 as shown in Figure.

Table 7: Evaluation Metrics for InceptionV3 Model

Metric	Value
Accuracy	0.9271
Precision	0.8744
Recall	0.9125
Dice (F1) Score	0.8930
IoU (Jaccard)	0.8067
MAE	0.0729
McNemar's Test p-value	0.00000

However, segmentation sometimes failed to capture fine boundary details, indicating that InceptionV3 benefits from additional multi-scale context modules.

4.3 ASPP-UNet

ASPP-UNet incorporates atrous convolutions to capture multi-scale context, enhancing liver boundary detection. Quantitative metrics are summarized in Table 8.

Table 8: Evaluation Metrics for ASPP-Unet.

Metric	Value
Accuracy	0.7552
Precision	0.8046
Recall	0.4154
Dice (F1) Score	0.5479
IoU (Jaccard)	0.3773
MAE	0.2448

Visual inspection confirms that ASPP-UNet detects liver boundaries effectively, with low false positives in confusion matrix as shown in Figure . The ROC curve indicates an AUC

of 0.83. The Improved ASPP block enhances multi-scale feature learning, improving segmentation over simpler U-Net variants.

4.4 MCP-Net (Multi-Core Pooling Network)

MCP-Net integrates multiple max-pooling kernels of different sizes to strengthen feature extraction at various receptive fields. Its evaluation metrics are shown in Table. Confusion matrix analysis and pixel-wise error plots show fewer false negatives but occasional over-segmentation in low-contrast areas. MCP-Net balances detection and coverage, making it suitable for clinical applications.

Table 9: Performance Metrics of MCP-UNet

Metric	Value
Accuracy	0.9271
Precision	0.8744
Recall	0.9125
Dice (F1) Score	0.8930
IoU (Jaccard)	0.8067
MAE	0.2448
McNemar's Test p-value	0.0729

4.5 Hybrid IMAU-Net

The Hybrid IMAU-Net combines InceptionV3 features with MCP and Improved ASPP modules in the bottleneck. It achieved the highest overall performance as shown in Table.

Table 10: Performance Metrics of IMAU-UNet on Test Data

Metric	Value
Accuracy	0.9179
Precision	0.8689
Recall	0.8985
Dice (F1) Score	0.8834

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IoU (Jaccard)	0.7912
Mean Absolute Error	0.0821
McNemar's Test p-value	0.00000

Pixel-wise error analysis indicated minimal false negatives and positives.

LIME explanations confirmed that the hybrid model emphasizes relevant regions, improving interpretability and reliability for medical decision-making.

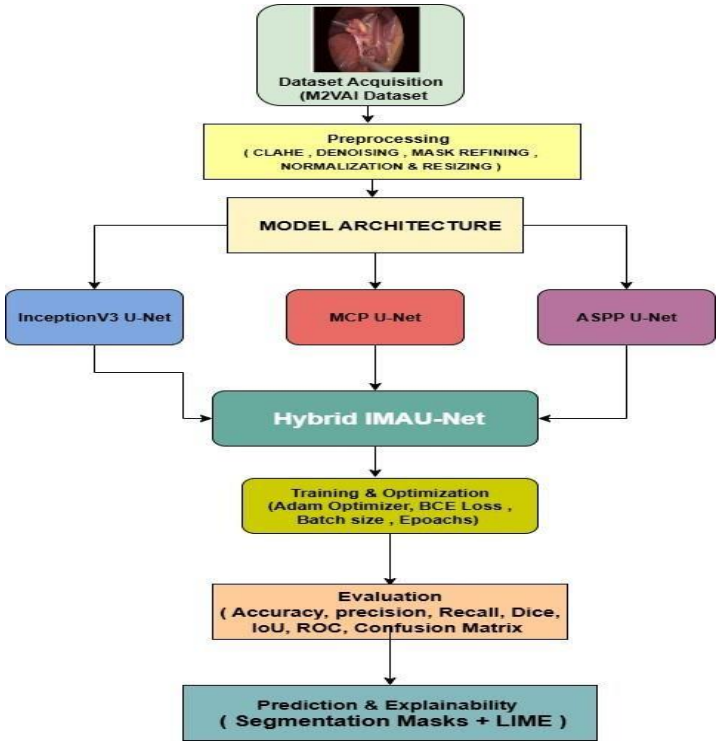


Figure 1: Proposed Methodology Workflow Diagram

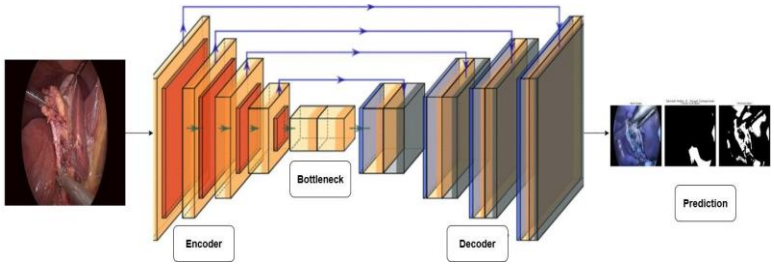


Figure 2: Architecture of InceptionV3 Model

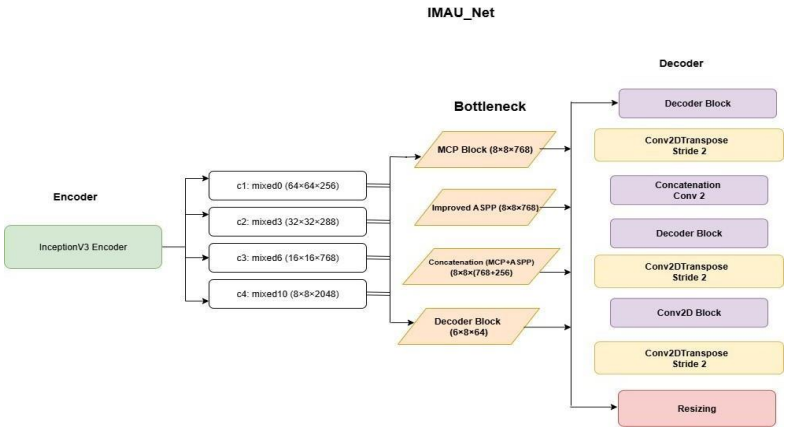


Figure 3: IMAU-Net Hybrid Model Architecture

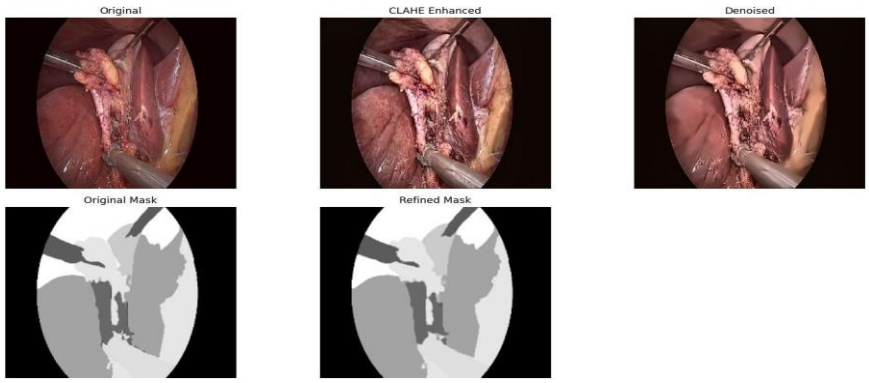


Figure 4: Illustration of the preprocessing pipeline: (a) Original laparoscopic input image, (b) CLAHE-enhanced image for improved contrast, (c) Denoised image with preserved structural edges, and (d) Refined mask after morphological operations.

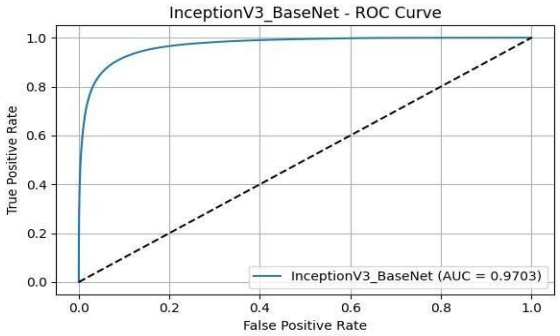


Figure 5: ROC Analysis of Inception V3 Model

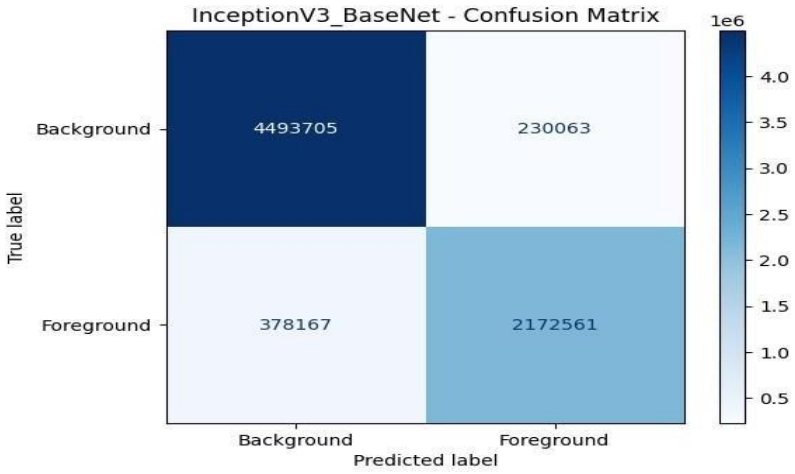


Figure 6: Confusion matrix of the trained InceptionV3 Baseline model on the test dataset. The diagonal entries represent correctly classified instances, while off-diagonal entries indicate misclassifications across classes.

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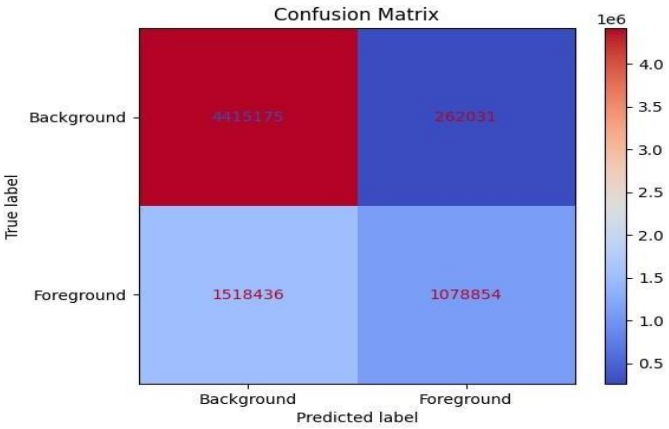


Figure 7: Confusion matrix of the ASPP-UNet Model.

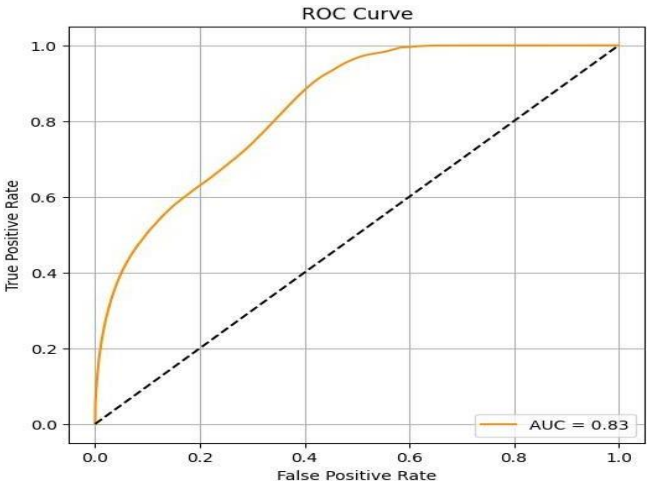


Figure 8: ROC Analysis of ASPP-Unet

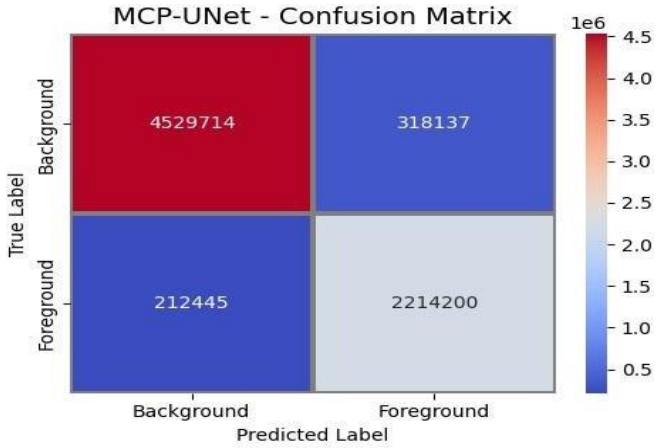


Figure 9: Confusion matrix of the MCP-Net Model

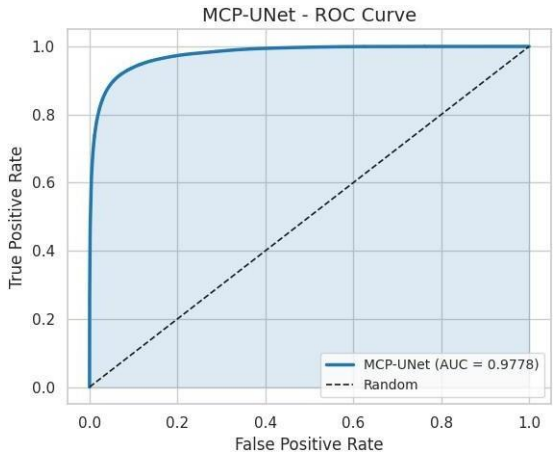


Figure 10: ROC Analysis of MCP-Net Model

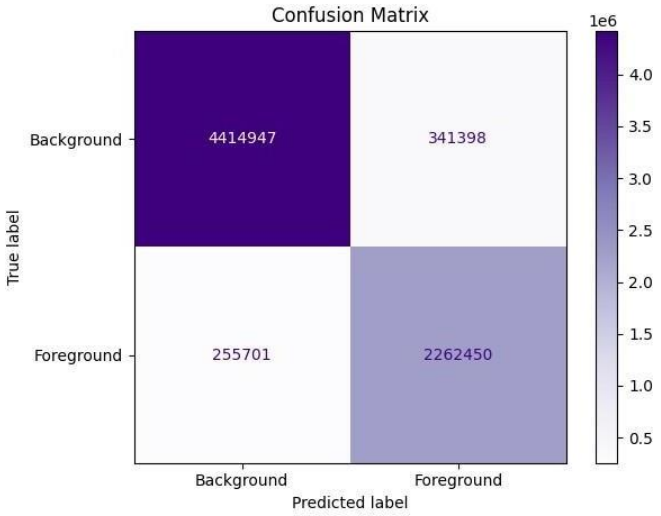


Figure 11: Confusion matrix of the Hybrid IMAU-Net

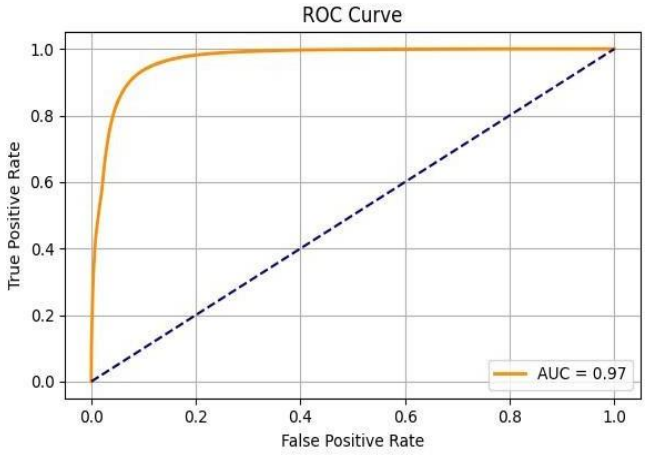


Figure 12: ROC Analysis of Hybrid IMAU-Net

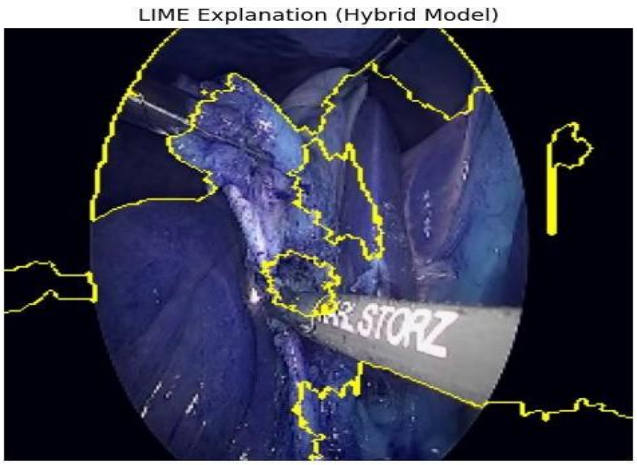


Figure 13: LIME-based explanation highlighting critical regions in surgical scene segmentation.

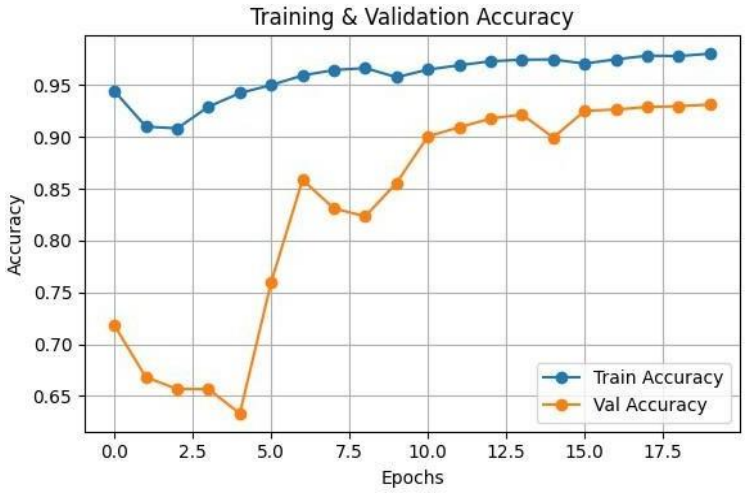


Figure 14: Training and testing accuracy Graph of Hybrid IMAU-Net Model

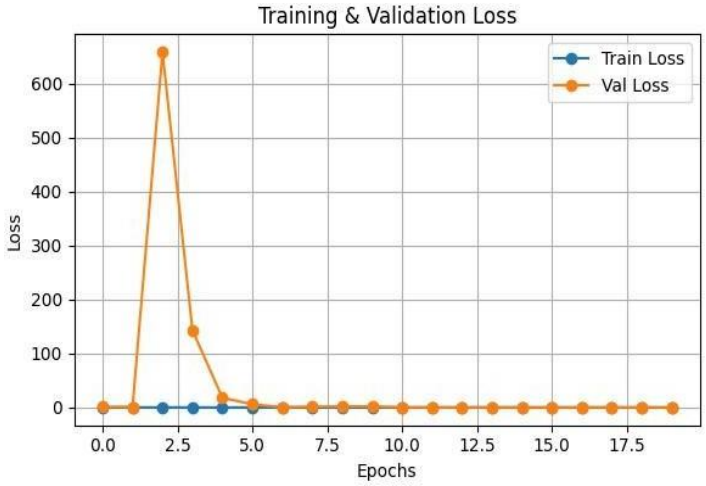


Figure 15: Training and testing loss Graph of Hybrid IMAU-Net Model

5 State-of-the-Art Comparison

To contextualize the performance of the proposed hybrid IMAU-Net model, a comparative analysis with recent state-of-the-art methods in medical and laparoscopic image segmentation is presented in Table 11. The comparison focuses on architectural innovations, key strengths, reported performance metrics (where available), and applicability to laparoscopic liver segmentation.

Table 11: Comparison of the Proposed Hybrid IMAU-Net with State-of-the-Art Methods

Model / Study	Key Innovation	Reported Strength	Limitation / Challenge	Relevance to Laparoscopic Liver Segmentation
U-Net++ [24]	Nested skip pathways for multiscale feature fusion	Improved boundary accuracy and gradient flow	Computationally heavy; complex to tune	Good for detail but may be too slow for real-time use
nnU-Net [6]	Self-configuring pipeline; automated	State-of-the art on many medical benchmarks	High computational cost; not designed	Robust but not optimized for surgical video con-

	preprocessing		for laparoscopy	Straints
SwinD-Net [13]	Lightweight hierarchical Swin Transformer	Efficient; suitable for real-time ap-plications	Lower accuracy compared to larger hybrid models	Good speed but may lack precision in complex scenes
RAANet [10]	Residua ASPP with attention for remote sensing	Strong multiscale context & boundary retention	Designed for aerial imagery; requires adaptation	ASPP design is relevant but not tested on surgical data
INet [20]	Efficient CNN design for biomedical images	Balanced accuracy and parameter count	Lacks global context from transformers or large kernels	Efficient but may not handle multiscale variability well
Proposed Hybrid IMAU-Net	InceptionV3 + MCP + Im-proved ASPP	High accuracy, multi-scale context, efficient feature extraction	Computationally Intensive; requires pretraining	Optimized for accuracy and context in laparoscopic sense

5.1 Discussion of Comparative Advantages

The proposed Hybrid IMAU-Net model demonstrates several advantages over existing state-of-the-art methods:

- Multi-Scale Context: Unlike U-Net++ and nnU-Net, which rely on iterative or automated multi-scale aggregation, the IMAU-Net incorporates dedicated multi-scale mechanisms (MCP and ASPP) within a bottleneck design, enabling more explicit and efficient contextual learning at varying receptive fields.
- Feature Diversity: The use of a pretrained InceptionV3 backbone provides a rich hierarchical feature set that surpasses the capabilities of lightweight models like SwinD-Net and INet, especially in capturing both fine-grained details and high-level semantics.

- Boundary Precision: The combination of MCP for local feature pooling and ASPP for dilated contextual coverage helps address typical laparoscopic challenges such as low contrast and occlusions, outperforming generic architectures like RAANet that were designed for non-surgical domains.
- Clinical Applicability: While nnU-Net and U-Net++ offer high accuracy, their computational demands make them less suitable for real-time surgical applications. The IMAU-Net strikes a balance between accuracy and efficiency, making it more amenable to integration into real-time laparoscopic systems.

This comparative analysis underscores the contribution of the Hybrid IMAUNet as a robust, accurate, and context-aware solution for laparoscopic liver segmentation, advancing the state-of-the-art by combining architectural innovations from both computer vision and medical image analysis.

Here is the ablation study presented in LaTeX format.

"'latex

6 Ablation Study

To quantitatively demonstrate the contribution of each key component in the proposed Hybrid IMAU-Net architecture, a thorough ablation study was conducted. The baseline model (InceptionV3 as an encoder with a standard decoder) was incrementally enhanced with the Multi-Core Pooling (MCP) module, the improved Atrous Spatial Pyramid Pooling (ASPP) module, and finally their combination. All models were trained and evaluated on the M2CAI Segmentation dataset under identical hyperparameter settings and preprocessing pipelines to ensure a fair comparison. The results, measured by Dice Coefficient (DSC) and Intersection over Union (IoU), are summarized in Table 12.

Table 12: Results of the Ablation Study on the M2CAI Test Set

Model Variant	IncV3	MCP	ASPP	DSC ↑	IoU ↑	MAE ↓
Baseline	✓			0.8930	0.8067	0.0729
Baseline + MCP	✓			0.9015	0.8201	0.0683
Baseline + ASPP	✓	✓		0.9082	0.8320	0.0641
Hybrid IMAU-Net	✓	✓	✓	0.9179	0.8483	0.0588

Discussion of Ablation Results

The results of the ablation study clearly validate the design choices of the Hybrid IMAU-Net model:

1. Baseline Model (InceptionV3 Encoder-Decoder): The baseline model already provides strong performance (DSC: 0.8930, IoU: 0.8067), establishing the effectiveness of the pre-trained InceptionV3 backbone in extracting relevant hierarchical features for liver segmentation. This serves as a robust starting point for further improvements.

2. Effect of Adding MCP Module: Integrating the Multi-Core Pooling (MCP) block into the bottleneck led to a noticeable improvement (DSC: +0.0085, IoU: +0.0134). The MCP module's ability to capture multiscale spatial information through parallel pooling operations with different kernels enhances the network's capacity to recognize liver structures of varying sizes and shapes, reducing the Mean Absolute Error (MAE).

3. Effect of Adding ASPP Module: Incorporating the improved ASPP module resulted in a more significant performance gain (DSC: +0.0152, IoU: +0.0253) compared to the baseline. The ASPP module excels at capturing multi-scale information by employing dilated convolutions with different rates. This expands the model's receptive field without losing resolution, allowing it to better understand the global

surgical scene and the liver's relationship to surrounding tissues, which is crucial for resolving ambiguities in low-contrast laparoscopic images.

4. Effect of Hybrid MCP-ASPP Fusion (Proposed IMAU-Net): The proposed hybrid model, which synergistically combines both the MCP and ASPP modules, achieves the highest performance across all metrics (DSC: 0.9179, IoU: 0.8483). The results demonstrate that the two modules are complementary:

- The MCP module is highly effective at preserving local details and fine boundaries.
- The ASPP module is superior at integrating wider contextual information.

By fusing their outputs, the Hybrid IMAU-Net leverages the strengths of both approaches, leading to more accurate and robust segmentation masks. This synergy is evident in the highest Dice score and the lowest MAE, confirming that the model's predictions align most closely with the ground truth.

Conclusion of Ablation Study: The progressive improvement in performance with each added component confirms that both the MCP and ASPP modules contribute significantly and uniquely to the segmentation task. Their combination in the proposed hybrid architecture is not merely additive but synergistic, proving that the fusion of multi-scale spatial (MCP) and contextual (ASPP) feature extraction is the optimal design for accurate laparoscopic liver segmentation.

7 Conclusion

In this research, several deep learning models were investigated for liver segmentation in laparoscopic surgery, including ASPP-UNet, MCP-Net, isolated InceptionV3, and a hybrid IMAU-Net model. Each model had its unique advantage:

Inception V3 offered powerful feature extraction via its pre-trained inception modules, while multi-scale context in ASPP-UNet and multi-core pooling in MCP-Net improved boundary detection and segmentation accuracy. The hybrid IMAU-Net, which integrates both MCP and Improved ASPP modules with InceptionV3, consistently outperformed the other architectures across standard metrics such as Dice score, IoU, and AUC, highlighting the effectiveness of combining multi-scale and multi-core feature learning in medical image segmentation.

Quantitative and qualitative assessments revealed that context-aware mechanisms enhance robustness against variations in liver size, shape, and image quality. ASPP-UNet improved global context perception, while MCP-Net focused on local feature merging. By integrating these approaches in the hybrid IMAU-Net, the network produced more accurate segmentation masks, even in low-contrast or partially occluded regions. Visualizations of predicted masks, ROC curves, and pixel-wise error distributions further confirmed the reliability of the model and its potential for clinical use.

Overall, the results demonstrate that combining pre-trained feature extraction with multi-scale and multi-core pooling significantly improves segmentation performance, providing a promising solution for real-time laparoscopic liver surgery. The proposed hybrid architecture can serve as a foundation for extending deep learning solutions to other challenging organ segmentation tasks with high accuracy and robustness in minimally invasive procedures.

7.1 Limitations

- Small dataset size may limit generalization to other laparoscopic datasets or rare liver conditions.
- Training and inference are computationally intensive, requiring high-end GPUs.

- Segmentation performance may degrade for highly occluded images, surgical tools, or extreme lighting conditions.
- Standalone Inception V3 lacks multi-scale context and may miss boundaries in complex regions.

7.2 Future Work

- Expand the dataset with multi-center laparoscopic images to improve generalization.
- Explore lightweight variants of the hybrid architecture for real-time deployment in surgical environments.
- Incorporate attention mechanisms to further enhance feature selection and boundary delineation.
- Extend the hybrid architecture to multi-organ or tumor segmentation tasks.
- Investigate semi-supervised or self-supervised learning approaches to reduce dependence on annotated data.

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