Balancing Shared and Task-Specific Representations: A Hybrid Approach to Depth-Aware Video Panoptic Segmentation

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BACKGROUND

Depth-aware video panoptic segmentation (DVPS) combines segmentation, depth estimation, and object tracking in video. Such information has a critical role in autonomous driving and robotics applications.

Current approaches share information across tasks either explicitly, *i.e.* modeling interactions between task-specific embeddings [4, 5], or implicitly through a shared object representation [2].

We propose **Multiformer**, a hybrid architecture that combines task-specific and shared object representations ('queries'). Furthermore, we show that this architecture can be extended with metric depth estimation. Finally, a design space exploration on various query decoder designs is provided.

KEY COMPONENTS

- **Mask transformer model** with masked-attention [1] extended to depth estimation and tracking.
- **Branched decoder block** with task-specific query refinement branches.
- **Context adapter** that seeds the initial (shared) queries.
- **Depth head** that directly estimates metric depth without min-max denormalization.

DATASETS & TRAINING

Name	Train videos (frames)	Val. videos (frames)	Annotations
Cityscapes-DVPS [4]	400 (12,000)	50 (1,500)	Every 5th frame
SemKITTI-DVPS [4]	10 (19,130)	1 (4,071)	Sparse reprojected

Models were trained on **4 NVIDIA H100 GPUs** for **20K steps** in **batches of 32 annotated images**. Furthermore, the **AdamW optimizer** was adopted, having **0.0005 peak learning rate** in a polynomial decay schedule. Additionally, random color jitter and horizontal flip augmentations were applied.

MAIN RESULTS

Method	Backbone	DVPQ ↑ [%]			Depth error ↓	
		All	Thing	Stuff	Abs.Rel.	RMSE
ViP-DeepLab [4]	ResNet-50	42.0	27.6	51.5	0.070	3.67
MonoDVPS [3]	ResNet-50	48.8	31.0	61.7	0.070	3.67
PolyphonicFormer [5]	ResNet-50	48.1	35.6	57.1	0.081	4.01
UniDVPS [2]	ResNet-50	51.8	37.1	62.5	0.067	3.88
Multiformer (ours)	ResNet-50	**54.8**	**37.4**	**67.4**	**0.066**	**3.35**
PolyphonicFormer [5]	Swin-B	55.4	43.3	63.6	0.065	3.80
Multiformer (ours)	Swin-B	**59.4**	**46.0**	**69.2**	**0.048**	**2.81**

State-of-the-art performance on *Cityscapes-DVPS* [4], surpassing previous methods by **3.0** (ResNet-50) and **4.0** (Swin-B) depth-aware video panoptic quality (DVPQ) %-points and improving depth estimation accuracy. Measured using Multiformer with $N_B = 9$ decoder blocks (large).

CONCLUSION & IMPACT

- **Hybrid architecture.** Introduces a hybrid decoder that effectively balances shared and task-specific representations through a *context adapter* that produces initial queries from task-specific image features and using a *branched decoder block* that enables task-specific decoding while maintaining a shared representation between blocks.
- **Metric depth estimation.** Incorporates an innovative depth estimation head that eliminates the dataset-specific depth hyper-parameters and improves accuracy.
- **Design insights.** Provides valuable insights into multi-task decoder architectures, demonstrating the benefits of task-specific branching with shared interfaces for complex vision tasks.

REFERENCES

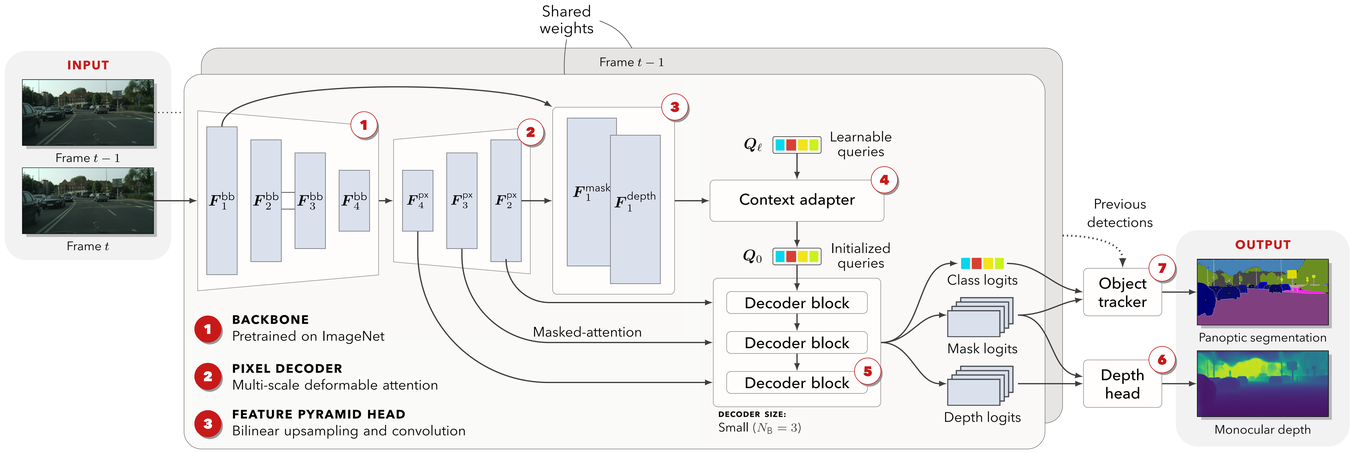
[1] Bowen Cheng, Ishan Misra, Alexander G Schwing, Alexander Kirillov, and Rohit Girdhar. Masked-attention mask transformer for universal image segmentation. In *CVPR*, pages 1290–1299, 2022.

[2] Kim Ji-Yeon, Oh Hyun-Bin, Kwon Byung-Ki, Dahun Kim, Yongjin Kwon, and Tae-Hyun Oh. UniDVPS: Unified model for depth-aware video panoptic segmentation. *IEEE Robotics and Automation Letters*, pages 1–8, 2024.

[3] Andra Petrovai and Sergiu Nedevschi. MonoDVPS: A self-supervised monocular depth estimation approach to depth-aware video panoptic segmentation. In *Proceedings of the IEEE/CVF Winter Conference on Applications of Computer Vision*, pages 3077–3086, 2023.

[4] Siyuan Qiao, Yukun Zhu, Hartwig Adam, Alan Yuille, and Liang-Chieh Chen. ViP-DeepLab: Learning visual perception with depth-aware video panoptic segmentation. In *CVPR*, 2020.

[5] Haobo Yuan, Xiangtai Li, Yibo Yang, Guangliang Cheng, Jing Zhang, Yunhai Tong, Lefei Zhang, and Dacheng Tao. PolyphonicFormer: Unified query learning for depth-aware video panoptic segmentation. In *ECCV*, 2022.



BRANCHED DECODER BLOCK

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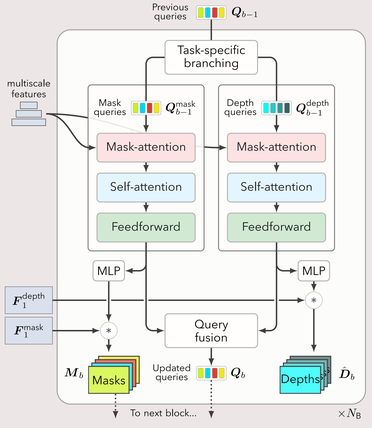
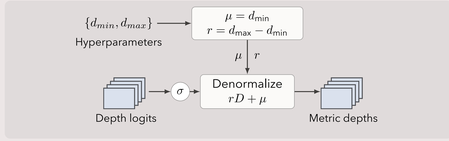


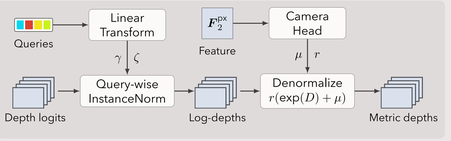
1. **Learnable queries are split** into task-specific branches through a learnable linear transform.
2. **Each branch incorporates task-specific nuances** via masked-attention, self-attention and a feed-forward layer.
3. **Task-specific queries are fused** at the interface between blocks via a linear transform and normalization.

MONOCULAR DEPTH ESTIMATION

6



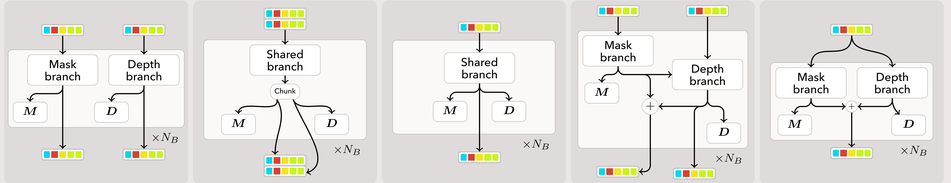
Min-max denormalization head [4, 5, 2]	Abs.Rel ↓	RMSE ↓
Multiformer (large)	0.069	3.54
– Weighted merge	0.073	3.74
– Context adapter	0.074	3.84



Direct metric depth head (ours)	Abs.Rel ↓	RMSE ↓
Multiformer (large)	0.066	3.35
– Weighted merge	0.076	3.81
– Context adapter	0.078	3.86

DECODER BLOCK DESIGN SPACE

Exploration of various decoder block designs on the overall depth-aware video panoptic quality (DVPQ) on *Cityscapes-DVPS* [4] with $N_B = 3$ blocks.



Separated design
DVPQ $= 45.7$ ($N_P = 17.8$ M)

Concatenated design
DVPQ $= 51.2$ ($N_P = 19.8$ M)

Unified design
DVPQ $= 52.3$ ($N_P = 17.6$ M)

Sequential design
DVPQ $= 52.4$ ($N_P = 18.2$ M)

Hybrid design (ours)
DVPQ $= 52.7$ ($N_P = 18.0$ M)

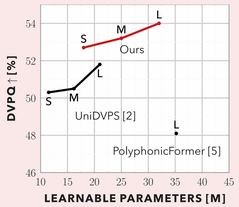
MODEL SCALING

The proposed model is scaled through the amount of decoder blocks N_B.

Small
3 blocks

Medium
6 blocks

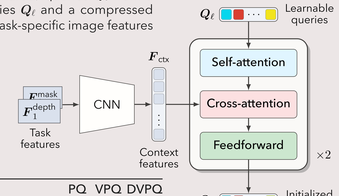
Large
9 blocks



CONTEXT ADAPTER

4

Produces the initial (shared) queries Q_0 from a set of learnable queries Q_ℓ and a compressed representation of the task-specific image features $\{F_1^{mask}, F_1^{depth}\}$.



Ablation	PQ	VPQ	DVPQ
Passthrough ($Q_0 = Q_\ell$)	65.1	57.1	52.3
Context adapter	65.2	57.5	52.7

Evaluated on Cityscapes-DVPS with $N_B = 3$ (small).

OBJECT TRACKER

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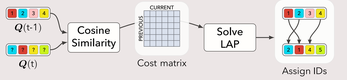

Method	Backbone	DVPQ$^\lambda_\kappa$		κ=1	κ=5	κ=10	κ=20	Avg.
ViP-DeepLab	WR-50			48.9	45.8	44.4	43.4	45.6
PolyphonicFormer [5]	Swin-B		λ=0.50	58.5	52.0	50.6	49.9	52.8
			λ=0.25	56.3	49.7	48.4	47.7	50.5
			λ=0.10	41.8	35.1	33.7	33.0	35.9
			Avg.	52.2	45.6	44.2	43.4	46.4
Multiformer (ours)	Swin-B		λ=0.50	56.6	55.2	54.6	49.6	54.0
			λ=0.25	51.4	49.6	49.5	48.5	49.7
			λ=0.10	49.1	47.2	46.6	46.2	47.3
			Avg.	**52.3**	**50.6**	**50.2**	**48.2**	**50.3**

Depth-aware video panoptic quality on *SemKITTI-DVPS* [4] for varying window size (κ) and depth threshold (λ) using $N_B = 9$ decoder blocks (large). The proposed method achieves state-of-the-art performance, and exhibits less DVPQ degradation at larger window sizes than previous methods.

CODE & MODELS

research.khws.io/multiformer

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