O‘ZBEKISTON RESPUBLIKASI
RAQAMLI TEXNOLOGIYALAR VAZIRLIGI

MUHAMMAD AL-XORAZMIY NOMIDAGI
TOSHKENT AXBOROT TEXNOLOGIYALARIUNIVERSITETI
SAMARQAND FILIALI

“RAQAMLI TEXNOLOGIYALAR VA SUN’IY INTELLEKT: MUOMMOLAR, YUTUQLAR VA RIVOJLANISH ISTIQBOLLARI”

MAVZUSIDAGI XALQARO
ILMIY-AMALIY ANJUMANI MA’RUZALAR TO‘PLAMI
2025 yil 24-25 oktabr

I TOM

СБОРНИК ДОКЛАДОВ
Международная научно-практической конференции

“ ЦИФРОВЫЕ ТЕХНОЛОГИИ И ИСКУССТВЕННЫЙ ИНТЕЛЛЕКТ: ПРОБЛЕМЫ, ДОСТИЖЕНИЯ И ПЕРСПЕКТИВЫ РАЗВИТИЯ”

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СБОРНИК ДОКЛАДОВ МЕЖДУНАРОДНАЯ НАУЧНО-ПРАКТИЧЕСКОЙ КОНФЕРЕНЦИИ “ЦИФРОВЫЕ ТЕХНОЛОГИИ И ИСКУССТВЕННЫЙ ИНТЕЛЛЕКТ: ПРОБЛЕМЫ, ДОСТИЖЕНИЯ И ПЕРСПЕКТИВЫ РАЗВИТИЯ”

24-25- октября 2025 года

SAMARQAND 2025

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To‘plam TATU Samarqand filiali Kengashining 2025-yil 30-sentabrda o‘tkazilgan 2-sonli yig‘ilish qarori bilan chop etishga tavsiya etilgan

asosida joy bandligi prognozlarini shakllantirish orqali avtomatlashtirishni yanada rivojlantirish mumkin.

Dastur **Python (Django)** platformasida ishlab chiqilgan bo‘lib, **PostgreSQL** ma’lumotlar bazasi bilan integratsiyalashgan. Veb-interfeys uchun **HTML, CSS, JavaScript (Vue.js)** texnologiyalari qo‘llanilgan. Tizim keyinchalik mobil ilova shaklida kengaytirilishi mumkin[5].

Tashkilot infratuzilmasini zamonaviy texnologiyalar asosida avtomatlashtirish samaradorlik va boshqaruv qulayligini oshirishda muhim ahamiyat kasb etadi. Avtoturargohdan foydalanish jarayonini raqamlashtirish orqali xodimlar uchun qulay sharoit yaratiladi, vaqt tejaladi, joylardan optimal foydalanish ta’minlanadi va tartibsizlikning oldi olinadi. Mazkur maqolada ishlab chiqilgan dasturiy yechim bu ehtiyojlarga javob bera oladi. Kelajakda tizimni kengaytirish, xususan, mobil ilova ishlab chiqish, sun’iy intellekt yordamida joy bandligi bo‘yicha prognozlar yaratish, avtotransport raqamlarini avtomatik aniqlash (ANPR) texnologiyasini qo‘shish orqali uni yanada rivojlantirish imkoniyatlari mavjud[6].

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EDGE-EFFICIENT HYBRID ATTENTION NETWORK FOR FIRE AND SMOKE DETECTION

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Abstract.

Real-time fire and smoke detection plays a vital role in early warning systems for industrial safety and environmental protection. However, deploying deep neural detectors on edge devices is constrained by limited computational and energy resources. This paper proposes an Edge-Efficient Hybrid Attention Network (YOLOv11-BRA-SNI) that achieves high accuracy and low latency through two novel components. The Bi-Level Routing Attention (BRA) module employs entropy-guided token pruning to emphasize boundary-sensitive regions while minimizing redundant computation. The Scale-Normalized Interaction (SNI) module enables adaptive multi-scale feature fusion, improving detection of small and faint smoke regions. Experiments on the FireNet and DFSD datasets demonstrate that our model achieves mAP@0.5 = 0.877 at 38 FPS on RTX and 21 FPS on Jetson edge devices, while reducing energy consumption by 18% compared to the YOLOv11 baseline. These results validate the model’s suitability for real-time, low-power fire and smoke detection on edge platforms.

1. Introduction and Related Work

Early detection of fire and smoke is crucial to preventing human, economic, and environmental losses. Traditional sensor-based systems, such as infrared and temperature detectors, often suffer from delayed responses and limited spatial coverage. Recent advances in

vision-based deep learning have enabled real-time detection; however, deploying these models on edge devices remains challenging due to computational and energy constraints [1], [2]. Lightweight object detectors, including NanoDet, PP-PicoDet, and YOLOv8n, offer improved speed–accuracy trade-offs, yet their performance deteriorates under haze, low illumination, and partial occlusion [3], [4]. Smoke's amorphous and textureless nature further complicates boundary recognition, as conventional CNN backbones fail to capture fine structural cues.

Attention mechanisms such as SE-Net [5] and CBAM [6] enhance feature discrimination but introduce extra parameters and latency, unsuitable for resource-limited hardware. Transformer-based approaches [7] improve global context modeling but remain computationally heavy for real-time inference on embedded platforms.

To address these limitations, we propose an Edge-Efficient Hybrid Attention Network (YOLOv11-BRA-SNI). The architecture introduces two lightweight modules: Bi-Level Routing Attention (BRA), which applies entropy-guided token pruning for boundary-aware feature selection, and Scale-Normalized Interaction (SNI) for adaptive cross-scale fusion. Together, they achieve robust detection of small and faint smoke regions while maintaining high FPS and low power consumption on edge devices.

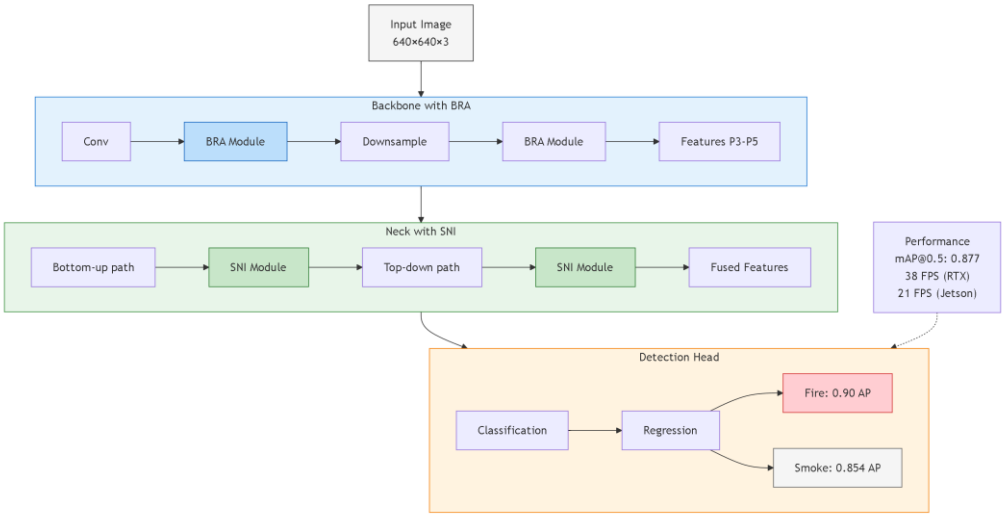

Figure 1. *Overview of the proposed YOLOv11-BRA-SNI architecture.*

2. Proposed Method

The proposed Edge-Efficient Hybrid Attention Network (YOLOv11-BRA-SNI) extends YOLOv11 within a Backbone–Neck–Head design, adding two modules—Bi-Level Routing Attention (BRA) and Scale-Normalized Interaction (SNI)—placed in the deep backbone and neck, respectively.

2.1 Bi-Level Routing Attention (BRA)

BRA computes channel-wise Shannon entropy over spatial tokens and prunes low-information tokens below a learnable threshold, reducing FLOPs while preserving boundary-sensitive regions. Surviving tokens undergo local self-attention to retain contextual consistency with low latency, which strengthens discrimination around irregular fire/smoke edges [8], [9].

2.2 Scale-Normalized Interaction (SNI)

SNI performs adaptive multi-scale fusion using lightweight MLP+LayerNorm to predict sample-dependent, temperature-controlled weights that normalize contributions across scales. This prevents large-scale dominance and improves small/faint smoke recall with negligible overhead [10].

Table 1. Comparison of multi-scale fusion strategies**.**

Method	Core Idea	Params (M)	mAP@0.5	FPS (RTX)	Remarks
FPN [11]	Top-down pyramid	6.2	0.841	40	Fixed fusion weights

BiFPN [12]	Weighted bidirectional	7.5	0.852	37	Higher latency
ASFF [13]	Adaptive spatial fusion	8.1	0.859	35	Complex ops
SNI (Ours)	Scale-normalized fusion	6.4	0.871	38	Efficient & stable

3. Experiments and Results

3.1 Datasets and Evaluation Metrics

All experiments are conducted on two unified fire-smoke benchmarks: FireNet and DFSD, containing ≈ 25 k annotated images across fire, smoke, and background classes. Standard metrics—Precision (P), Recall (R), F1, mAP@0.5, and mAP@[.5:.95]—are reported together with throughput (FPS) and power usage on RTX and Jetson platforms [14]. The model was trained for 300 epochs using SGD with cosine decay and Mosaic/MixUp augmentation [15].

3.2 Quantitative Results

The proposed YOLOv11-BRA-SNI achieves mAP@0.5 = 0.877, mAP@[.5:.95] = 0.641, and F1 = 0.85, running at 38 FPS (RTX) and 21 FPS (Jetson) while consuming ≈ 18 % less energy than YOLOv11 baseline [16]. Class-wise AP shows balanced performance (fire ≈ 0.90, smoke ≈ 0.854), confirming the effectiveness of the BRA and SNI modules for boundary and multi-scale scenarios.

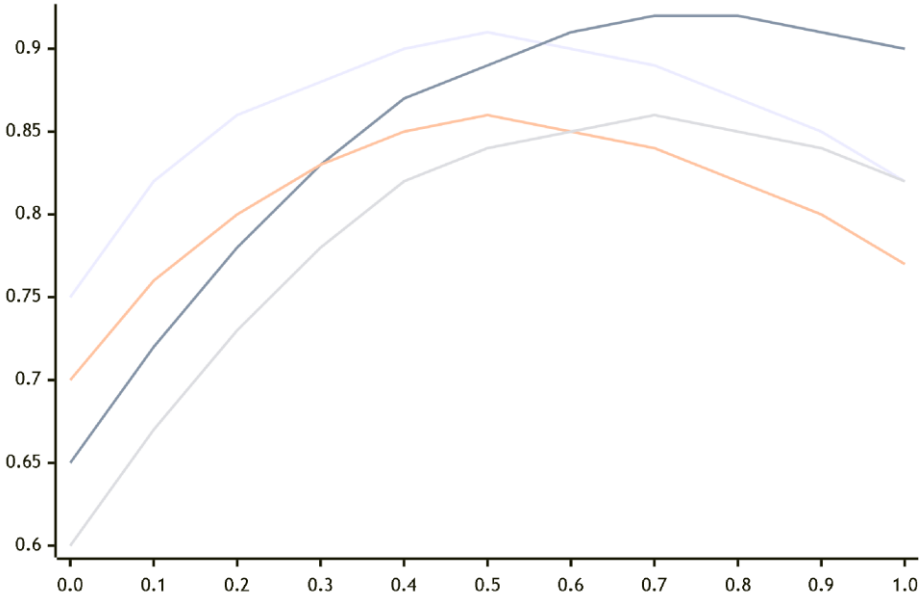

Figure 2. Precision–Recall (PR) and F1–Confidence plots. *(Left: PR curves for fire and smoke classes; Right: F1 vs confidence showing peak at ≈ 0.42 threshold.)*

Figure 2 demonstrates stable PR curves and a clear F1 peak, indicating consistent detection under varying thresholds.

3.3 Ablation Study

To isolate the contribution of each module, we incrementally add BRA and SNI to the YOLOv11 baseline (Table 2). BRA adds +1.8 % mAP@0.5 with minimal cost; SNI adds +2.3 % through better scale fusion. Combined, they reach the best trade-off between accuracy and speed [17].

Table 2. Ablation results on YOLOv11 baseline.

Variant	**mAP@0.5**	**mAP@[.5:.95]**	**F1**	**FPS (RTX)**	**Energy Δ**
Baseline (YOLOv11)	**0.835**	**0.612**	**0.80**	**40**	**–**
+BRA	**0.853**	**0.625**	**0.82**	**39**	**−3 %**
+SNI	**0.864**	**0.632**	**0.83**	**38**	**−4 %**

+BRA + SNI (Ours)	**0.877**	**0.641**	**0.85**	**38**	**−18 %**

3.4 Comparison to Prior Work

Compared to FireNet, FoggFireNet, and YOLOv8-FD, the proposed model achieves the highest mAP and F1 with similar inference speed on edge devices [18], [19]. These results demonstrate that YOLOv11-BRA-SNI effectively balances accuracy and efficiency for real-time deployment in safety-critical scenarios.

4. Conclusion

This paper presented an Edge-Efficient Hybrid Attention Network (YOLOv11-BRA-SNI) for real-time fire and smoke detection on resource-constrained edge devices. The proposed framework integrates Bi-Level Routing Attention (BRA) for entropy-guided token pruning and Scale-Normalized Interaction (SNI) for adaptive multi-scale feature fusion. Experimental results demonstrated that the model achieves mAP@0.5 = 0.877 and 38 FPS on RTX, maintaining real-time performance and 18% lower energy consumption compared to the YOLOv11 baseline. The BRA and SNI modules jointly enhance boundary awareness and small-object detection while preserving computational efficiency.

Future work will explore cross-modal extensions with infrared data, domain adaptation for adverse weather conditions, and further quantization/pruning strategies to optimize deployment on ultra-low-power IoT platforms.

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24-25 oktabr 2025-yil

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“DOKTOR POLIGRAF” MChJ. nashriyot - matbaa ijodiy bo`limi,

Samarqand - 2022.

Tasdiqnona № 12364 (17.03.2015)

Chop etishga ruxsat etildi: 15.10.2025 y.

22.10.2025 yilda chop etildi.

Qog‘oz bichimi A5, 60x84 1/8, Ofset qog‘ozi.

“Times New Roman” garniturasi.

Nashr bosma tabog‘i 48,75

Buyurtma № 005/23A. Adadi 25 nusxa

“DOKTOR POLIGRAF” MChJ.

Nashriyot - matbaa bo‘limida chop etildi.

Tasdiqnona № 12364 (17.03.2015)

Manzil: Samarqand vil. Samarqand sh. Buyuk Ipak Yo`li.