Physics-inspired Low-light Enhancement for Smart Vision on the Edge

Enhancing Real-time Object Detection and Tracking in Light-constrained Environments

PhyCV

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Taejus Yee, Yiming Zhou, Callen MacPhee, and Bahram Jalali

Electrical and Computer Engineering Department, UCLA

GitHub Repo: https://github.com/JalaliLabUCLA/phycv-cuda

UCLA

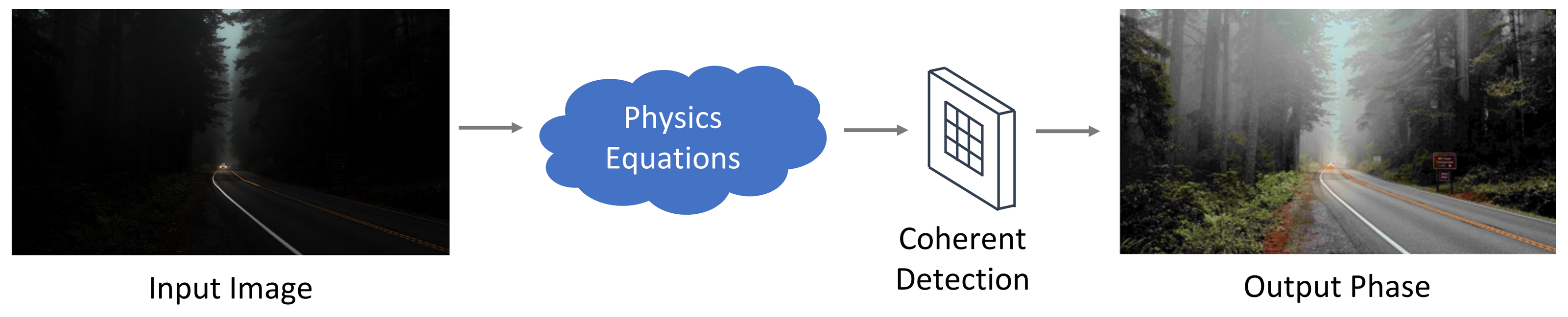
JALALI-LAB @ UCLA

Abstract

- Being part of the PhyCV library, VEViD (Vision Enhancement via Virtual Diffraction and Coherent Detection) is a physics-inspired low-light enhancement algorithm that features low-dimensionality and high-efficiency.
- We introduce the CUDA implementation of VEViD in C++ optimized for NVIDIA Jetson. The C++ version exhibits significant reductions in both memory consumption and execution time compared to the original Python version.
- VEViD serves as a powerful pre-processing tool for object detection models optimized by TensorRT on NVIDIA Jetson, showcasing the improvement of object detection in light-constrained environments. Object tracking is also demonstrated using a PTZ camera connected to the Jetson with feedback control.

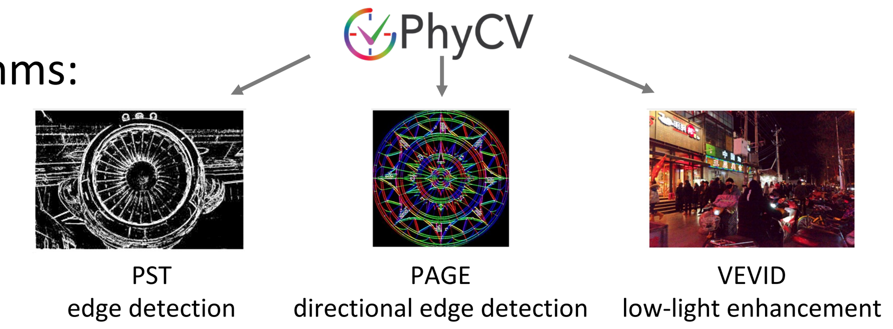
Introduction

- PhyCV (Physics-inspired Computer Vision) is a novel class of algorithms developed by the Jalali-Lab @ UCLA [1].
- Unlike traditional algorithms, PhyCV relies on physical laws of nature as blueprints rather than hand-crafted empirical rules.
- PhyCV emulates the propagation of light through a physical diffractive medium, converting a real-valued input into a complex function. Coherent detection yields useful features in the output phase.



PhyCV currently consists of three algorithms:

- PST (edge detection).
- PAGE (directional edge detection).
- VEViD (low-light enhancement).

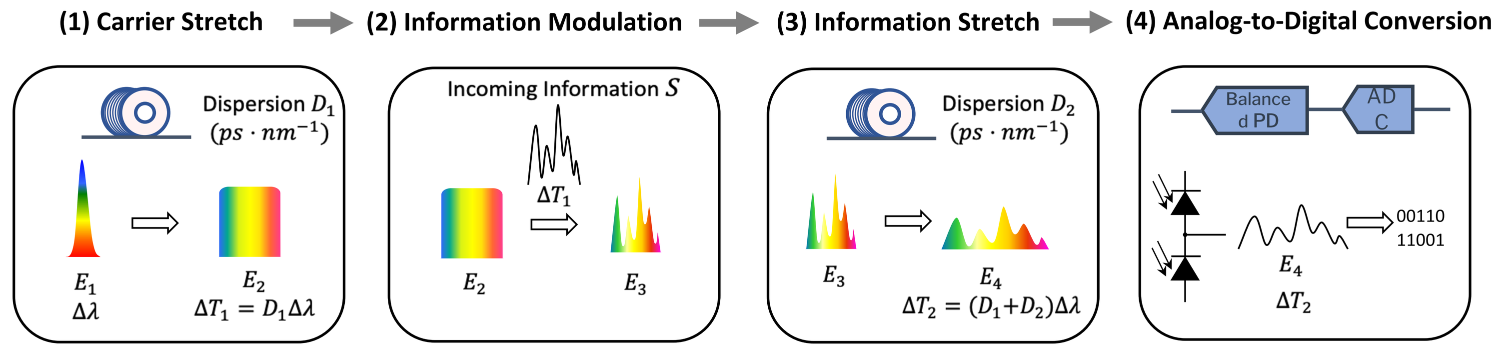


The low-dimensionality and high-efficiency of PhyCV make it ideal for edge computing applications. We implemented a C++ version of the VEViD algorithm with the native CUDA code for low-light enhancement on NVIDIA Jetson Nano and improved object detection and tracking in light-constrained environments.

Method

From Optical Physics to Algorithms

PhyCV algorithms are inspired by Photonic Time Stretch [2], a hardware technique for ultrafast and single shot data acquisition. The unified framework for Photonic Time Stretch can be seen below:



(2) $\tilde{E}_i(\omega) = \tilde{E}_{carrier}(\omega) \cdot S$

Information is modulated onto the optical spectrum

(3) $E_o(t) = \frac{1}{2\pi} \int \tilde{E}_i(\omega) \cdot e^{-i\phi(\omega)} \cdot e^{i\omega t} \, d\omega$

Spectrum is manipulated via optical dispersion

VEViD [3] is then derived by converting the *1D continuous time-stretch operator* to the discrete domain, extending it into 2D, switching from temporal to spatial coordinates, and using a spectral phase filter with a low-pass characteristic.

$$\mathbb{S}\{E_i[m,n]\} = IFFT^2\{FFT^2\{E_i(m,n)\} \cdot \tilde{K}(k_m,k_n)\}$$

2D discrete stretch operator $\mathbb{S}$

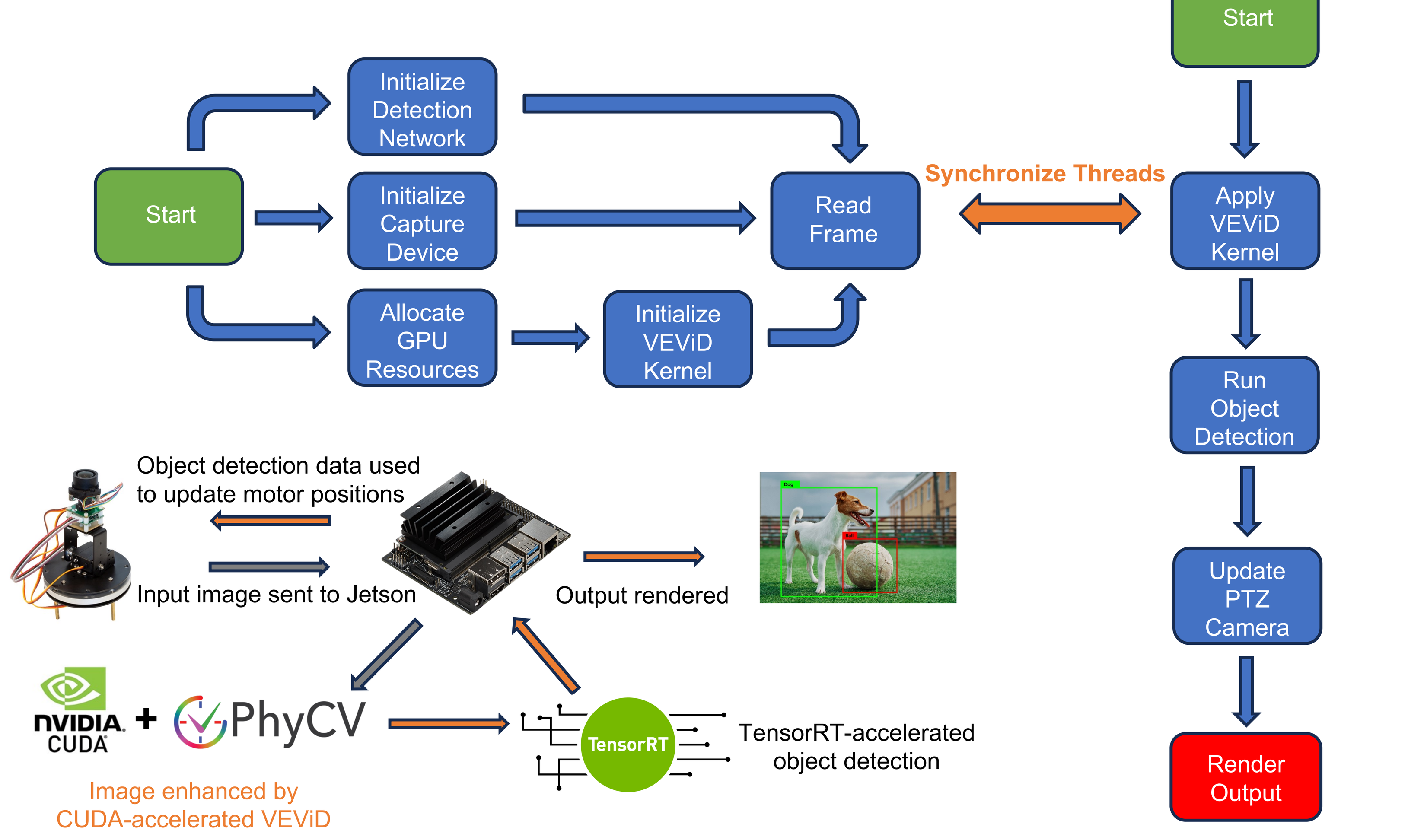
$$\mathbb{S}\{E_i[m,n;c]\} = IFFT^2\{FFT^2\{E_i(m,n;c)+b\} \cdot \tilde{K}(k_m,k_n)\}$$

$$\tilde{K}(k_m,k_n) = e^{-i\phi(k_m,k_n)}$$

$$VEViD\{E_i[m,n;c]\} = \tan^{-1}\left(G \cdot \frac{Im\{\mathbb{S}\{E_i[m,n;c]\}\}}{E_i[m,n;c]}\right)$$

$$\phi(k_m,k_n) = S \cdot \exp\left(-\frac{k_m^2+k_n^2}{T}\right)$$

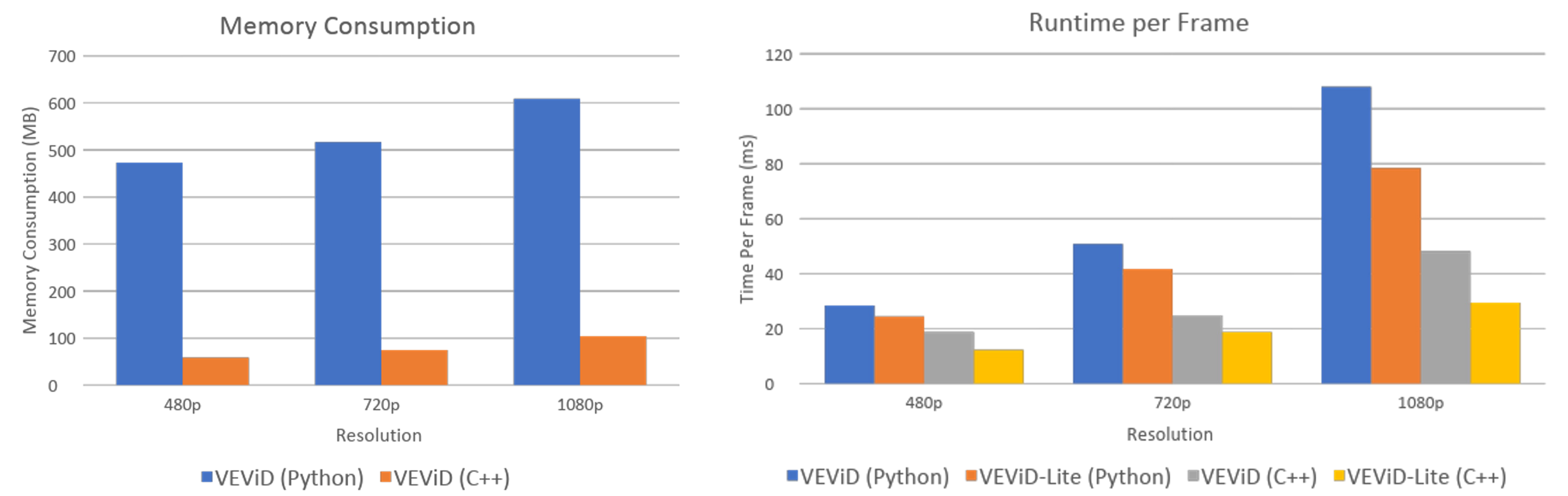
Real-time Processing Pipeline and Hardware Setup



Results

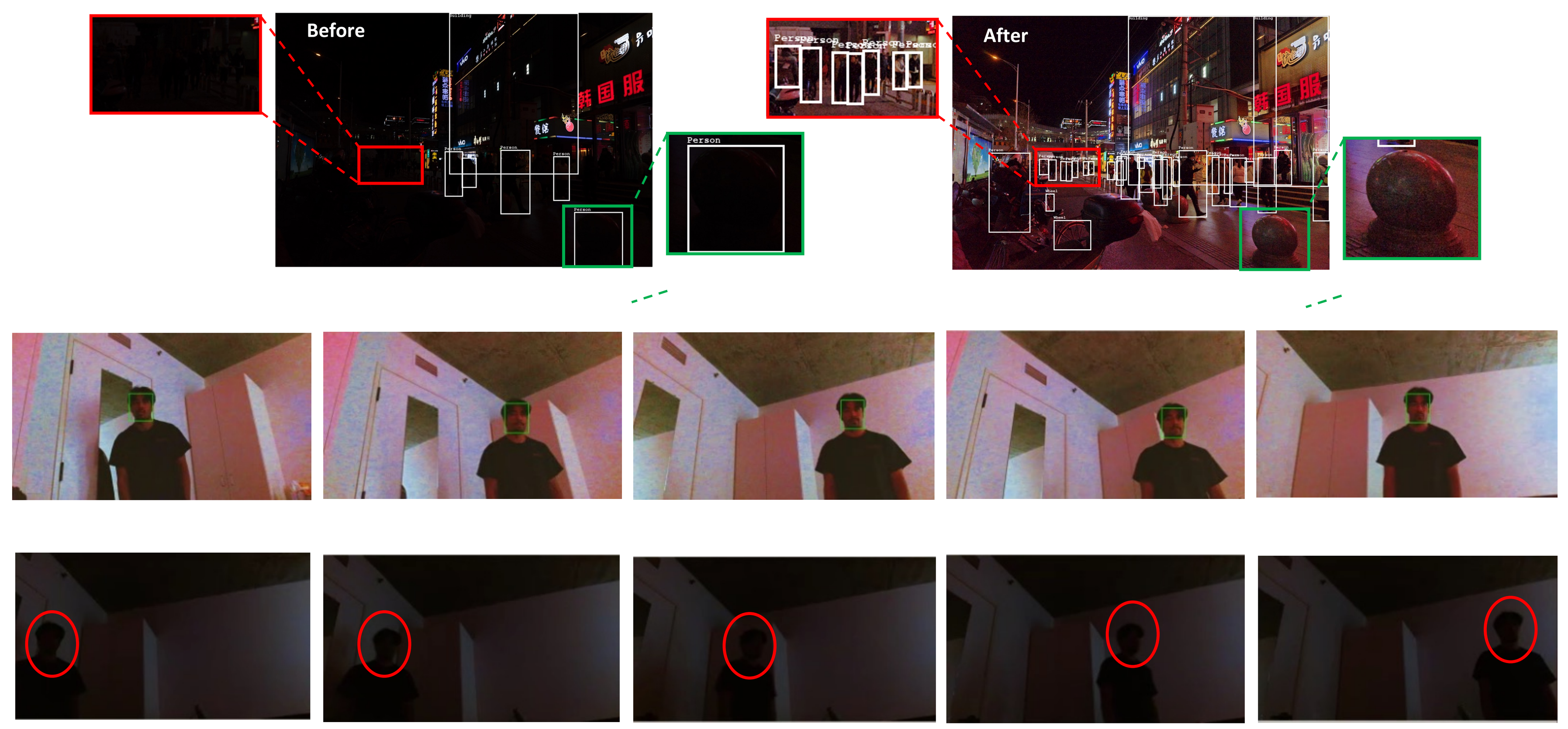
Runtime and Memory Efficiency

- Real-time low-light enhancement: 53 FPS for 720p videos, 33 FPS for 1080p videos.
- The C++ (implemented with native CUDA) version is ~2x faster and ~7x more memory efficient than the Python (implemented with PyTorch) version.



Real-time Object Detection and PTZ Camera Tracking

Results demonstrating how VEViD enhances object detection and classification (top) and how this enables improved automated tracking by a PTZ camera in real-time (bottom).



References

[1] PhyCV: The First Physics-inspired Computer Vision Library. Zhou et al., arXiv preprint arXiv:2301.12531

[2] A unified framework for photonic time-stretch systems. Zhou et al., Laser & Photonics Reviews, 2022

[3] VEViD: Vision Enhancement via Virtual diffraction and coherent Detection. Jalali et al. eLight, 2022