Real-time multi-stage deep neural network control for SCExAO

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Introduction

Motivation

- Extreme AO requires exquisite phase reconstruction and prediction in real-time
- Streamline AO pipeline (e.g., no need for gain selection)
- Experiment in a realistic environment

Proposal

- Develop plugin to handle real-time streams with ML and to connect to telescope software
  - **TensorRT**
  - **MILK**
- Test new ML methods on the SCExAO bench

Subaru Telescope and SCExAO

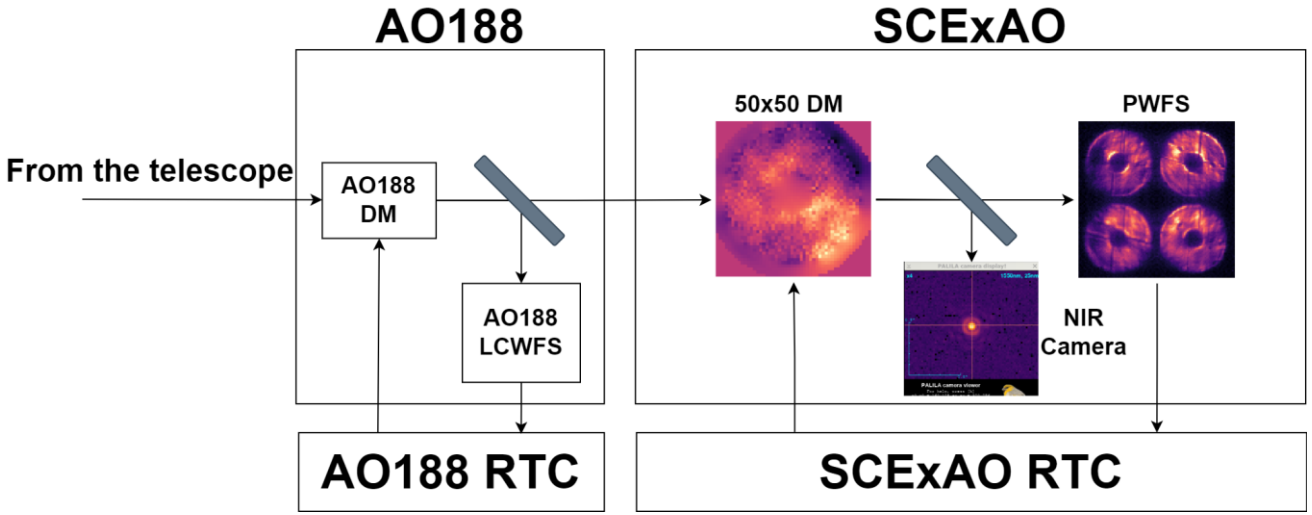
Subaru telescope

- 8.2 m diameter
- Altitude: 4139 m
- Hawaii, USA

Source: Subaru Telescope webpage

SCExAO

- 50x50 Deformable Mirror
- Visual Pyramid Wavefront Sensor
- **Hardware available**
  - AMD EPYC 7763 64-Core Processor (x2). 3.1 GHz, Max 3.5 GHz
  - GPUs: A6000, RTX 3080 Ti (x2), GPU 2080 Ti (x2)



Methods

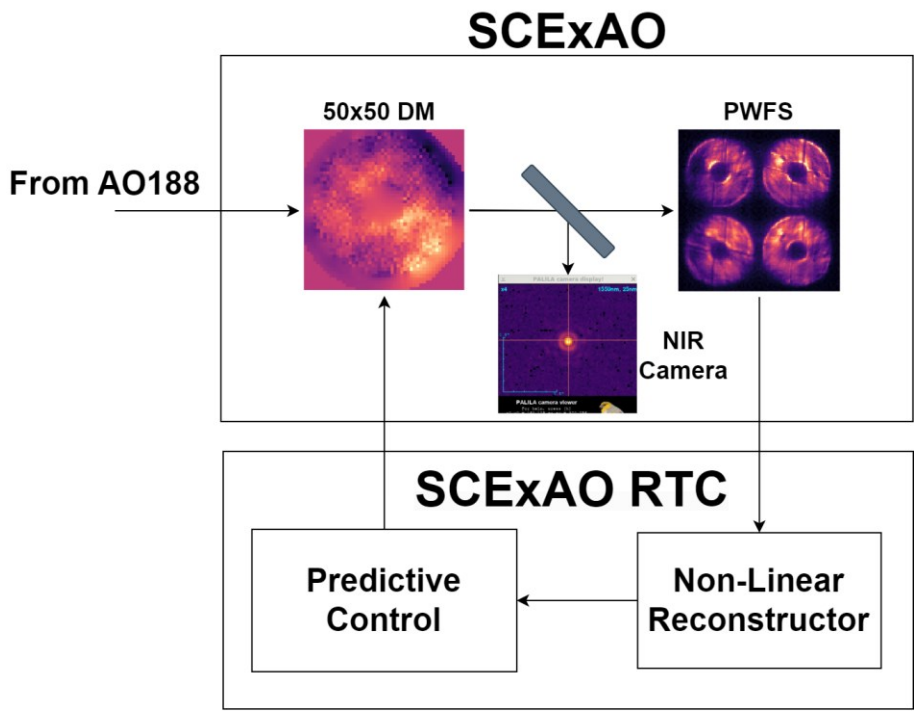
Methodology: multi-stage ML

Non-Linear Reconstruction – Supervised Learning

- P-WFS: non-linear relationship between P-WFS image and phase
- Close the loop even under strong non-linear behaviour

Predictive Control – Reinforcement Learning

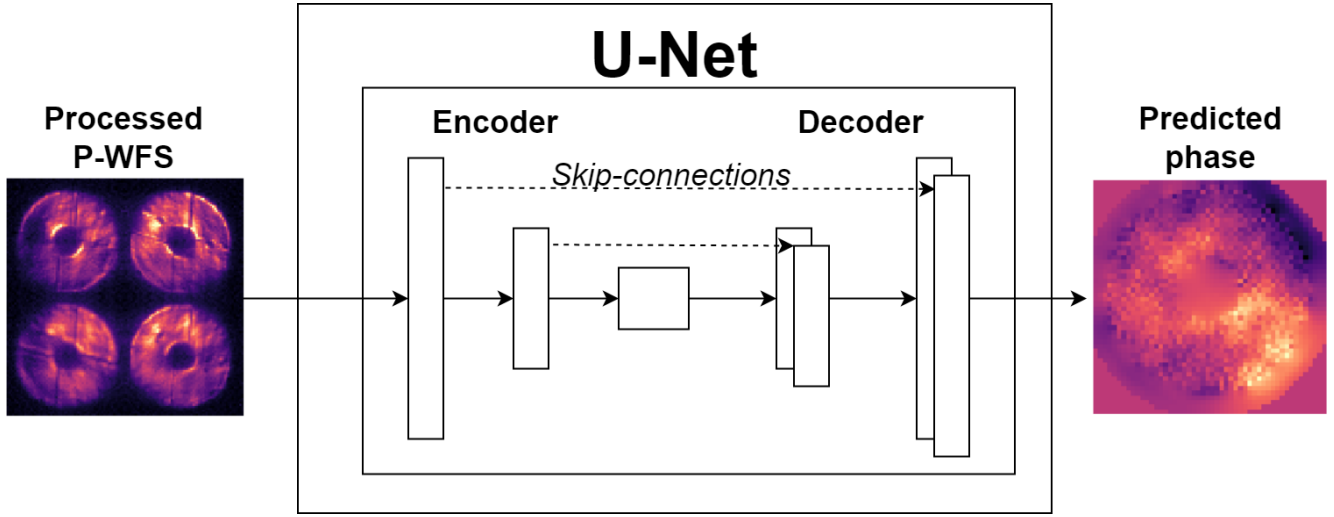
- Correct for error introduced by the system delay and atmospheric evolution



Non-linear reconstruction: U-Net

Training

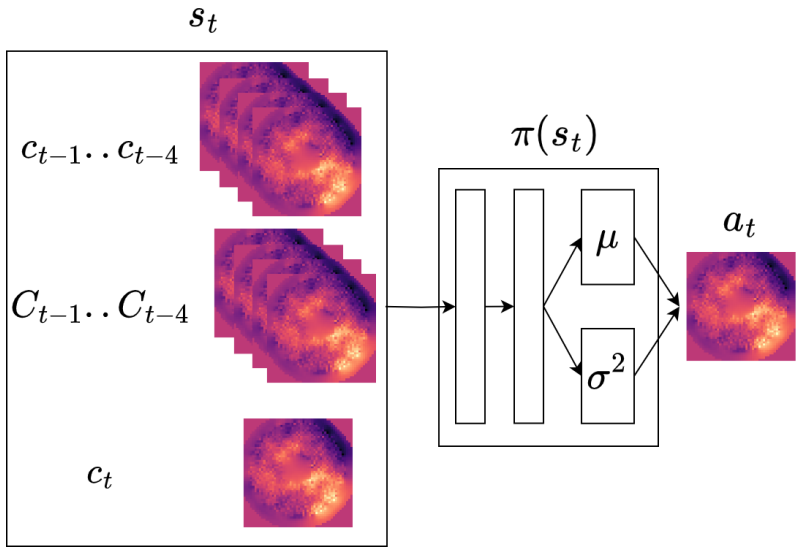
- Supervised Learning
- Gather data from the bench pushing modes/actuators randomly -> Generalize to any distribution
- U-Net with 8 layers
- L1 relative loss



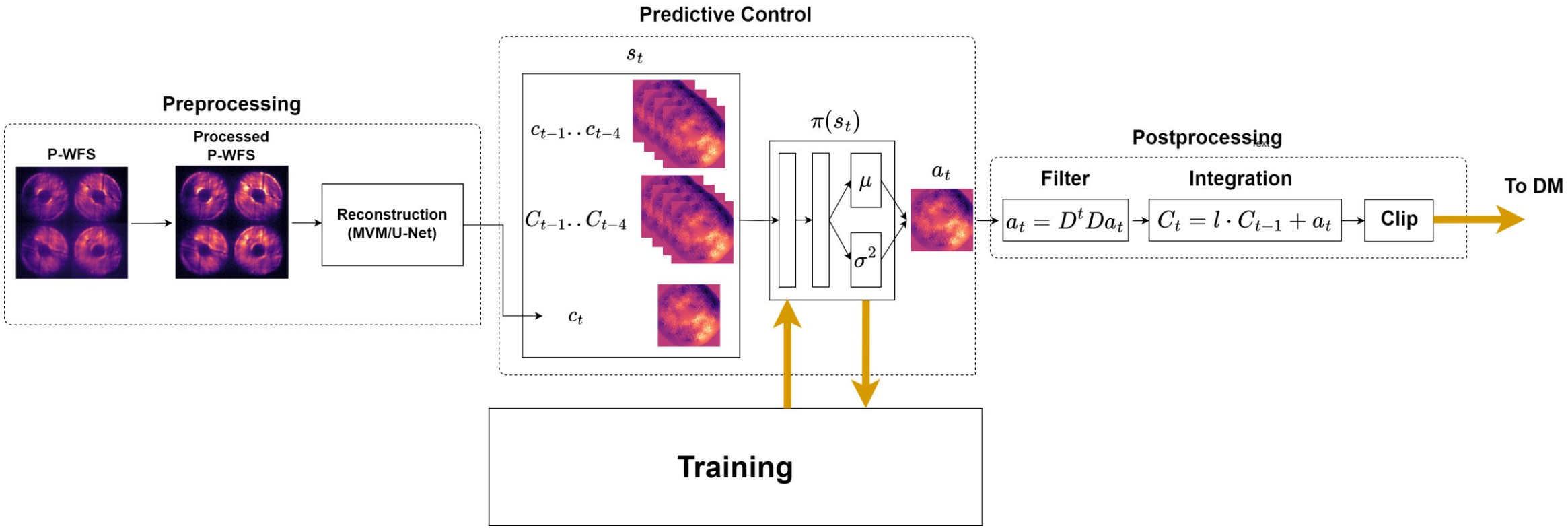
Predictive Control: Reinforcement Learning

Correct for **temporal error** with Deep **Reinforcement Learning (RL)**

- **Trial and error**
- **Policy** (π): given **state** predict **action** that maximises cumulative **reward**
  - State (s_t): reconstruction and history of reconstruction/history of commands
  - Reward (r_t): drives the policy to minimise future reconstructions
  - Action (a_t): residual command
- **Model-free RL**
- **Online training**



Pipeline

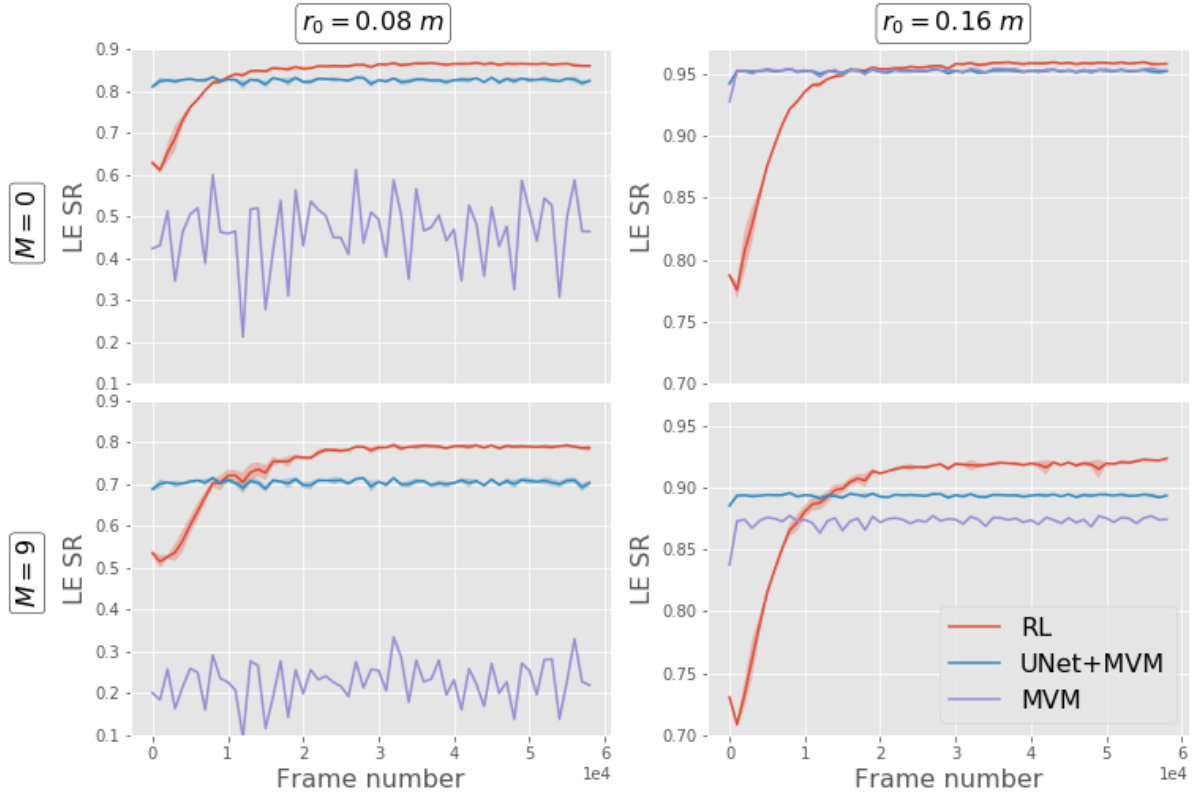

Predictive Control
s_t
Preprocessing
P-WFS
Processed P-WFS
Reconstruction (MVM/U-Net)
$c_{t-1}..c_{t-4}$
$C_{t-1}..C_{t-4}$
c_t
$\pi(s_t)$
μ
σ^2
a_t
Postprocessing
Filter
Integration
$a_t = D^t D a_t$
$C_t = l \cdot C_{t-1} + a_t$
Clip
To DM
Training

Simulation results (COMPASS)

- 40x40 DM, 56x56 P-WFS
- Various atmospheric conditions

Differences with real-world

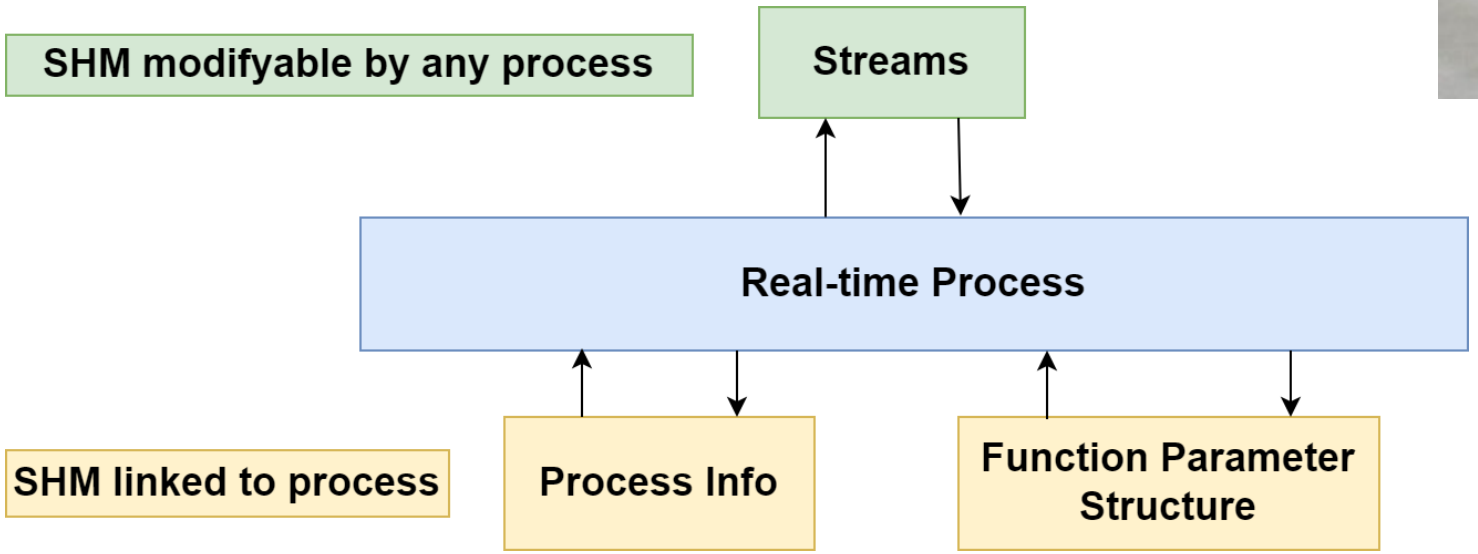
Ensure real time performance



MILK: Modular Image processing Library toolKit

Framework for high-performance image processing with shared memories (SHM)

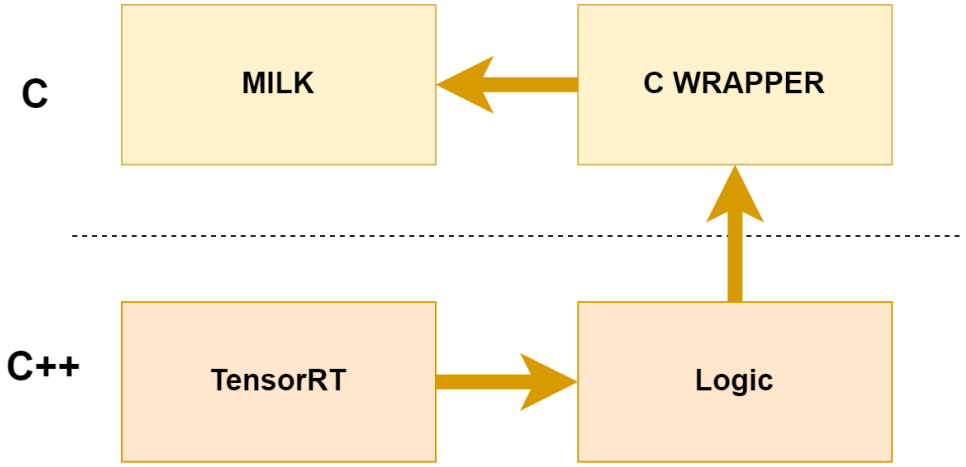
- **Main components:**
  - **Function Parameter Structure (FPS)**: Reading/writing parameters of processes
  - **Process information (ProcInfo):** Process management
  - **Streams**
- **Modularity**



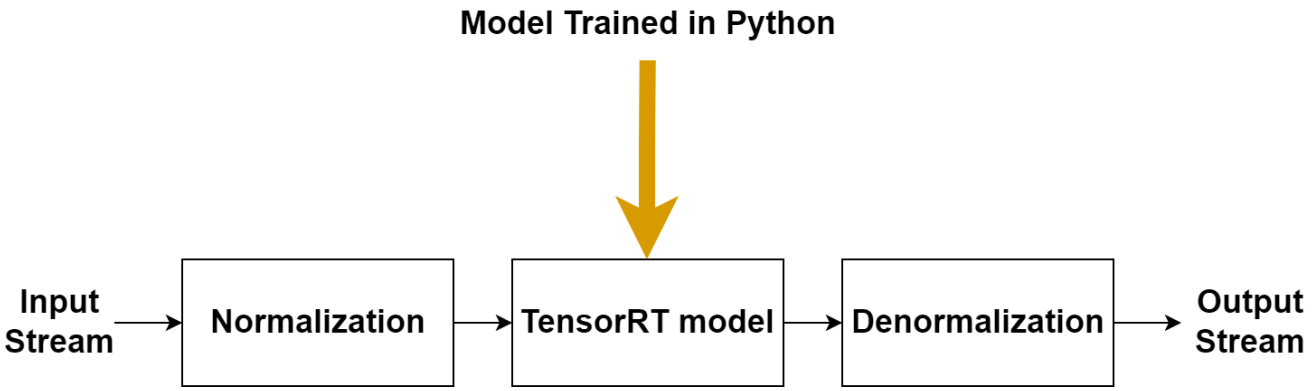
Deep neural network plugin for MILK

- Integrate MILK with high performance computing library TensorRT
  - Offline training models
  - Online training models

Code structure



Offline training models

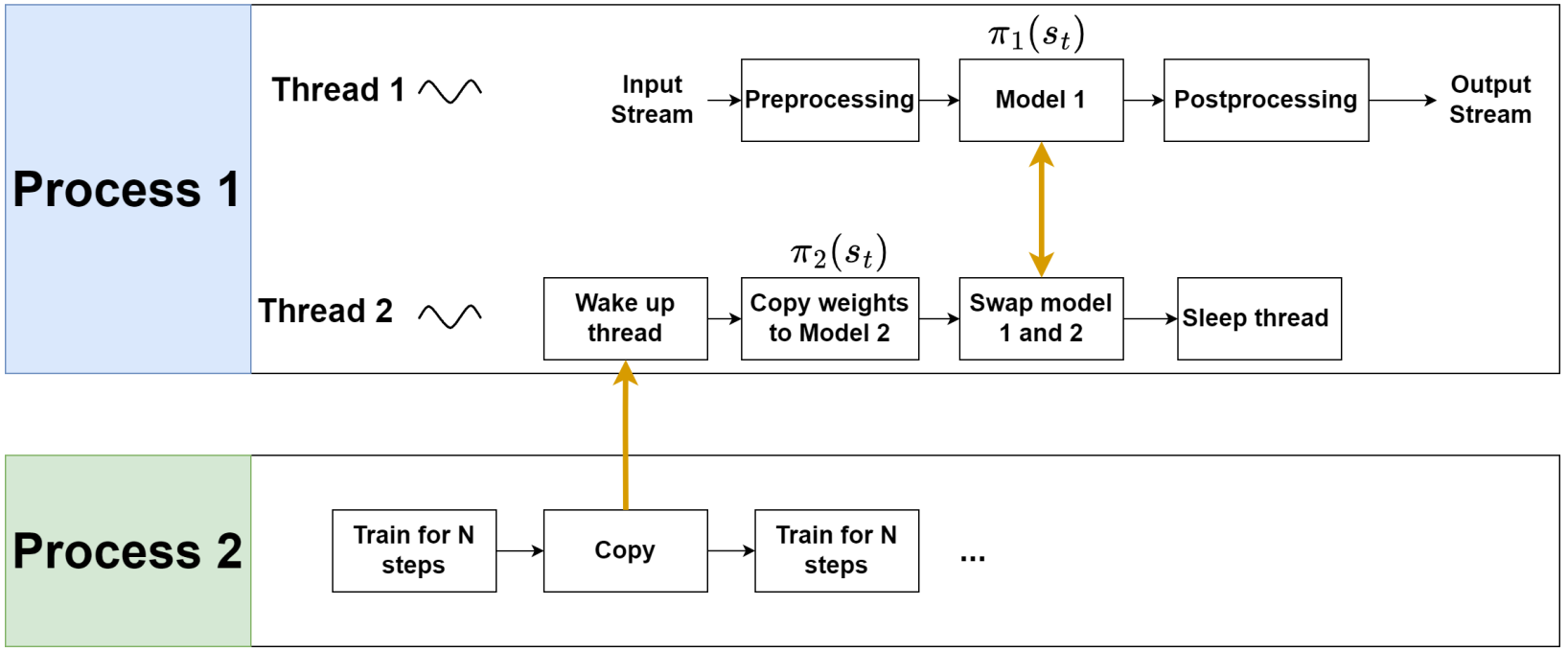


Deep neural network plugin for MILK II

Online training models

C/C++

(Hard real-time)



Python

(No hard real-time)

From ms to sub-ms!

Results

RL results: bench

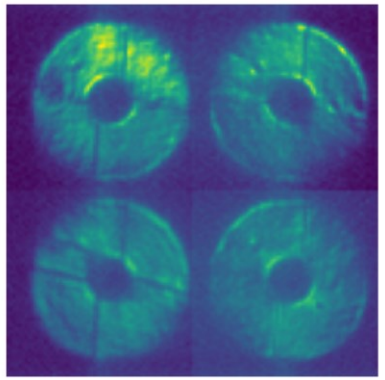
No fitting error

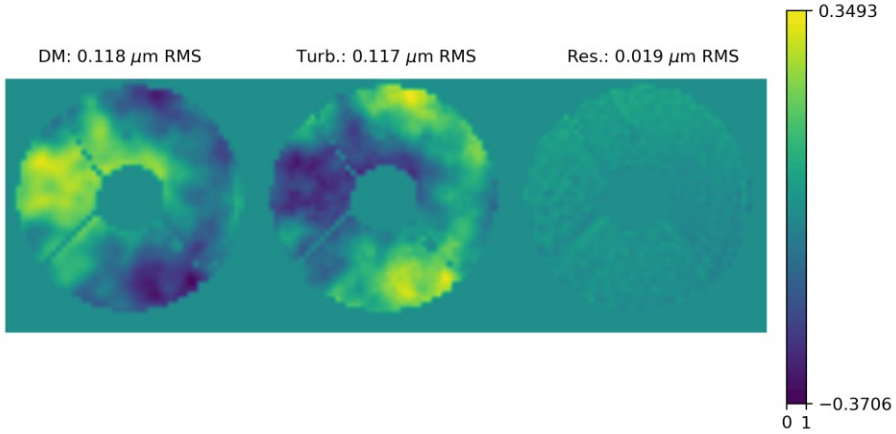
Loop parameters:

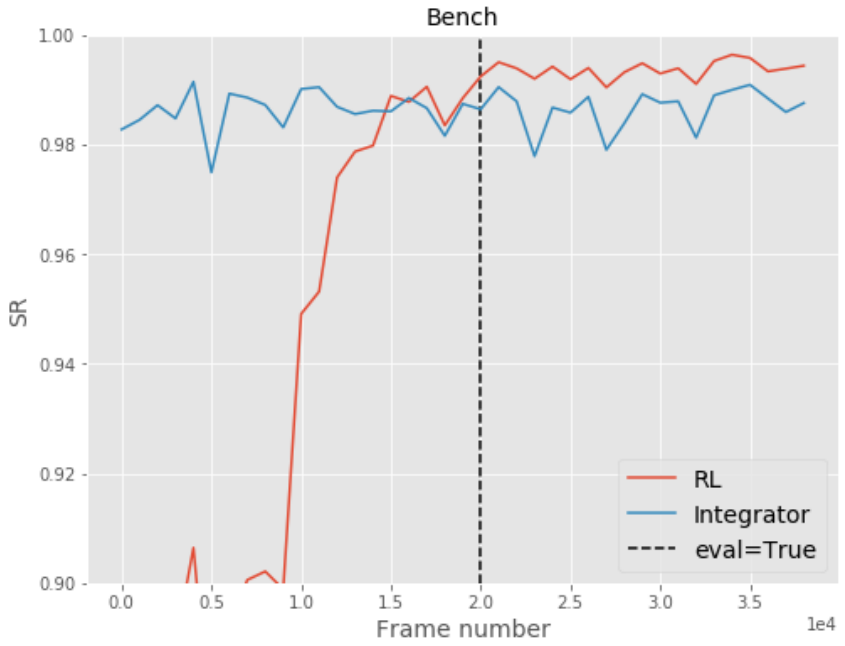
- 2 Khz
- Num. modes controlled = 500
- PWFS $r_{modulation} = 100$ mas
- Bright star

Atmos parameters:

- $A_{atmos} = 0.2$ µm
- Wind speed $= 20$ m/s
- Reduced amplitude on lower order modes (to simulate first stage)

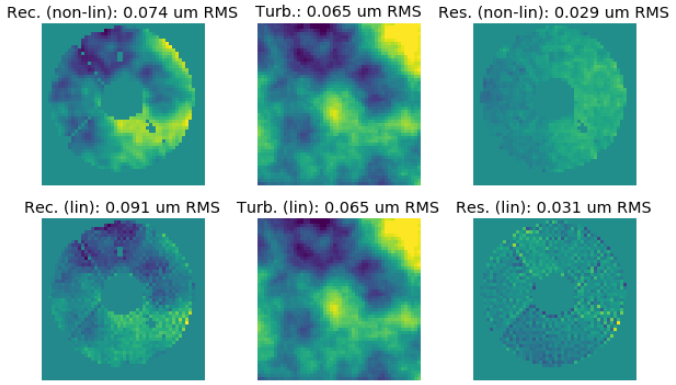




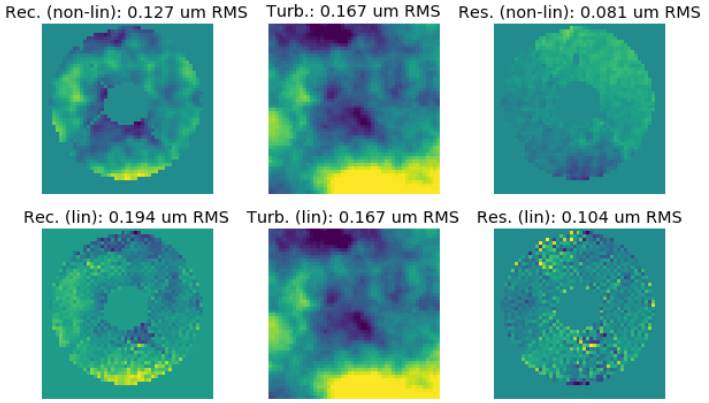


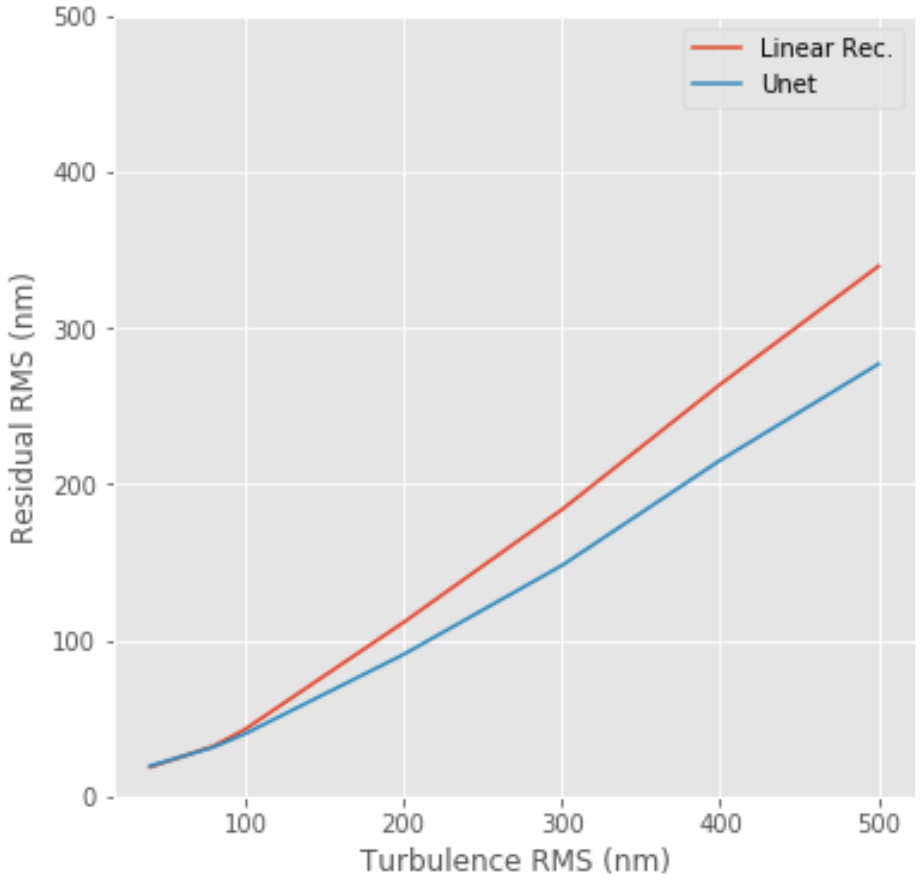
U-Net results: bench (same parameters)

Example 1



Example 2

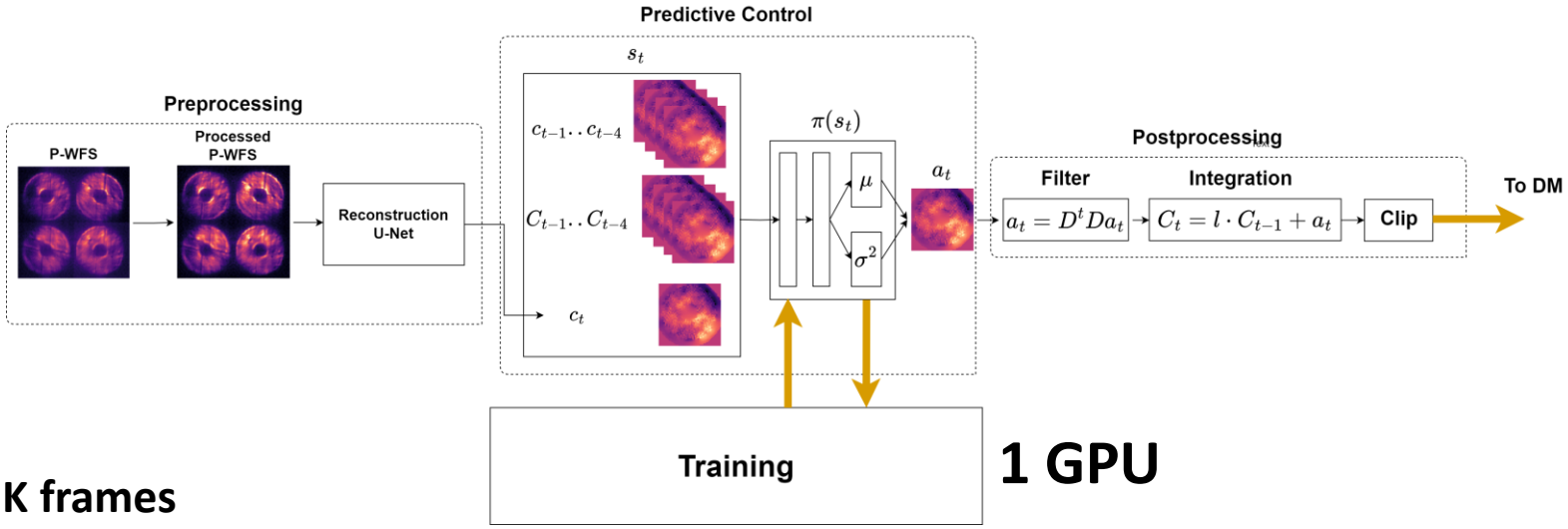




Tip tilt removed

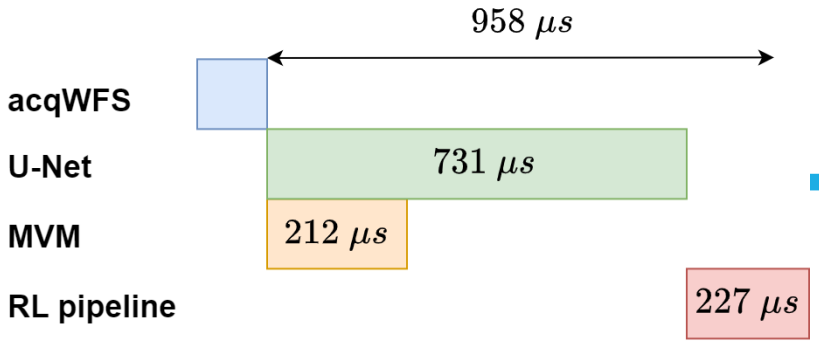
Real-time results: RL + U-Net

- Loop Frequency: 1 KHz
- Hardware:
  - Using 1 GPU A6000
  - Using 2 GPU RTX3080 Ti
  - Using 1 GPU RTX2080 Ti
  - 1 CPU Core per process



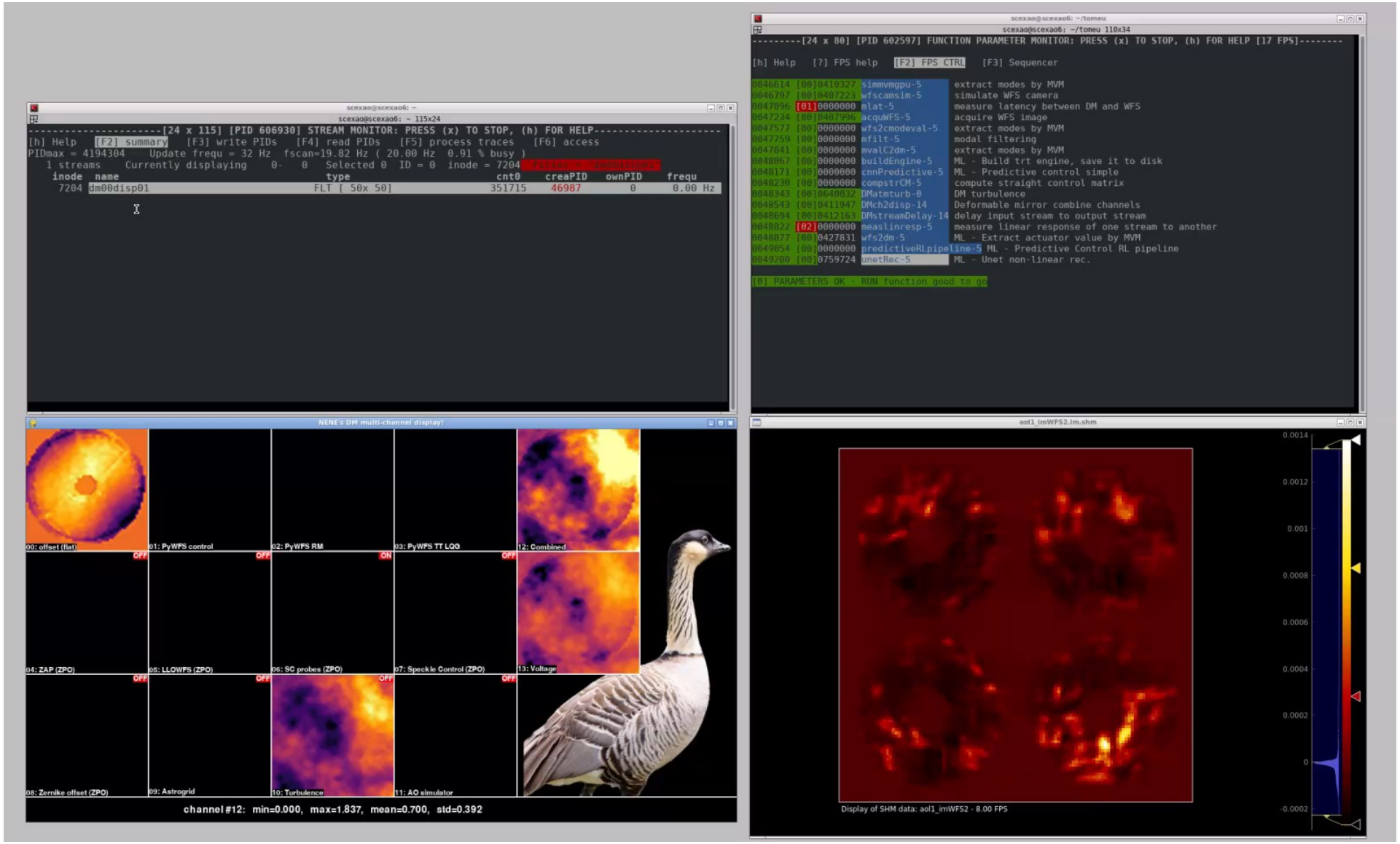
1 GPU

Average over 40 K frames



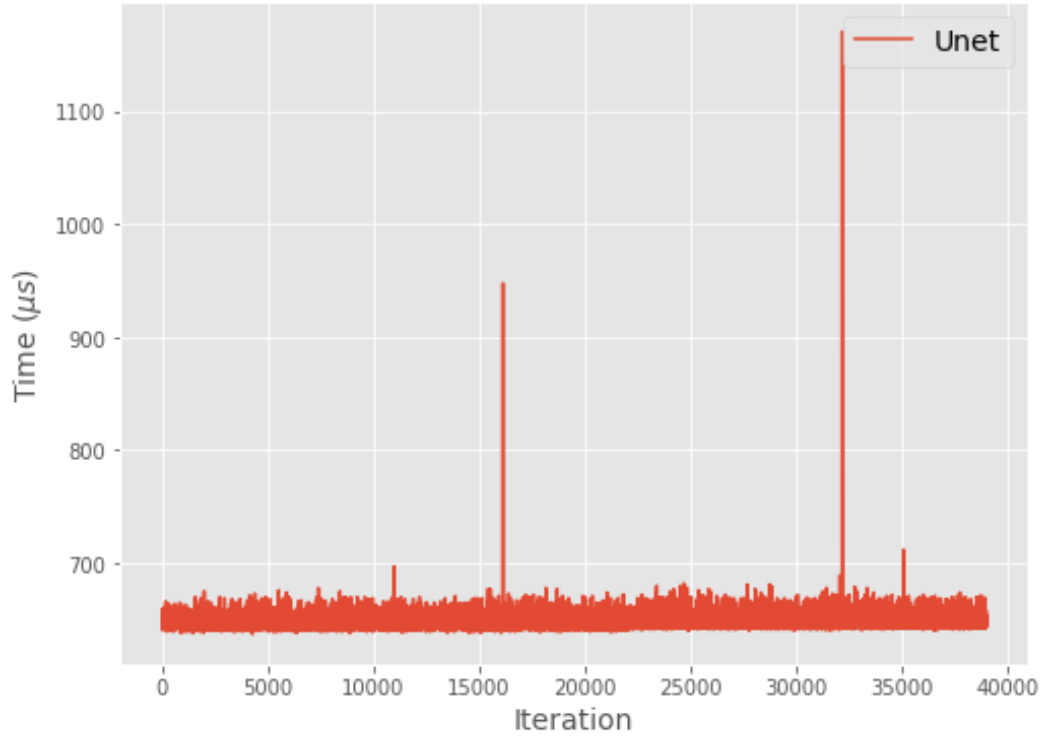
Critical Path

Could run at around 1 kHz


scexao@scexao6: ~
scexao@scexao6: ~ 115x24
[24 x 115] [PID 606930] STREAM MONITOR: PRESS (x) TO STOP, (h) FOR HELP
[h] Help [F2] summary [F3] write PIDs [F4] read PIDs [F5] process traces [F6] access
PIDmax = 4194304 Update frequ = 32 Hz fscan=19.82 Hz (20.00 Hz 0.91 % busy)
1 streams Currently displaying 0- 0 Selected 0 ID = 0 inode = 7204
inode name type cnt0 creaPID ownPID frequ
7204 dm00disp01 FLT [50x 50] 351715 46987 0 0.00 Hz
scexao@scexao6: ~/tomeu
scexao@scexao6: ~/tomeu 110x34
[24 x 80] [PID 602597] FUNCTION PARAMETER MONITOR: PRESS (x) TO STOP, (h) FOR HELP [17 FPS]
[h] Help [?] FPS help [F2] FPS CTRL [F3] Sequencer
0046614 [00]0410327 simmvmgpu-5 extract modes by MVM
0046797 [00]0407223 wfscamsim-5 simulate WFS camera
0047096 [01]0000000 mlat-5 measure latency between DM and WFS
0047234 [00]0407996 acquWFS-5 acquire WFS image
0047577 [00]0000000 wfs2cmodeval-5 extract modes by MVM
0047759 [00]0000000 mfilt-5 modal filtering
0047841 [00]0000000 mvalC2dm-5 extract modes by MVM
0048067 [00]0000000 buildEngine-5 ML - Build trt engine, save it to disk
0048171 [00]0000000 cnnPredictive-5 ML - Predictive control simple
0048230 [00]0000000 compstrCM-5 compute straight control matrix
0048343 [00]0640032 DMatmturb-0 DM turbulence
0048543 [00]0411947 DMch2disp-14 Deformable mirror combine channels
0048694 [00]0412163 DMstreamDelay-14 delay input stream to output stream
0048822 [02]0000000 measlinresp-5 measure linear response of one stream to another
0048877 [00]0427831 wfs2dm-5 ML - Extract actuator value by MVM
0049054 [00]0000000 predictiveRLpipeline-5 ML - Predictive Control RL pipeline
0049280 [00]0759724 unetRec-5 ML - Unet non-linear rec.
[0] PARAMETERS OK - RUN function good to go
NENE's DM multi-channel display!
00: offset (flat)
01: PyWFS control
02: PyWFS RM
03: PyWFS TT LQG
12: Combined
04: ZAP (ZPO)
05: LLOWFS (ZPO)
06: SC probes (ZPO)
07: Speckle Control (ZPO)
13: Voltage
08: Zernike offset (ZPO)
09: Astrogrid
10: Turbulence
11: AO simulator
channel #12: min=0.000, max=1.837, mean=0.700, std=0.392
aol1_imWFS2.im.shm
Display of SHM data: aol1_imWFS2 - 8.00 FPS
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
-0.0002

Real-time: Issues

Jitter



Time per update (RL)

- Time per update: 0.08 ms
- Total updates to learn from scratch: 20K
- Total time: 26 min
- Still, RL won't be learning from scratch all the time

Conclusion

SCExAO is a unique environment to test new ideas in a state-of-the-art 8m telescope

1. Demonstrated potential of new ML methods on the SCExAO bench (off-real time)
2. Highlighted the extra difficulties in real-life compared to a simulation
3. Implemented a library for real-time inference of deep neural networks which is integrated into RTC software – to be released soon …
4. Once the constraints are solved, I expect to try it on-sky with SCExAO

Integration into COSMIC

Questions?

Feel free to email me at
bartomeu.poumulet@bsc.es