SLAMBench, a performance and accuracy benchmarking methodology for SLAM

Luigi Nardi, Imperial College London

@La Sapienza, December 19th 2014

In collaboration with:
Bruno Bodin, M Zeeshan Zia, John Mawer, Andy Nisbet, Paul H J Kelly, Andrew J Davison, Mikel Luján, Michael F P O'Boyle, Graham Riley, Nigel Topham, Steve Furber

Outline

- SLAM application
- Holistically execution time/energy/accuracy: SLAMBench
- Experimental results
- Conclusion and opportunities

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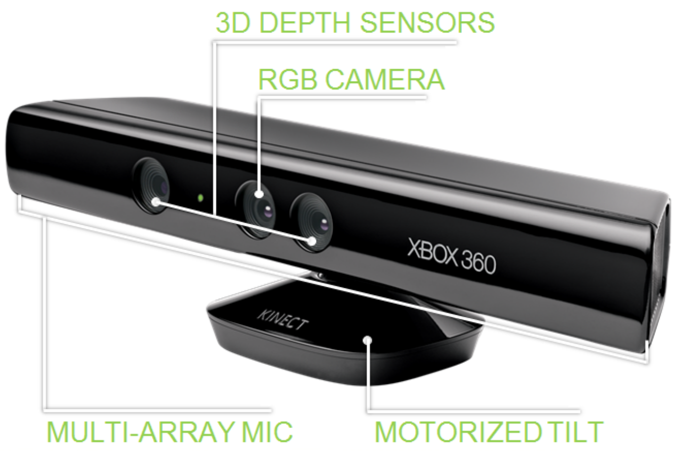
Simultaneous Localisation And Mapping (SLAM)

Build a coherent world representation and localise the camera in real-time



SIGGRAPH Talks 2011

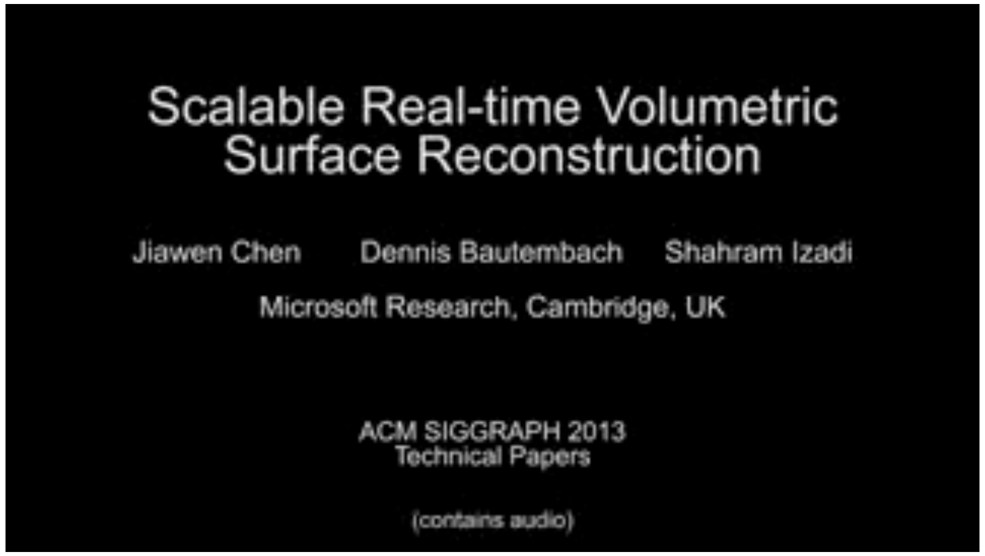
KinectFusion:

Real-Time Dynamic 3D Surface Reconstruction and Interaction

Shahram Izadi 1, Richard Newcombe 2, David Kim 1,3, Otmar Hilliges 1, David Molyneaux 1,4, Pushmeet Kohli 1, Jamie Shotton 1, Steve Hodges 1, Dustin Freeman 5, Andrew Davison 2, Andrew Fitzgibbon 1

1 Microsoft Research Cambridge 2 Imperial College London
3 Newcastle University 4 Lancaster University
5 University of Toronto

https://www.youtube.com/watch?v=quGhaggn3cQ#t=102
[Newcombe et al. ISMAR 2011]


Scalable Real-time Volumetric Surface Reconstruction

Jiawen Chen Dennis Bautembach Shahram Izadi

Microsoft Research, Cambridge, UK

ACM SIGGRAPH 2013
Technical Papers

(contains audio)

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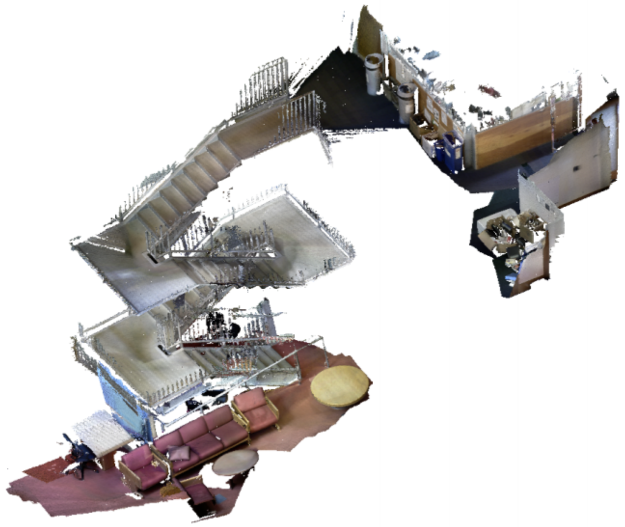
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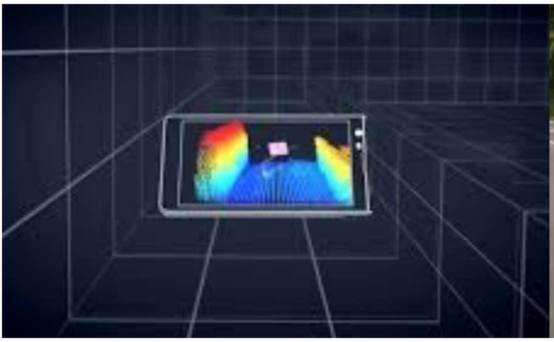

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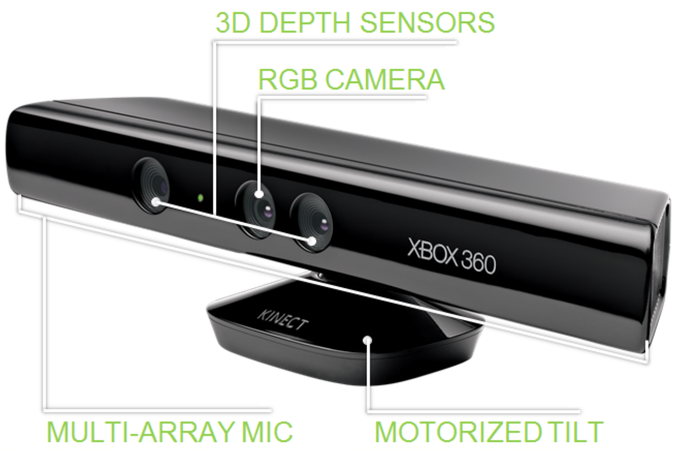

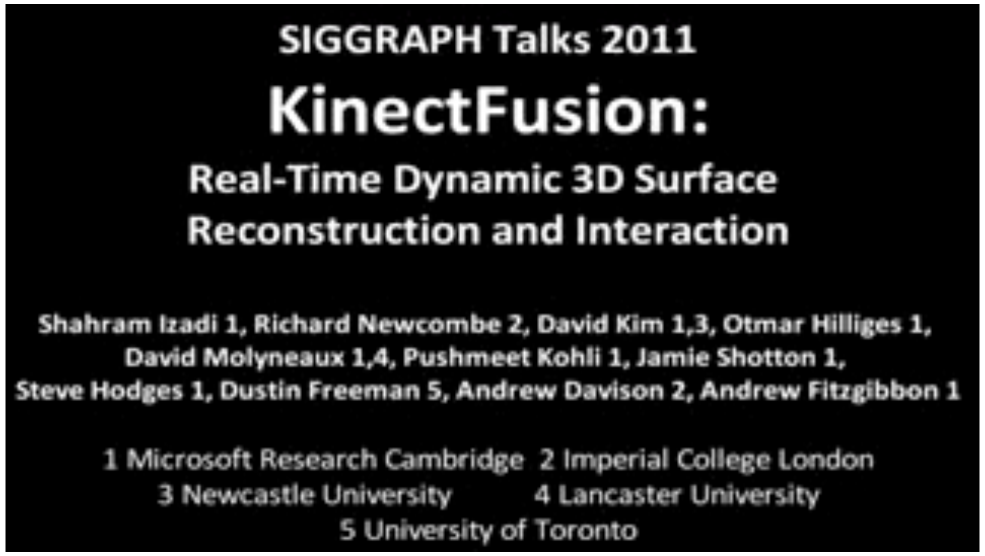

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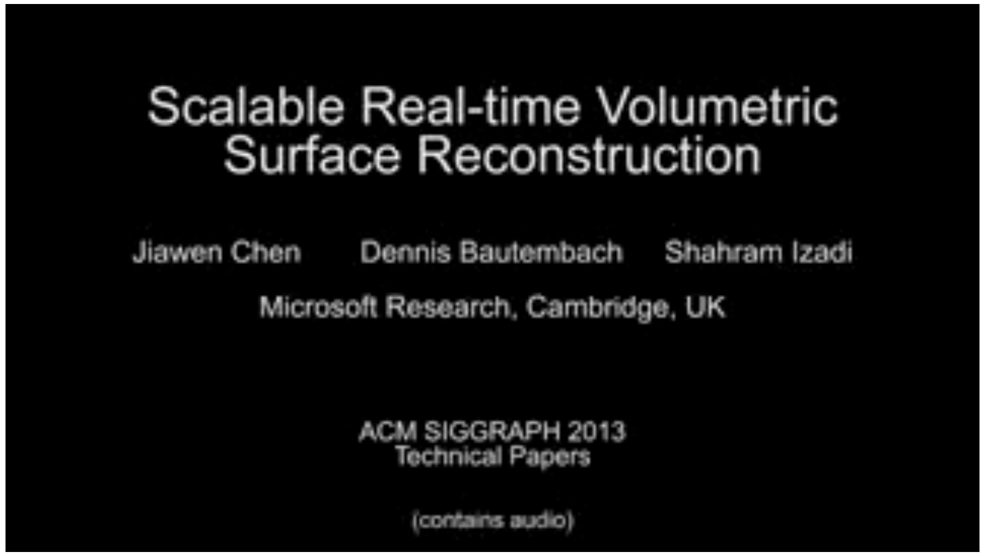

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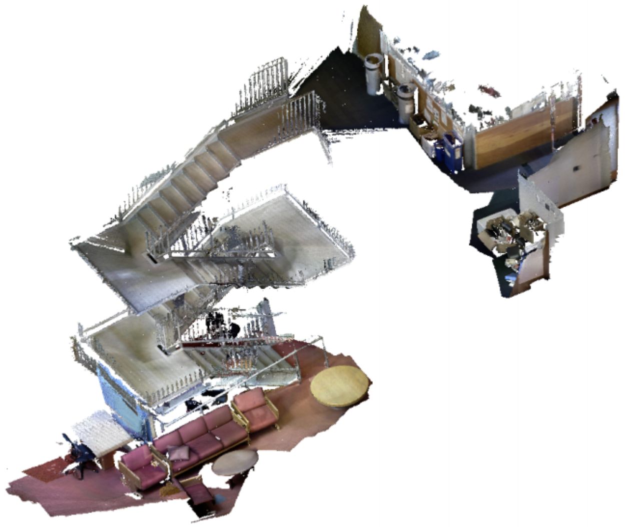

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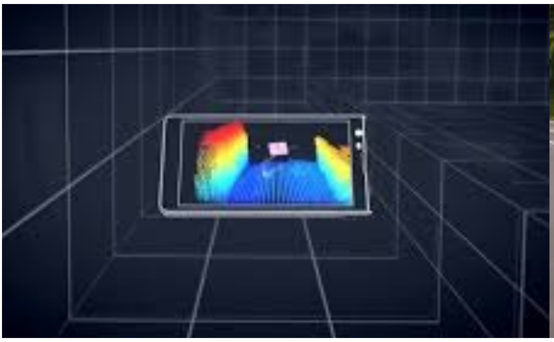
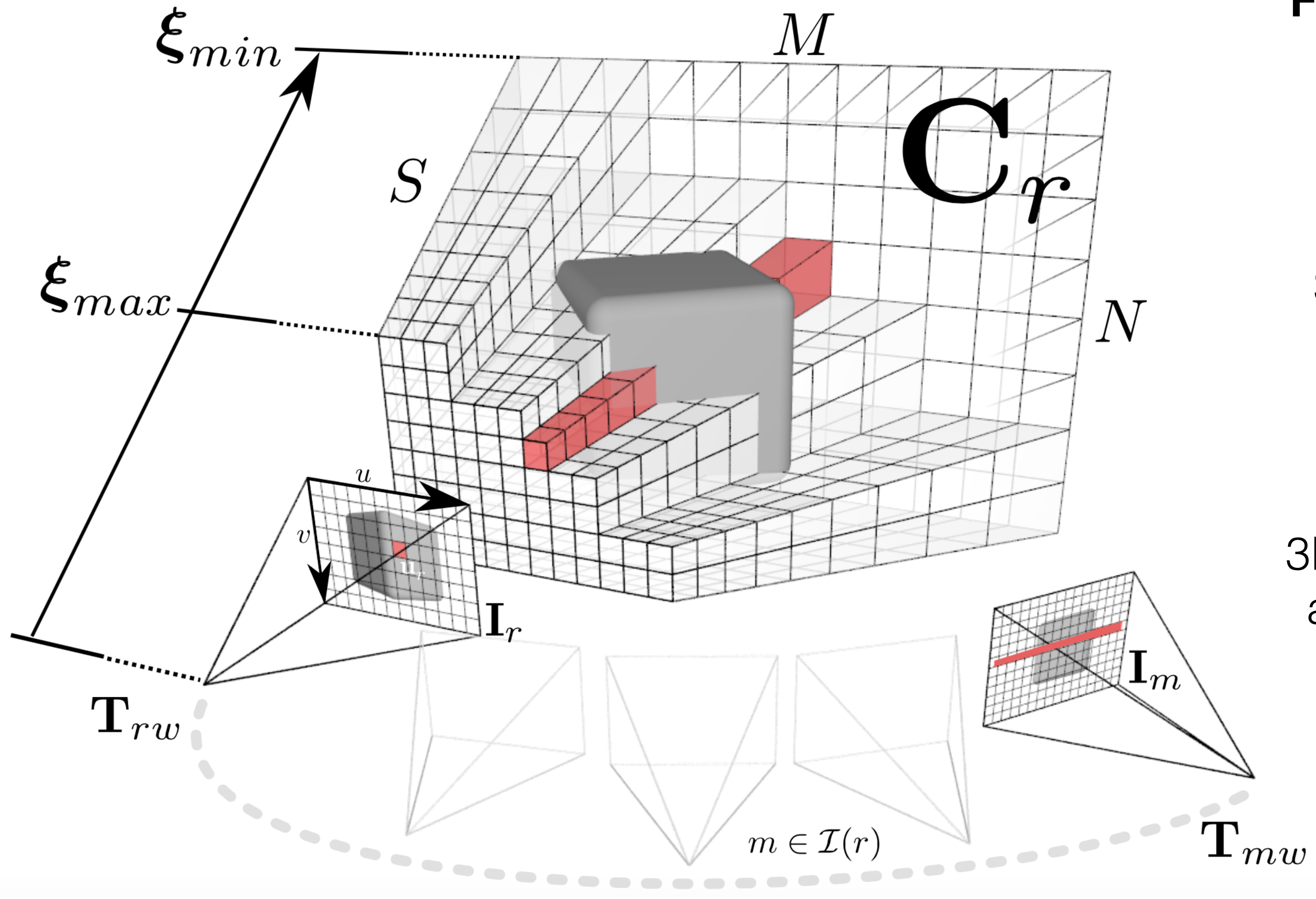


Dense SLAM implementation: KinectFusion



[Newcombe et al. ICCV 2011]

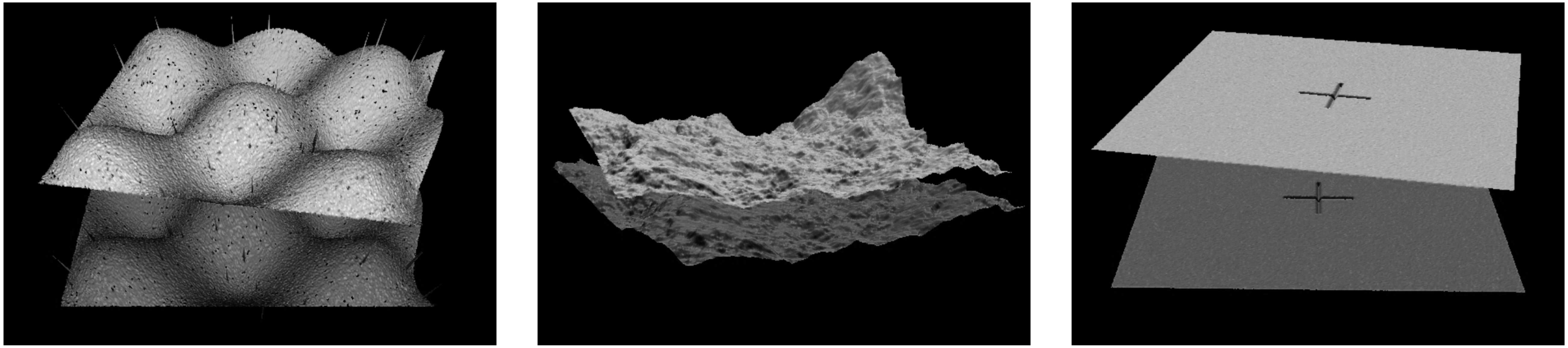
Fuses the stream depth frames into a **3D geometric map**

Voxel grid: Truncated Signed Distance Function (**TSDF**) to represent 3D surfaces [Curless and Levoy 1996]

3D surfaces recovered by raycasting at the **zero crossings** of the TSDF

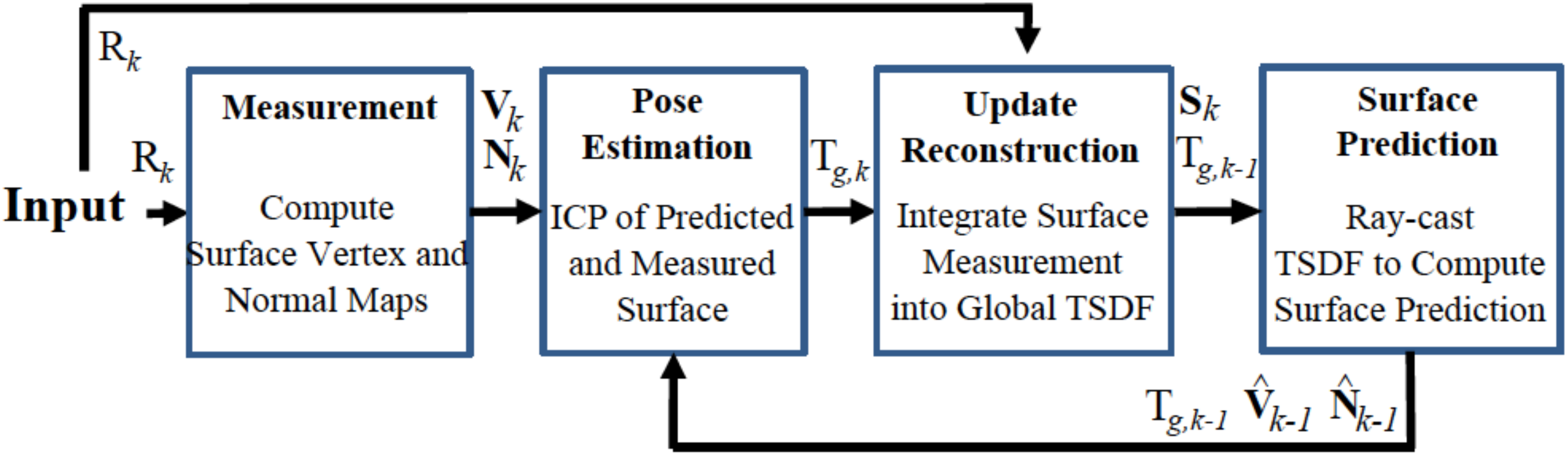
Localisation: estimates the location and pose

ICP registration



[Rusinkiewicz and Levoy 2001]

- Iterative Closest Point (ICP):
  rigid body transform (6 DoF) from frame k-1 to frame k.
- Iterative algorithm computing an energy function minimisation



Input

R_k

R_k

Measurement

Compute Surface Vertex and Normal Maps

V_k N_k

Pose Estimation

ICP of Predicted and Measured Surface

$T_{g,k}$

Update Reconstruction

Integrate Surface Measurement into Global TSDF

S_k $T_{g,k-1}$

Surface Prediction

Ray-cast TSDF to Compute Surface Prediction

$T_{g,k-1}$ $\hat{V}_{k-1}$ $\hat{N}_{k-1}$

KinectFusion pipeline

- First dense monocular SLAM algorithm [Newcombe et al. ISMAR 2011]
- Adopted as a major building block in more recent SLAM systems
- Implementation based on [Reitmayr 2011] CUDA implementation

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- **Holistically execution time/energy/accuracy: SLAMBench**
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- Conclusion and opportunities

Three “Performance” metrics

Benchmarks:

1. In computer vision targets **accuracy**

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2. Other benchmarks target **execution time** - however scarce in CV

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3. Is somebody targeting **energy**?

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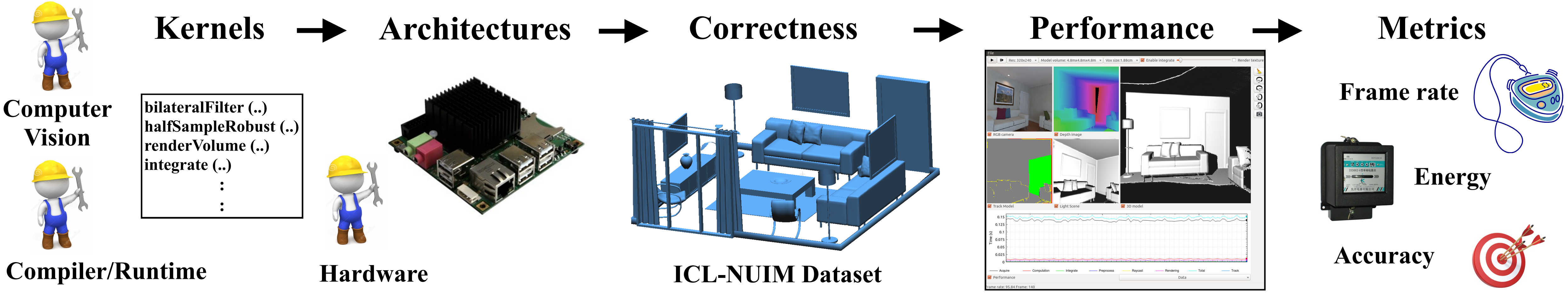
More holistic approach to SLAM “performance”: SLAMBench



Kernels → Architectures → Correctness → Performance → Metrics

Computer Vision

Compiler/Runtime

bilateralFilter (..)
halfSampleRobust (..)
renderVolume (..)
integrate (..)
:
:

Hardware

ICL-NUIM Dataset

Frame rate

Energy

Accuracy

How to measure SLAM “Performance”?

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1. Computation depends on:

    - Images acquired

    - Way the camera is moved

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      (depends on the hardware capability)

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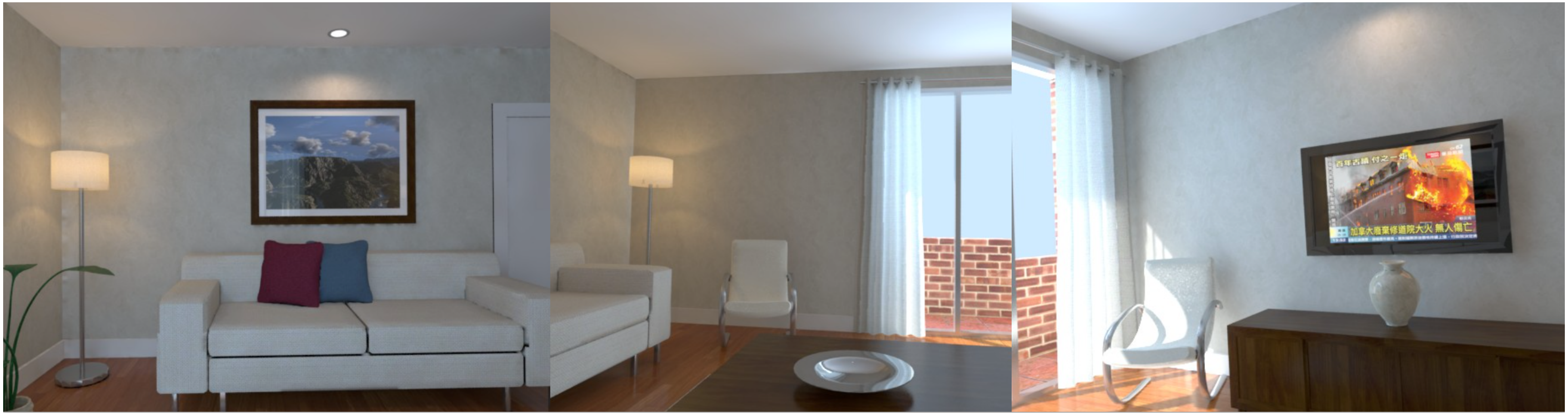
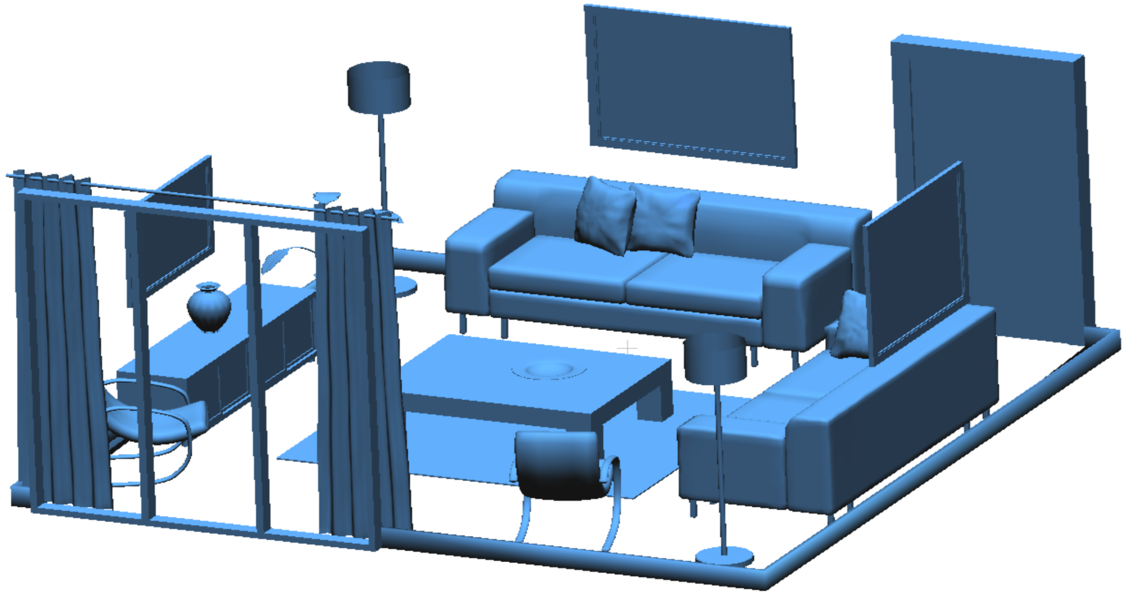
Need for accuracy check:
ICL-NUIM dataset *(frames and* ground truth)

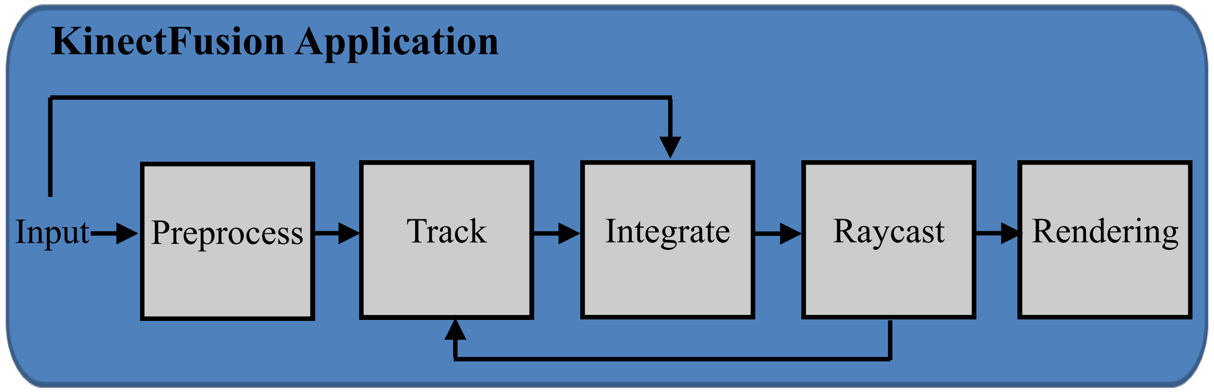
ICL-NUIM dataset



- ICL-NUIM synthetic dataset [Handa et al. 2014]
- RGB-D sequences
- Absolute Trajectory Error (ATE): ground truth and estimated trajectory error
- Microsoft's Kinect sensor modelled noise

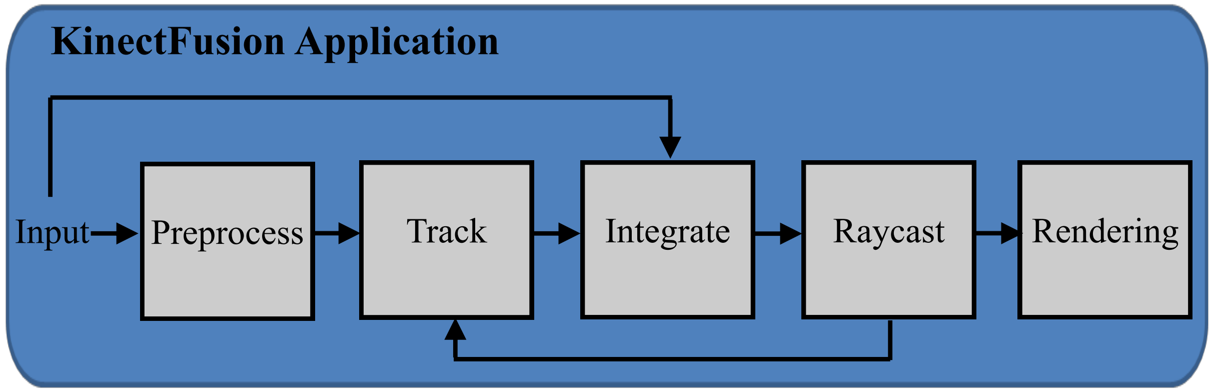


SLAMBench framework



high-level blocks

SLAMBench framework



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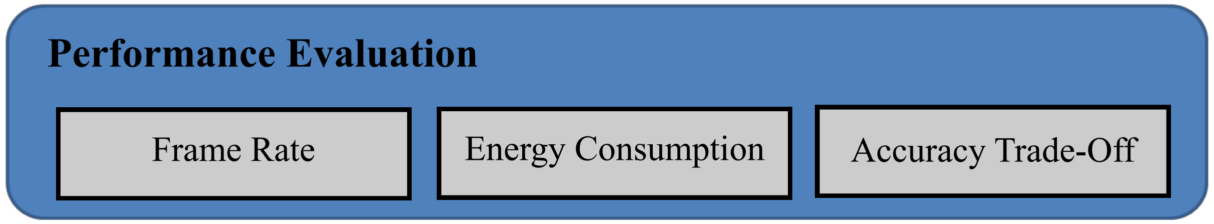
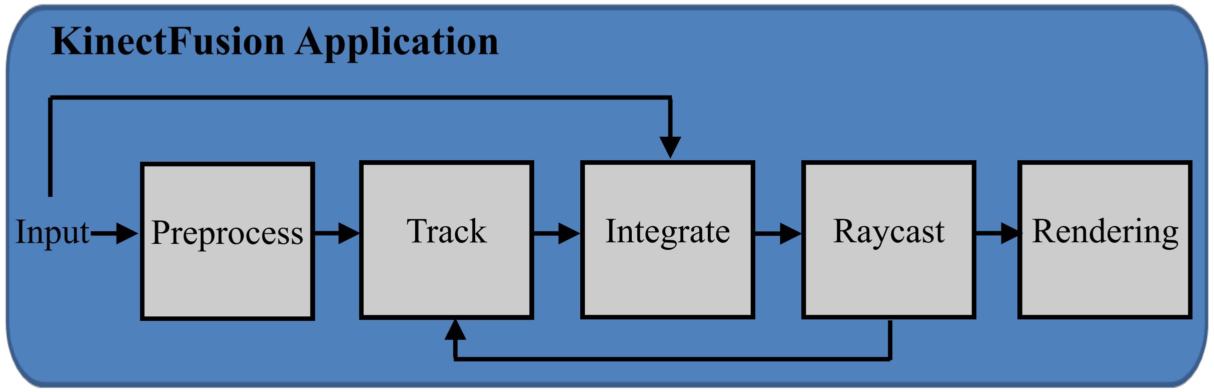


3 metrics:
execution time/energy/accuracy

SLAMBench framework



KinectFusion Application

Input → Preprocess → Track → Integrate → Raycast → Rendering

high-level blocks

Platforms

ARM | INTEL | NVIDIA | ...

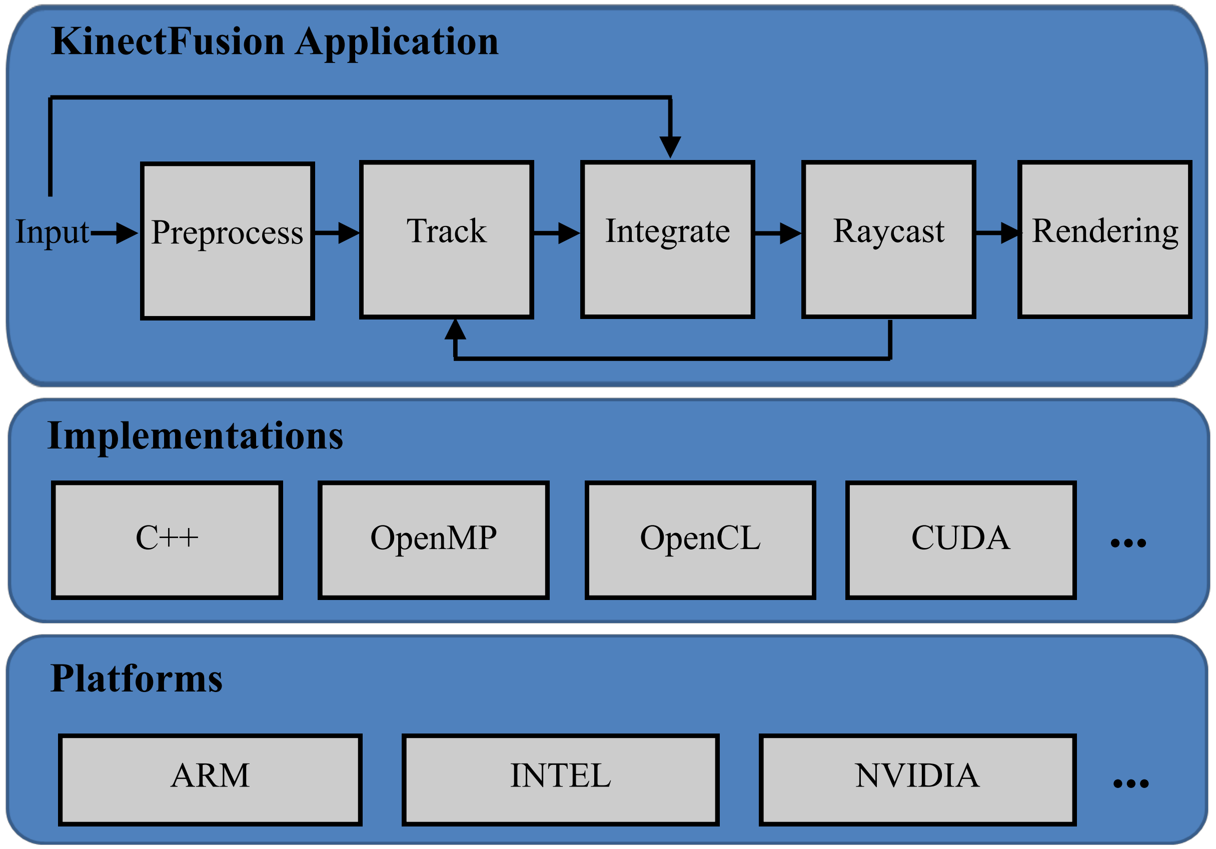
desktop, mobile, embedded: multi-core and many-core

Performance Evaluation

Frame Rate | Energy Consumption | Accuracy Trade-Off

3 metrics:
execution time/energy/accuracy

SLAMBench framework



high-level blocks

wide range of languages

desktop, mobile, embedded:
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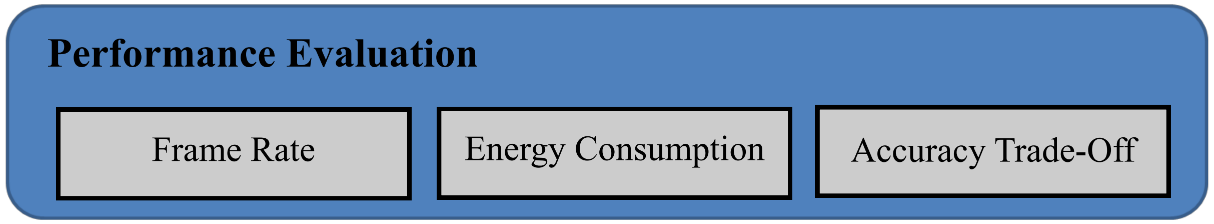

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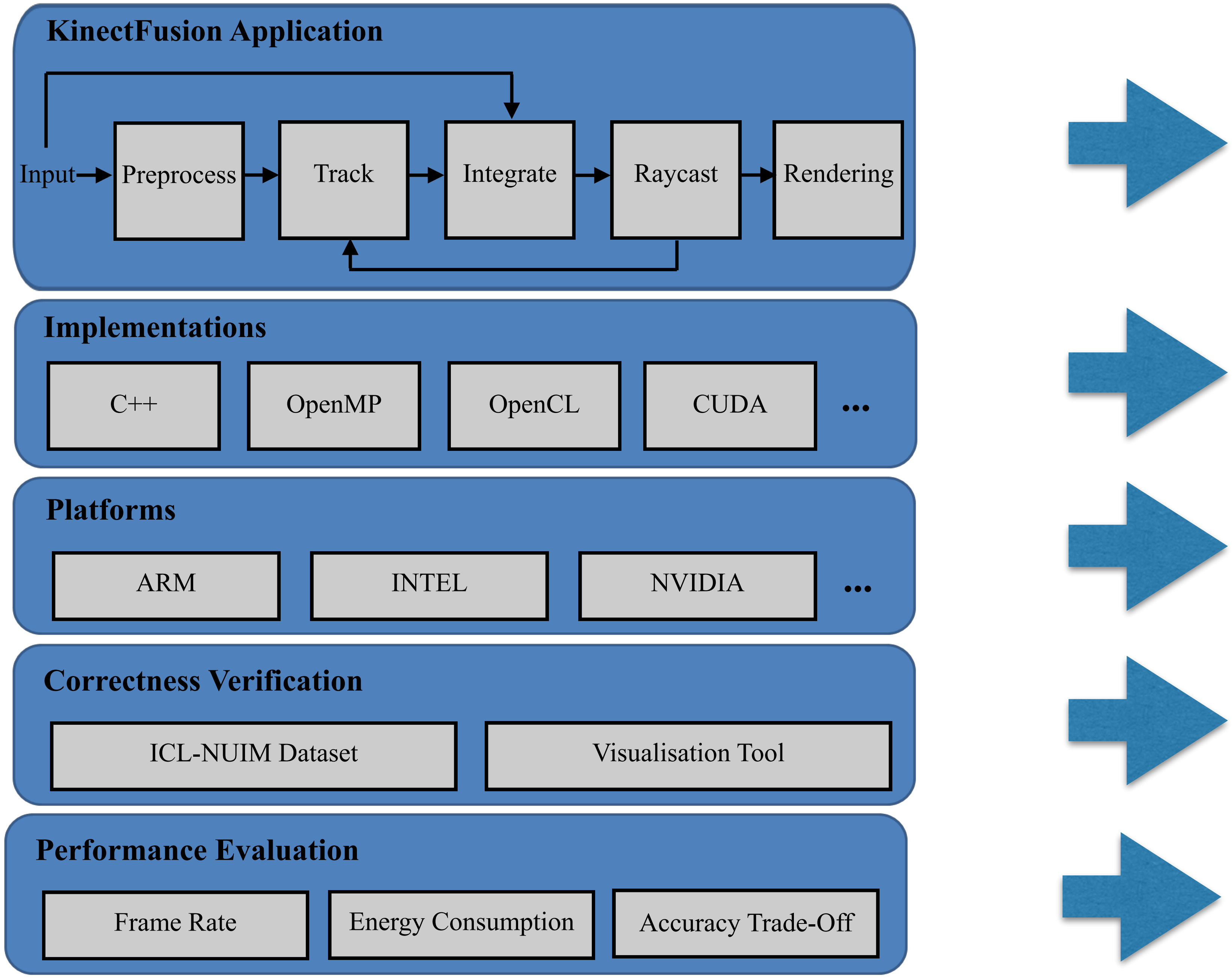


high-level blocks

wide range of languages

desktop, mobile, embedded:
multi-core and many-core

integrated
verification/visualisation

3 metrics:
execution time/energy/accuracy

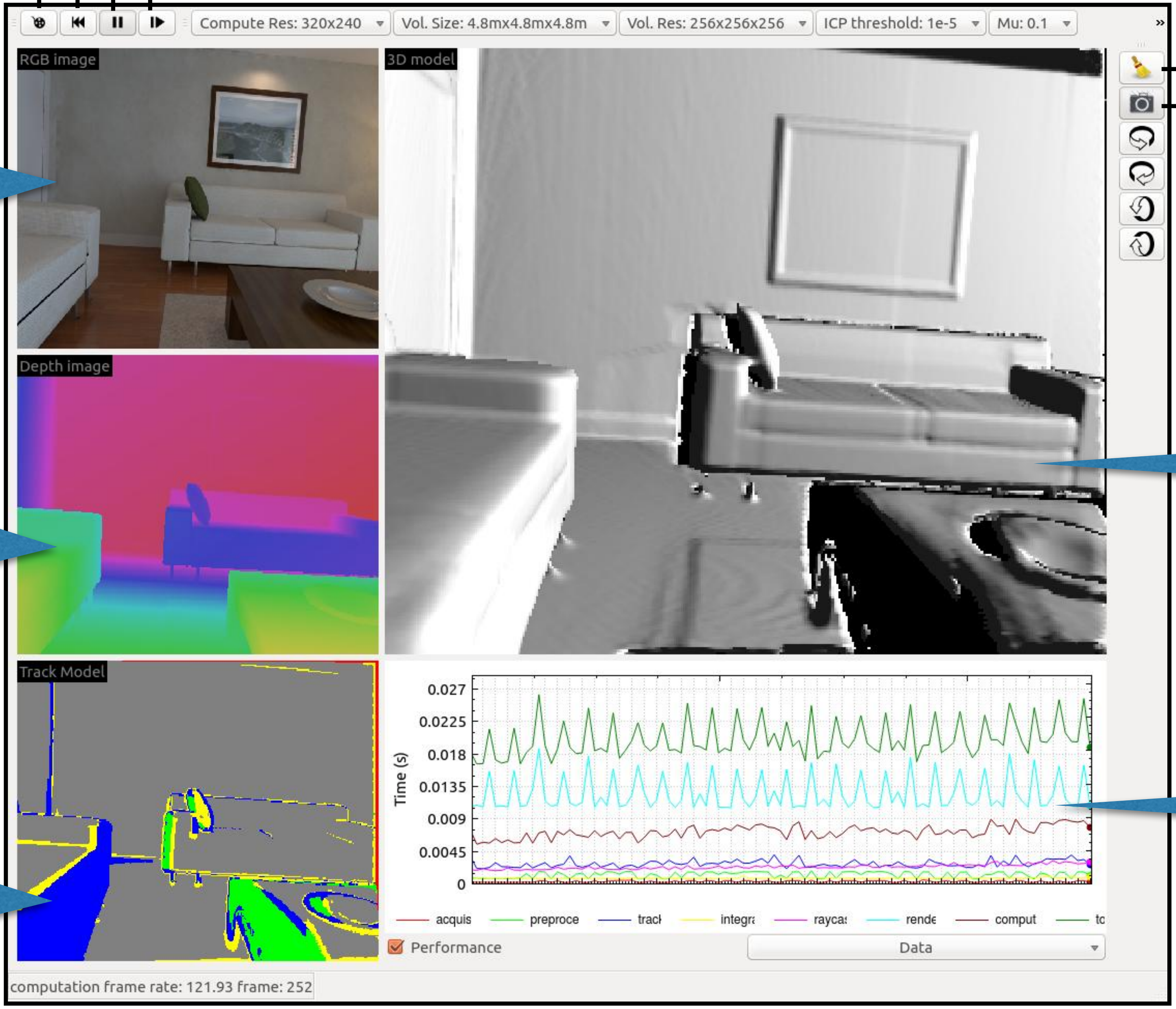
SLAMBench GUI

Camera input

Restart

Pause

Step



Compute Res: 320x240

Vol. Size: 4.8mx4.8mx4.8m

Vol. Res: 256x256x256

ICP threshold: 1e-5

Mu: 0.1

computation frame rate: 121.93 frame: 252

Reset volume

Toggle viewpoint of 3D model

RGB camera (not used)

Depth camera

Tracked points

3D model

Performance

SLAMBench kernels

Kernels	Pipeline	Pattern	In	Out	%
acquire	Acquire	n/a	pointer	2D	0.03
mm2meters	Preprocess	Gather	2D	2D	0.06
bilateralFilter	Preprocess	Stencil	2D	2D	33.68
halfSample	Track	Stencil	2D	2D	0.05
depth2vertex	Track	Map	2D	2D	0.11
vertex2normal	Track	Stencil	2D	2D	0.27
track	Track	Map/Gather	2D	2D	4.72
reduce	Track	Reduction	2D	6x6	2.99
solve	Track	Sequential	6x6	6x1	0.02
integrate	Integrate	Map/Gather	2D/3D	3D	12.85
raycast	Raycast	Search/Stencil	2D/3D	2D	35.87
renderDepth	Rendering	Map	2D	2D	0.12
renderTrack	Rendering	Map	2D	2D	0.06
renderVolume	Rendering	Search/Stencil	3D	2D	9.18

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Machines	TITAN	GTX870M	TK1	ODROID	Arndale
CPU	Intel	Intel	ARM	ARM	ARM
CPU cores	4	4	4 + 1	4 + 4	2
GPU	NVIDIA TITAN	NVIDIA GTX 870M	NVIDIA Tegra K1	ARM Mali-T628	ARM Mali-T604
GPU FLOPS	2250	1260	330	60 + 30	60

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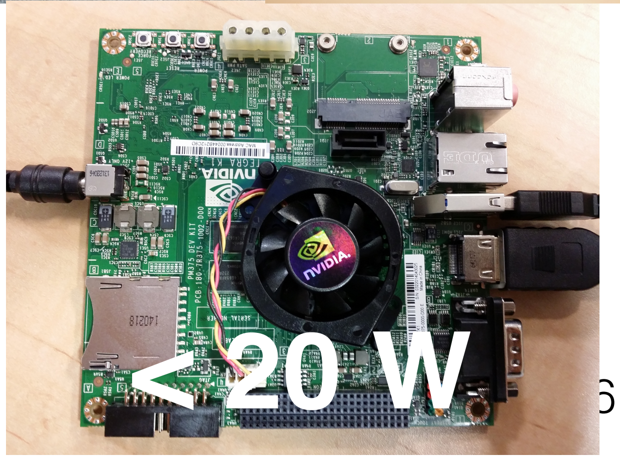

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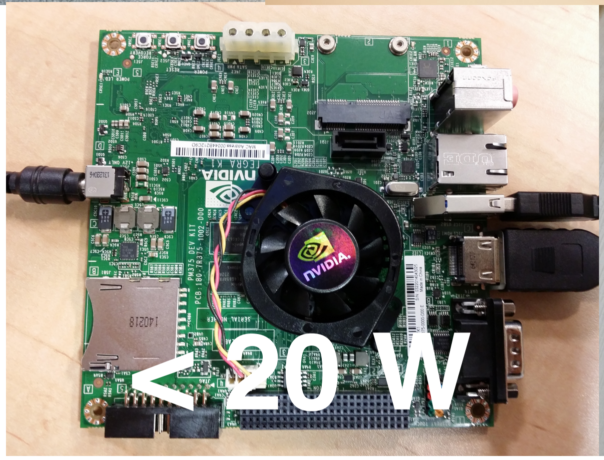

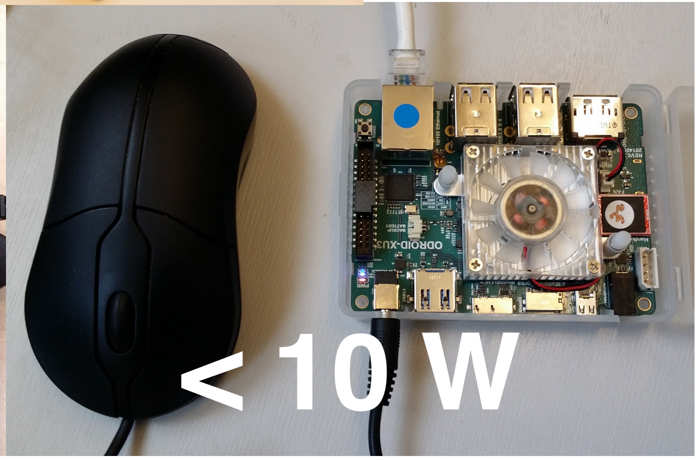

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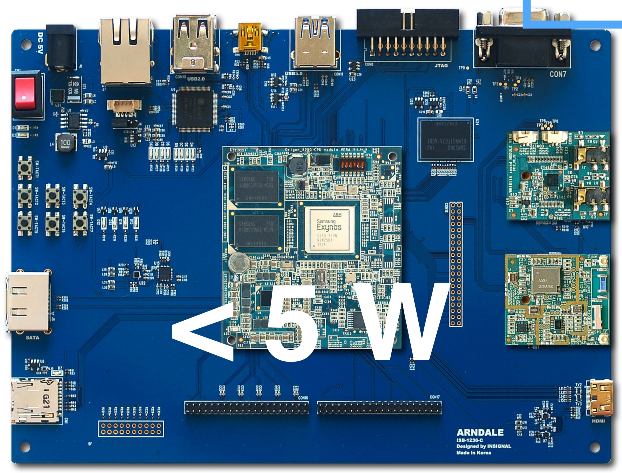

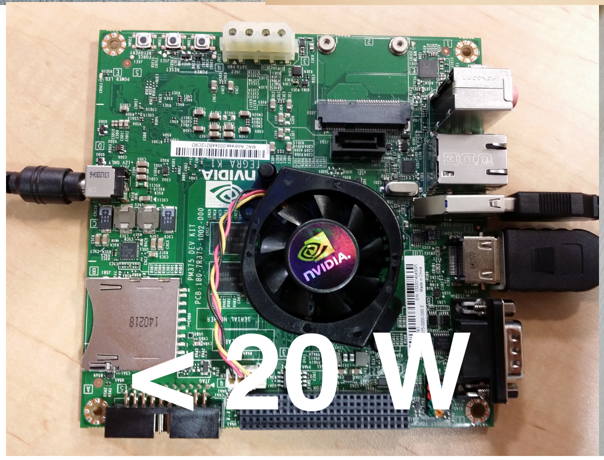

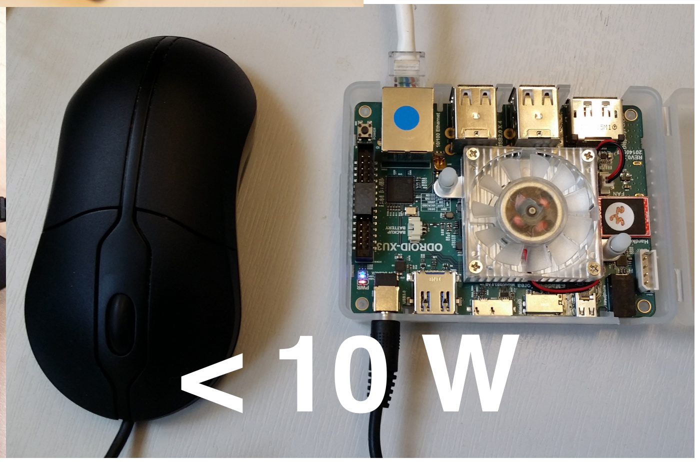

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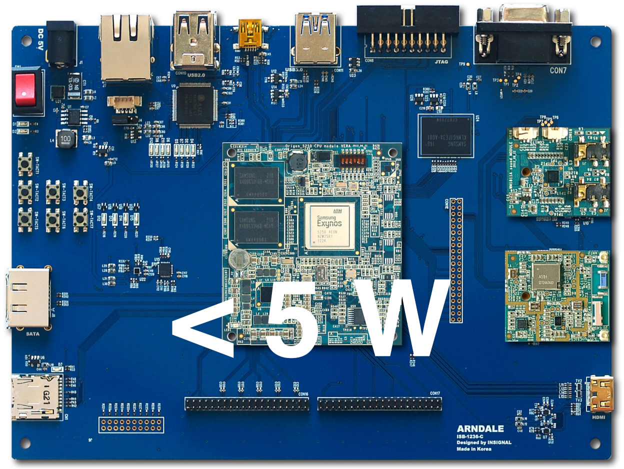

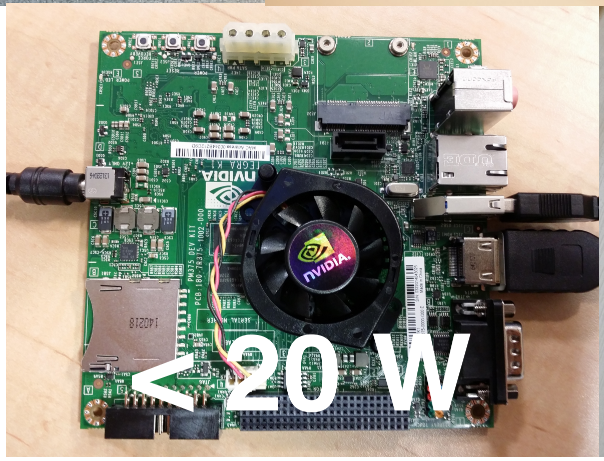

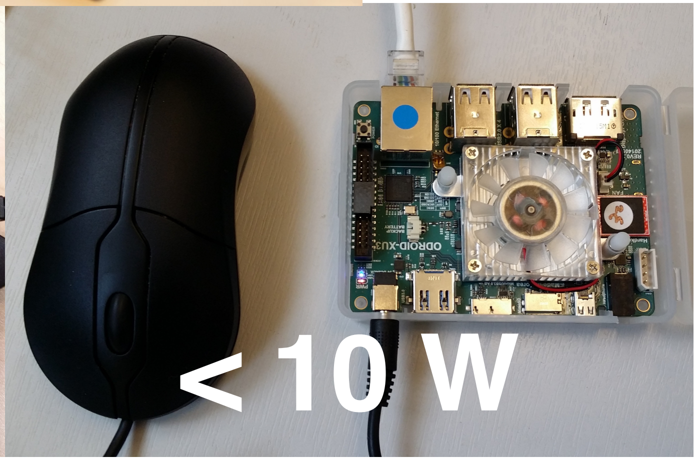

“Performance”: accuracy

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Application settings (default):

vol=4.8x4.8x4.8 m^3, res=256x256x256, μ=0.1cm, CR=320x240, IR=2, RR=4, TR=1, ICP=1e-5

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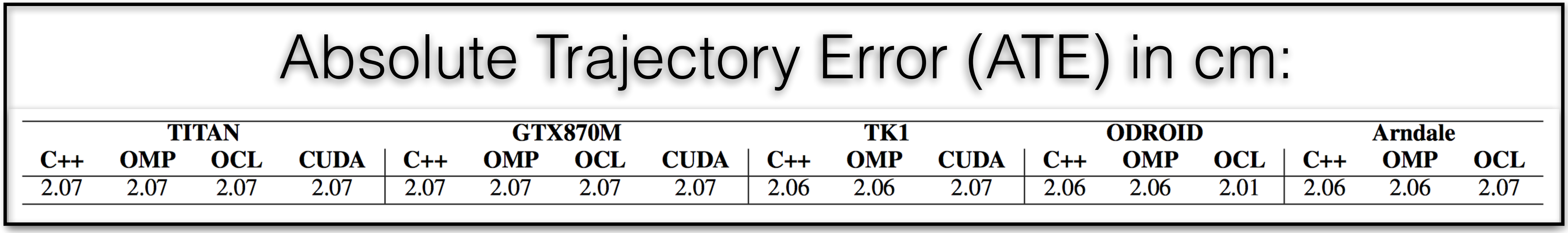

Absolute Trajectory Error (ATE) in cm:

TITAN				GTX870M				TK1			ODROID			Arndale		
C++	OMP	OCL	CUDA	C++	OMP	OCL	CUDA	C++	OMP	CUDA	C++	OMP	OCL	C++	OMP	OCL
2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.06	2.06	2.07	2.06	2.06	2.01	2.06	2.06	2.07

- Sanity check: similar error on all platforms

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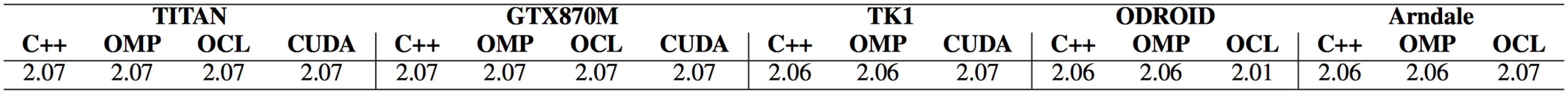

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C++	OMP	OCL	CUDA	C++	OMP	OCL	CUDA	C++	OMP	CUDA	C++	OMP	OCL	C++	OMP	OCL
2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.06	2.06	2.07	2.06	2.06	2.01	2.06	2.06	2.07

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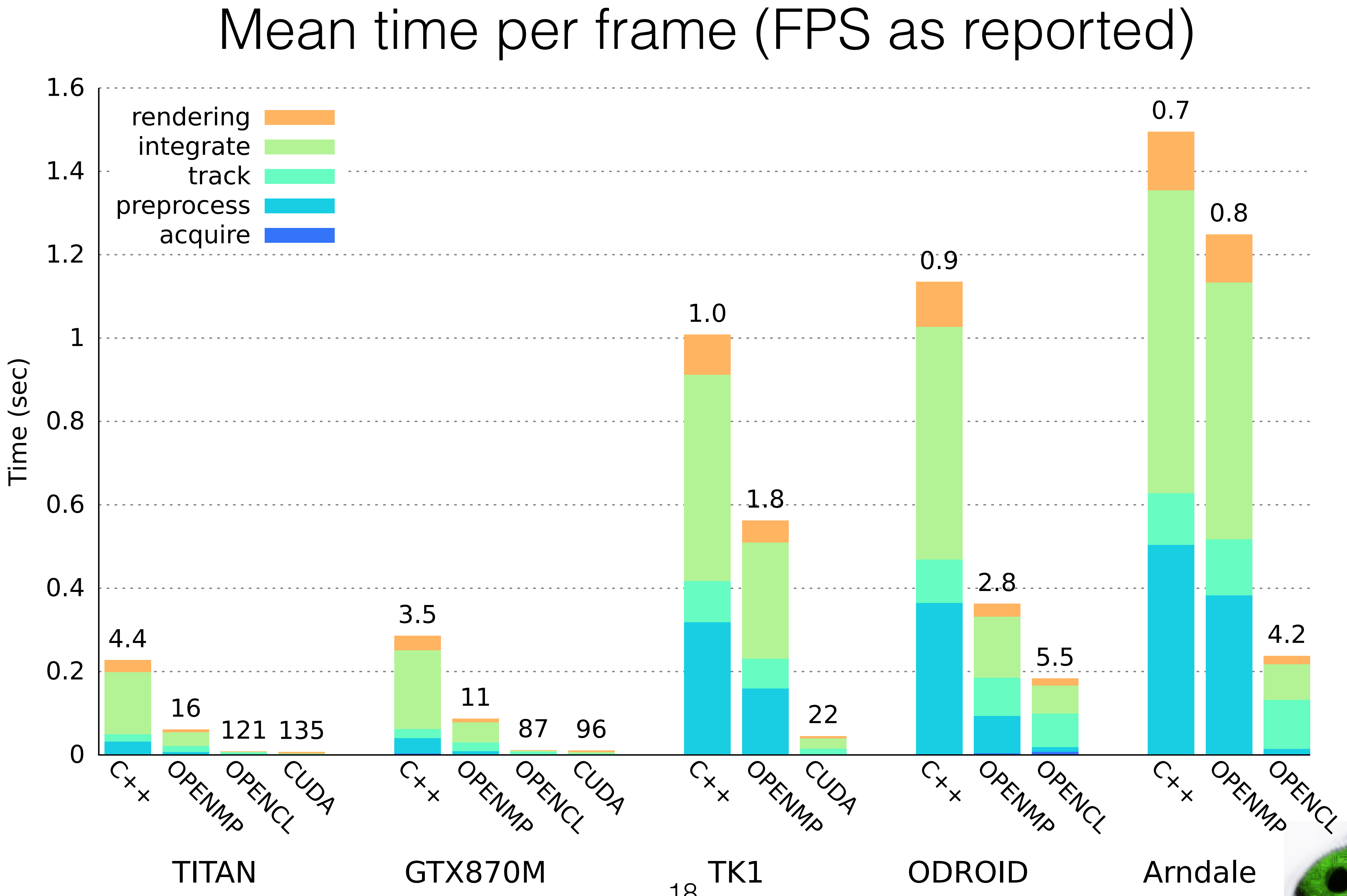
ATE enables aggressive design-space exploration:
Algorithmic, compiler and hardware parameters

“Performance”: execution time



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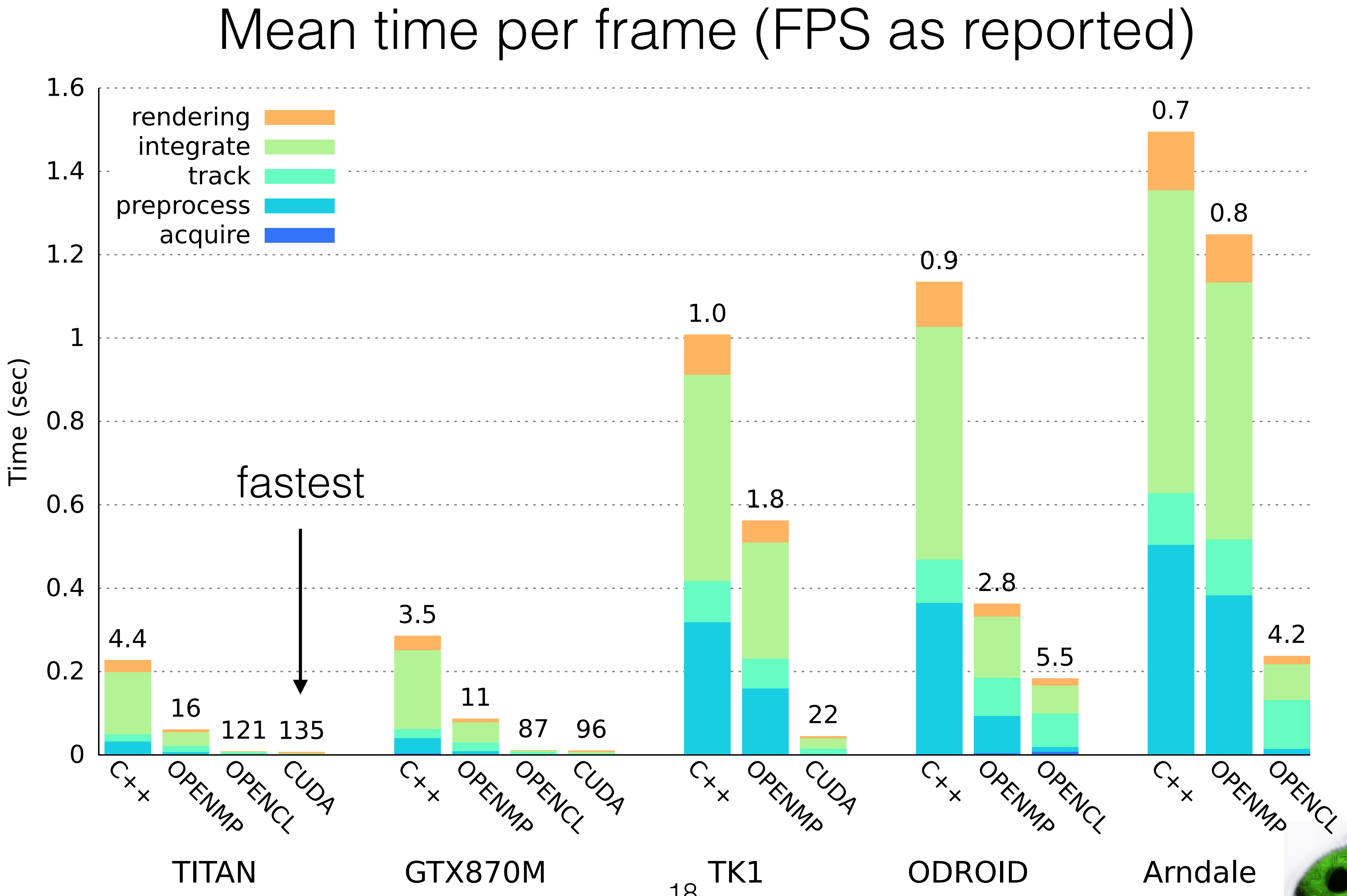
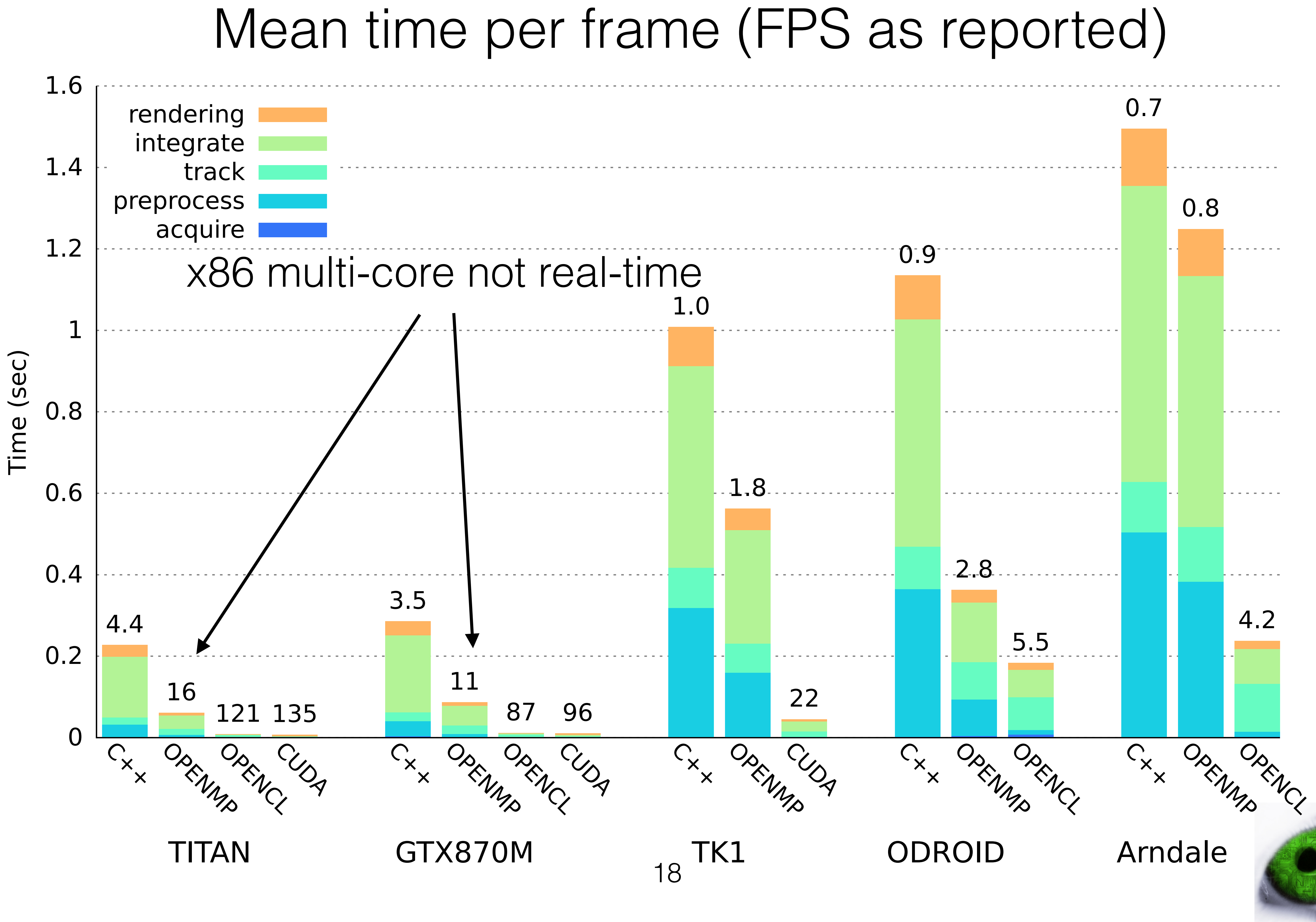


“Performance”: execution time



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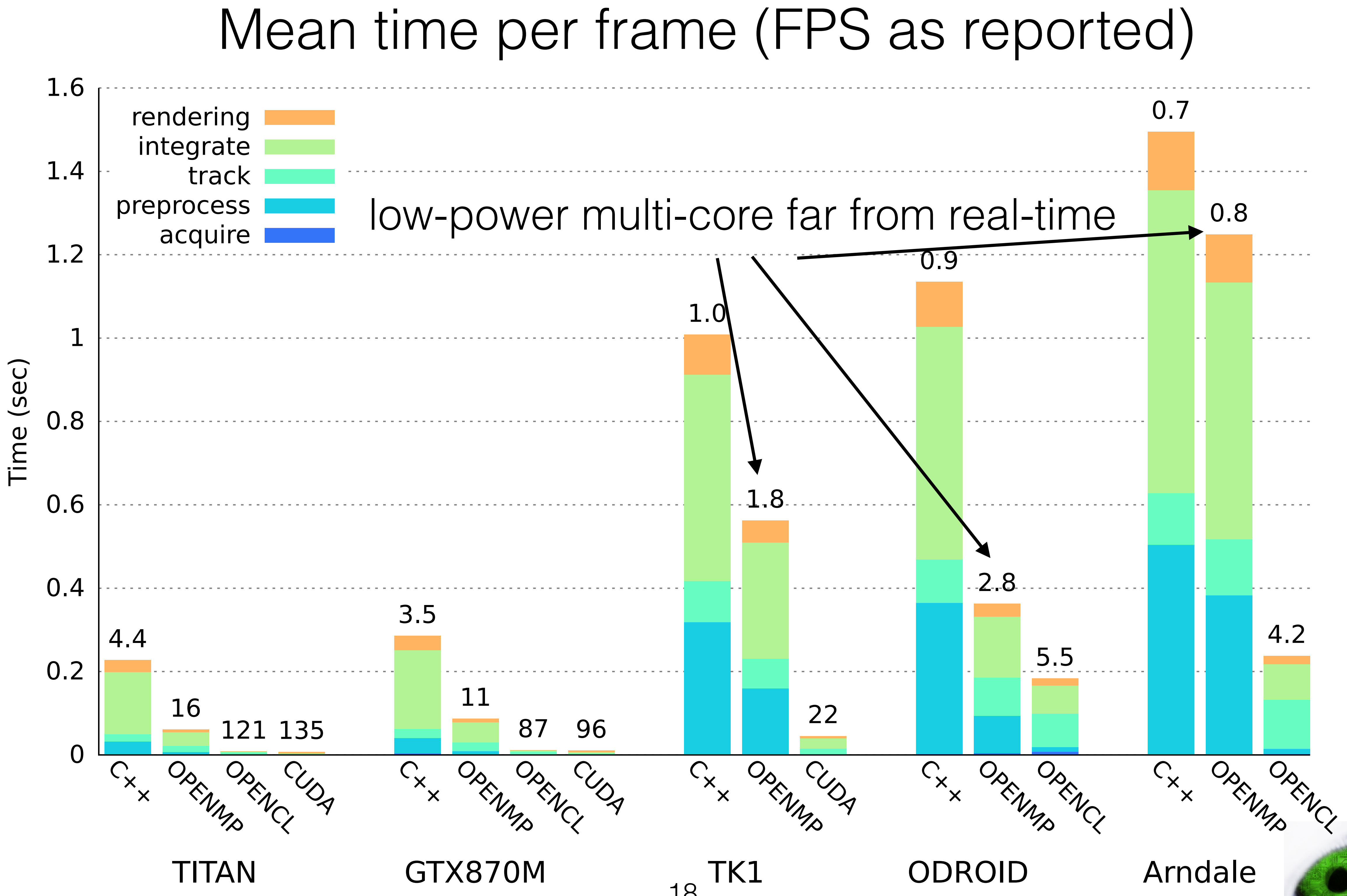
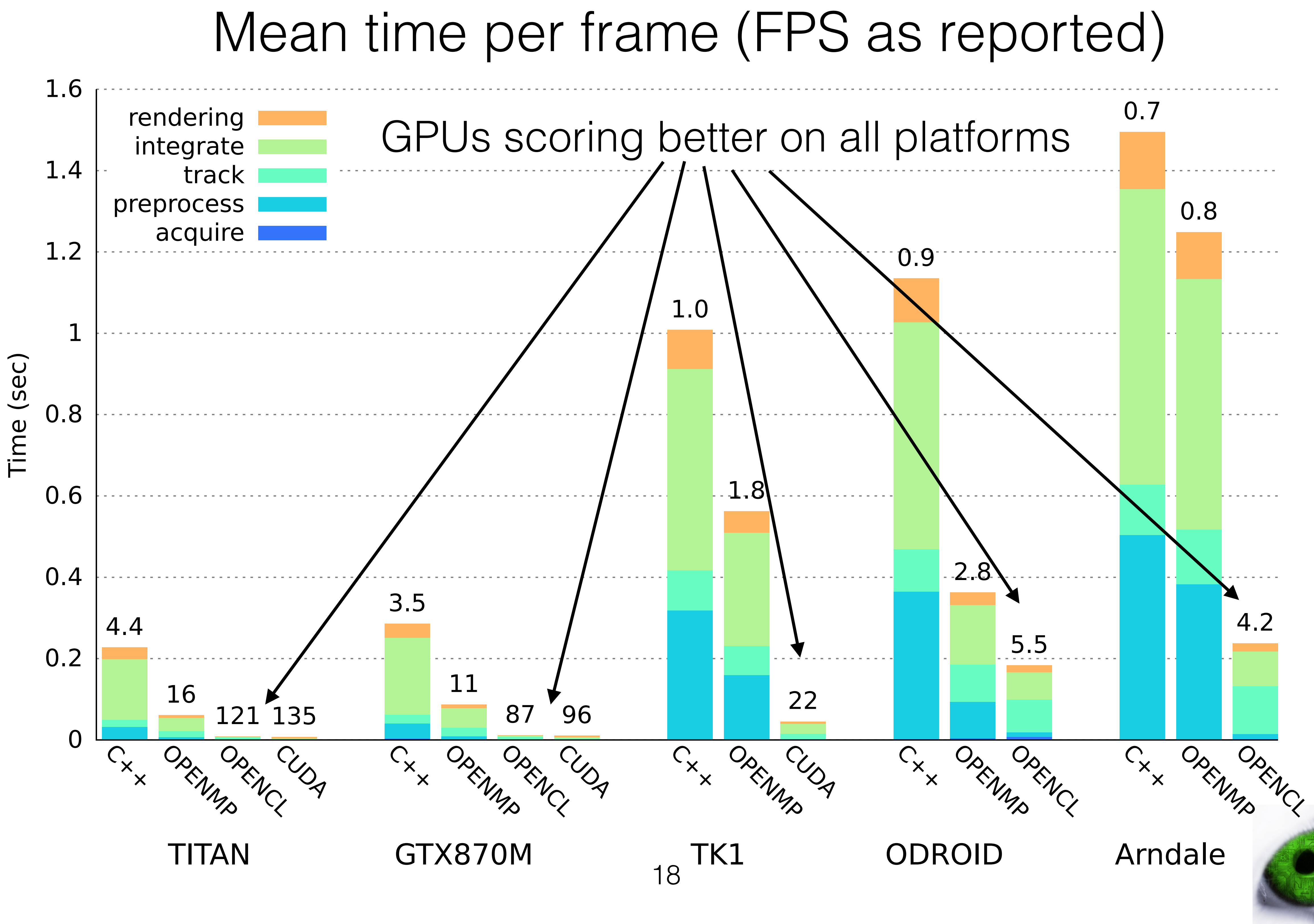


low-power multi-core far from real-time

"Performance": execution time



GPUs scoring better on all platforms

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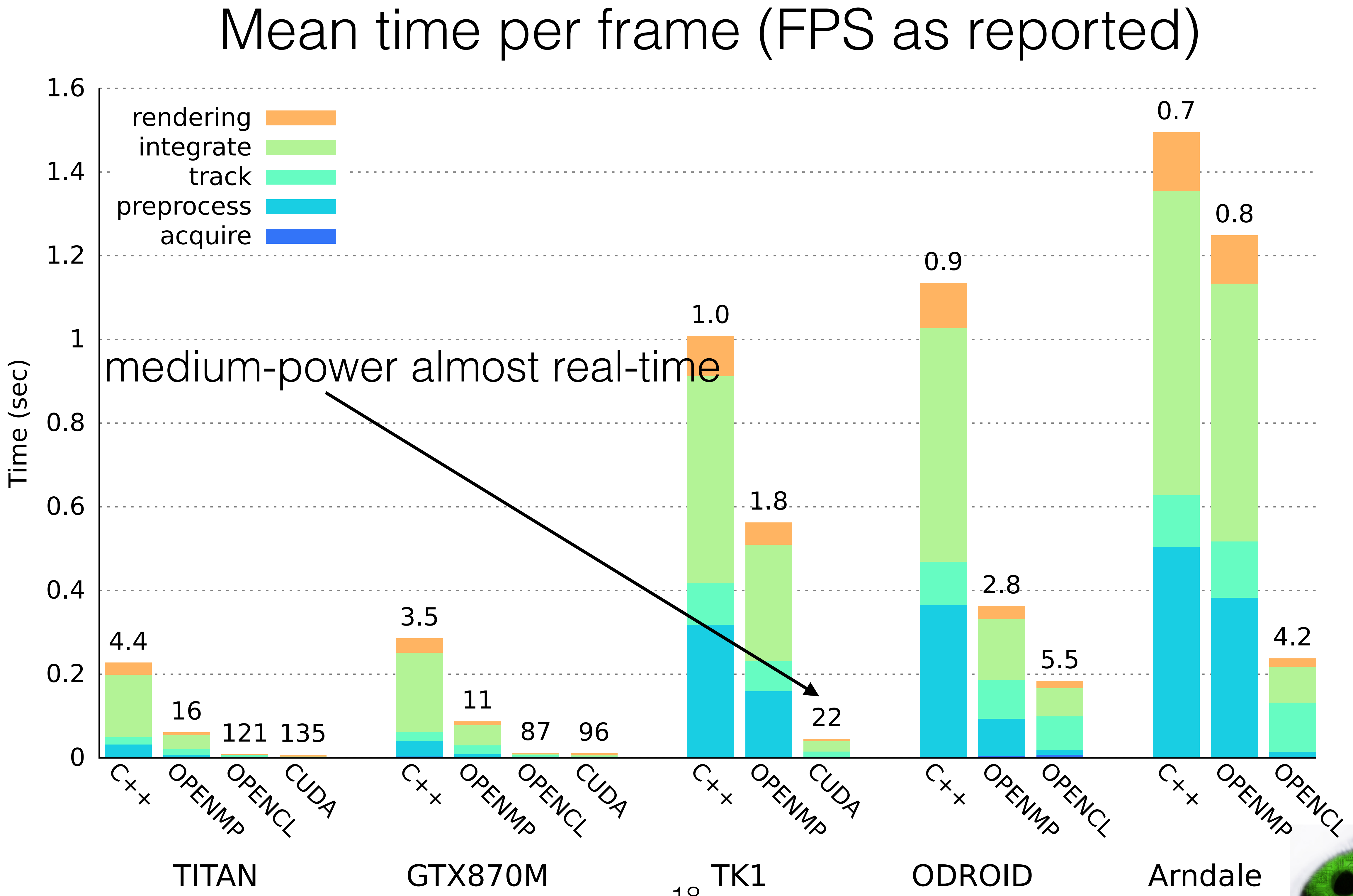

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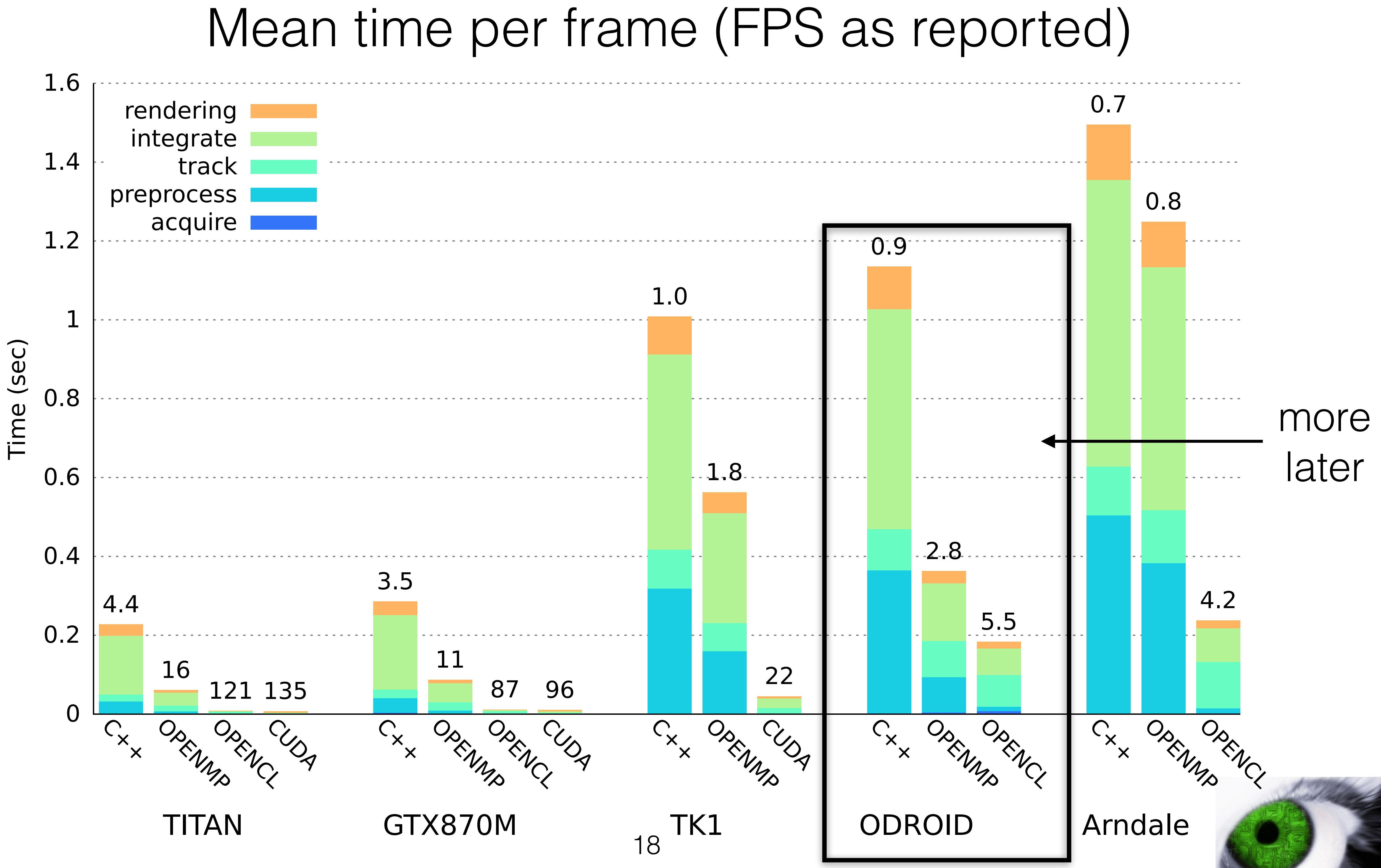

more later

“Performance” power (ODROID-XU3)

On-board voltage/current sensors and split power rails:
power measured individually on big (A15), LITTLE (A7), GPU and DRAM

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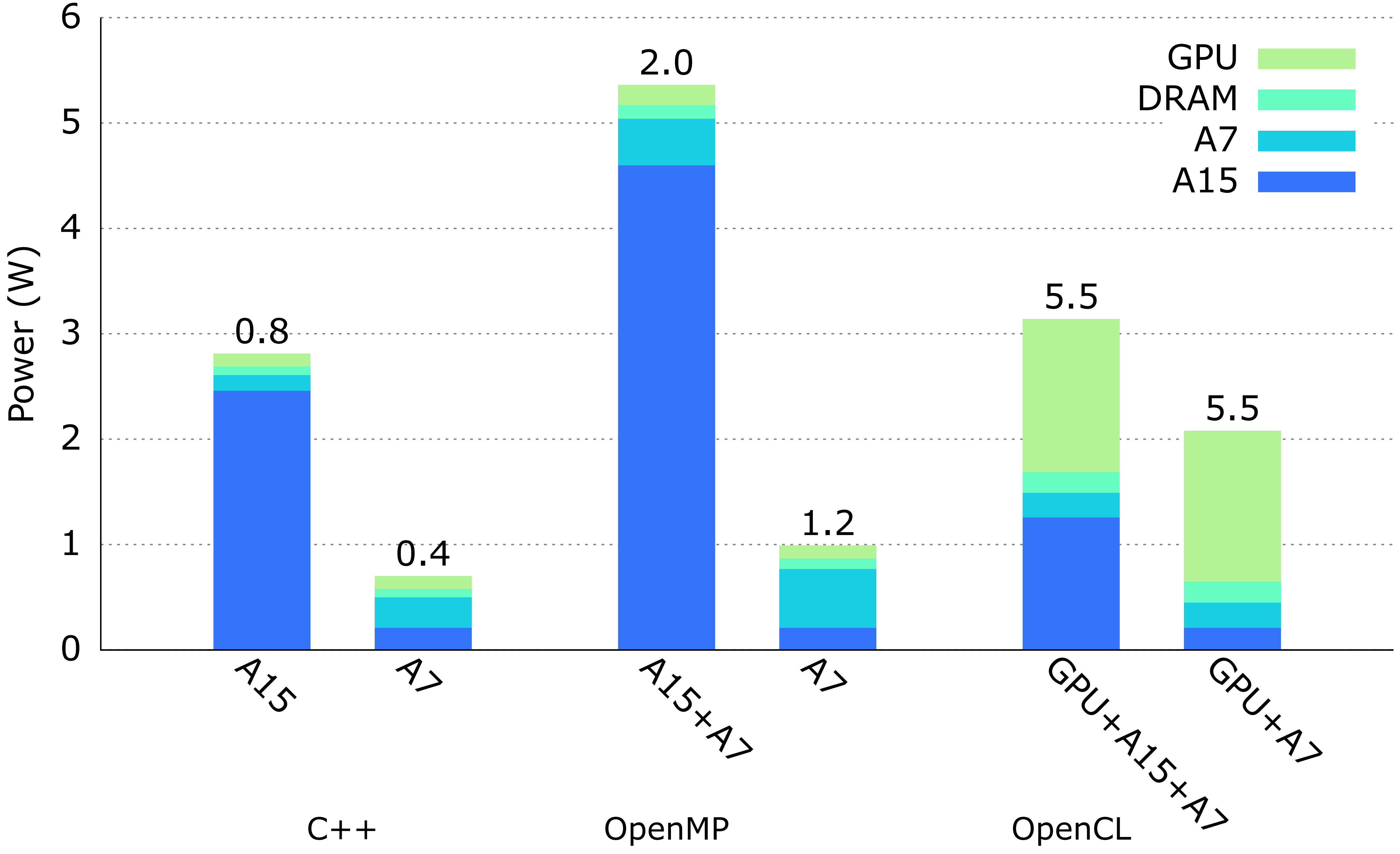

Power usage per frame rate as marked

Overview

- SLAM application
- Holistically execution time/energy/accuracy: SLAMBench
- Experimental results
- **Conclusion and opportunities**

SLAMBench today

- Publicly released 13/11/2014:
  http://apt.cs.manchester.ac.uk/projects/PAMELA/tools/SLAMBench/
- Early adopters: ARM, IBM Watson, LSU, SUTD, …
- Number of downloads: 120
- Submitted paper [Nardi et al. 2015]:
  "Introducing SLAMBench, a performance and accuracy benchmarking methodology for SLAM"

Conclusion

- **First vision benchmark** for accuracy, computational performance and energy consumption

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    - 4 configurations super real-time FPS (**135 FPS** peak performance on TITAN)
    - Tegra K1 achieves **22 FPS**
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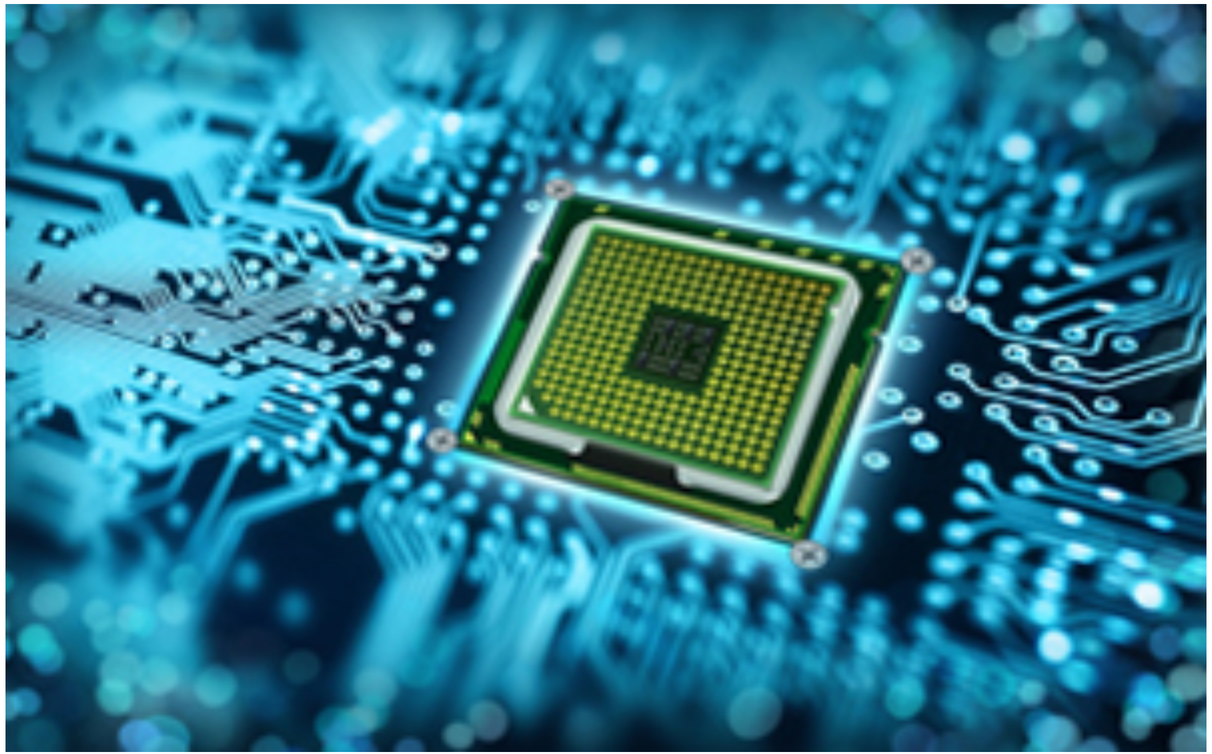
- SLAMBench **kernels characterisation**: i.e. parallel patterns and weights
- This research paves the way for **systematic holistic evaluation** using SLAMBench

SLAMBench opportunities



Chip design and simulation tools, e.g. GEM5

SLAMBench opportunities

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SLAMBench opportunities

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SLAMBench evolution:

- point-based fusion
- octrees
- voxel hashing-based
- moving volumes

Kernels can be improved individually

SLAMBench opportunities

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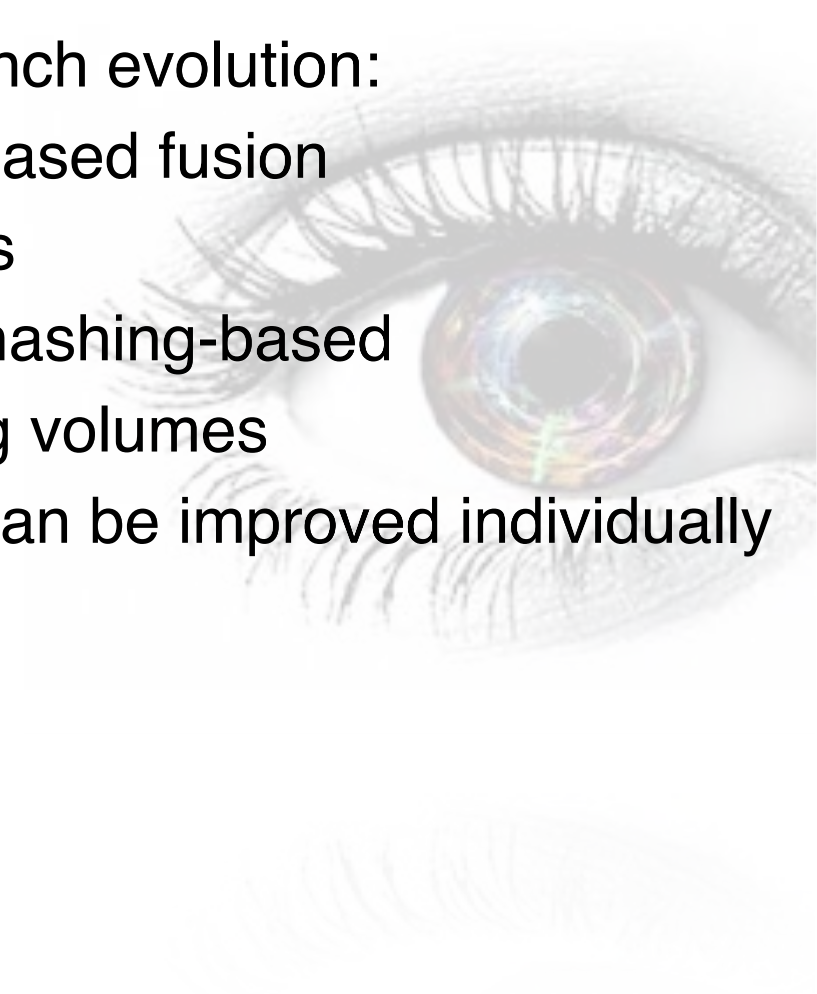

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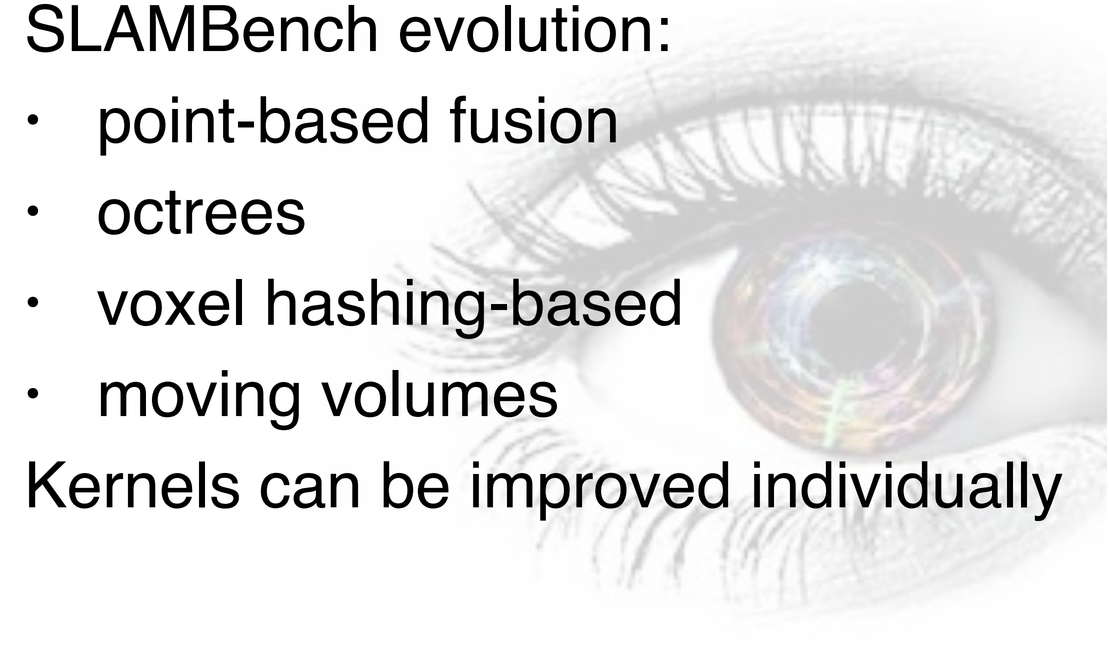

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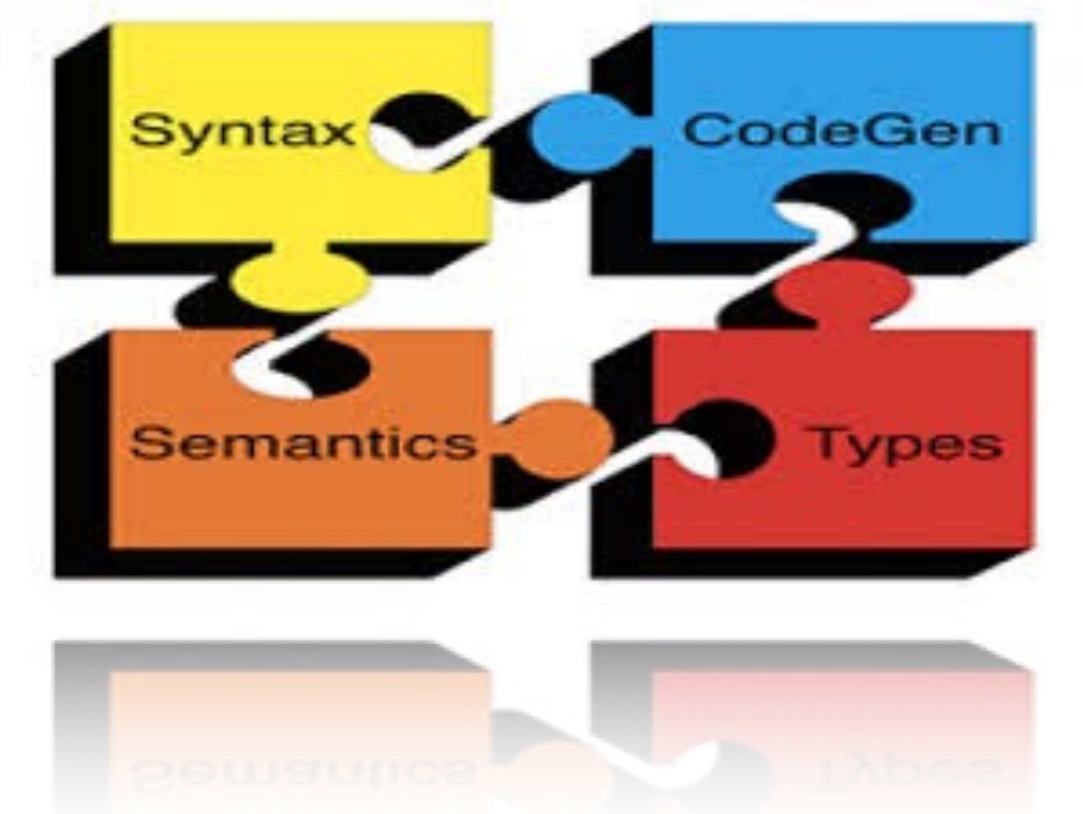

Domain-specific language targeting high performance, low-power dense SLAM

Design-space exploration, e.g. algorithmic, compiler and hardware parameters

SLAMBench kernels tuning, e.g. vectorisation, GPU occupancy, auto-tuning

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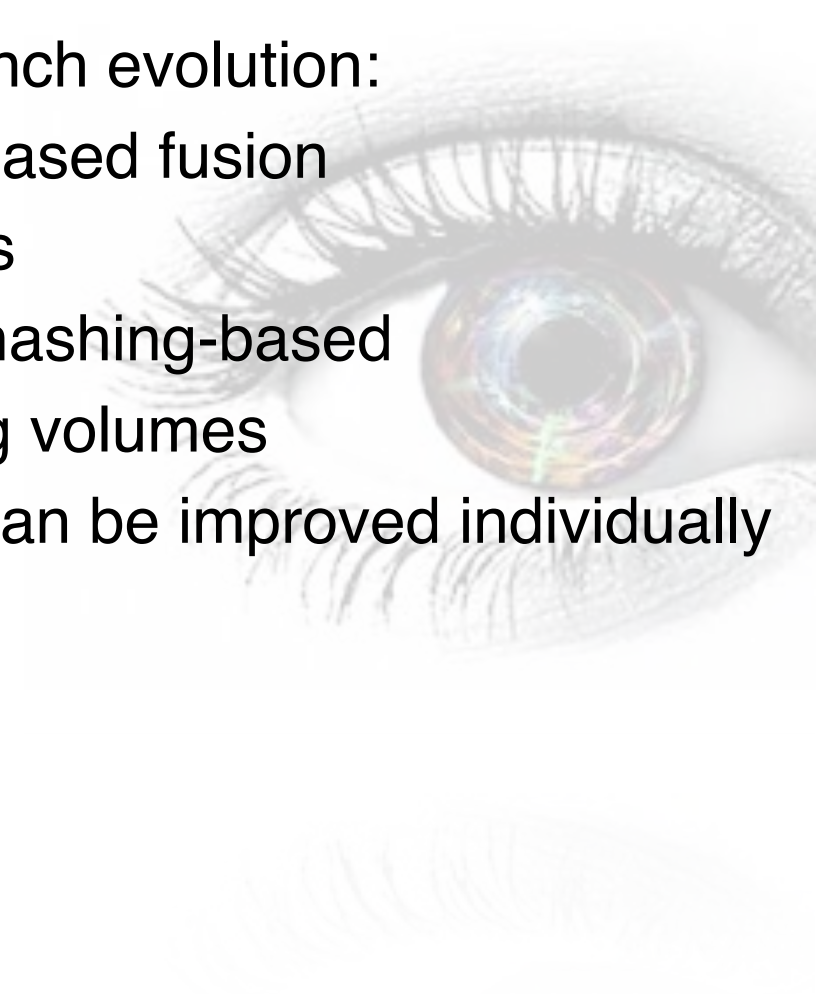

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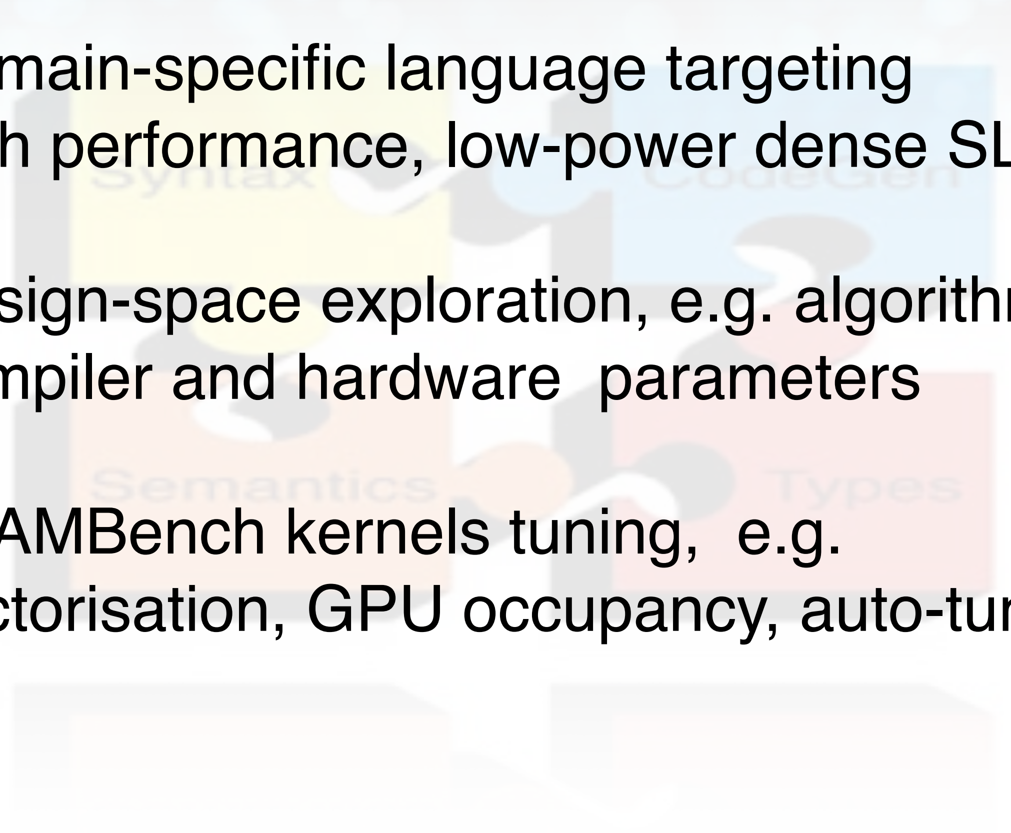

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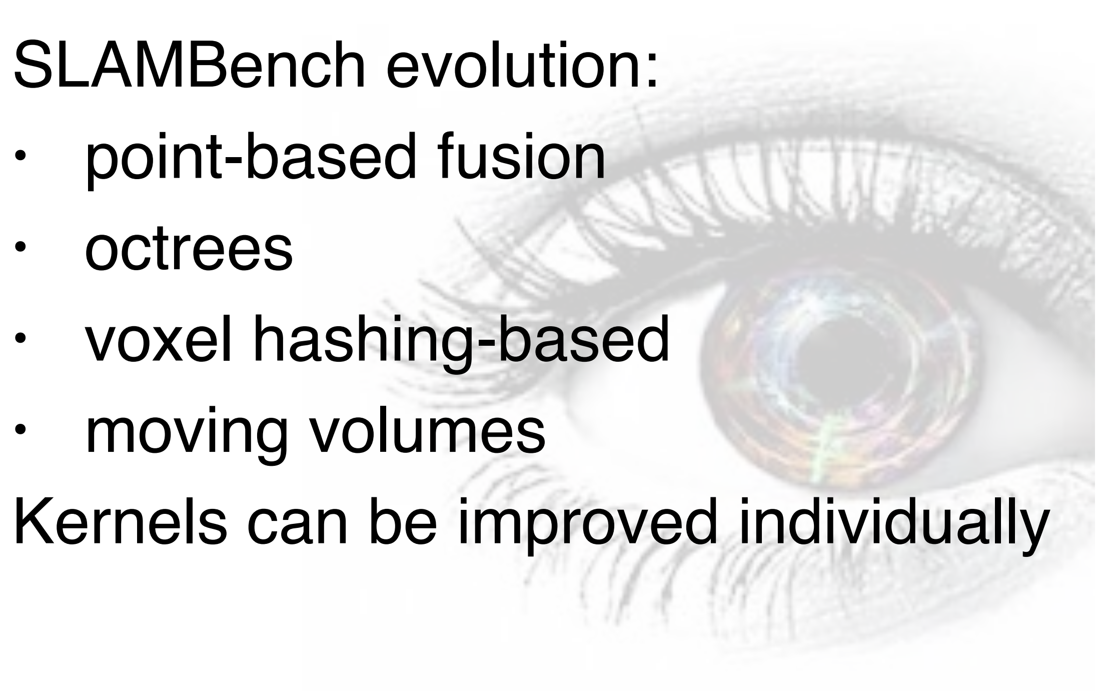

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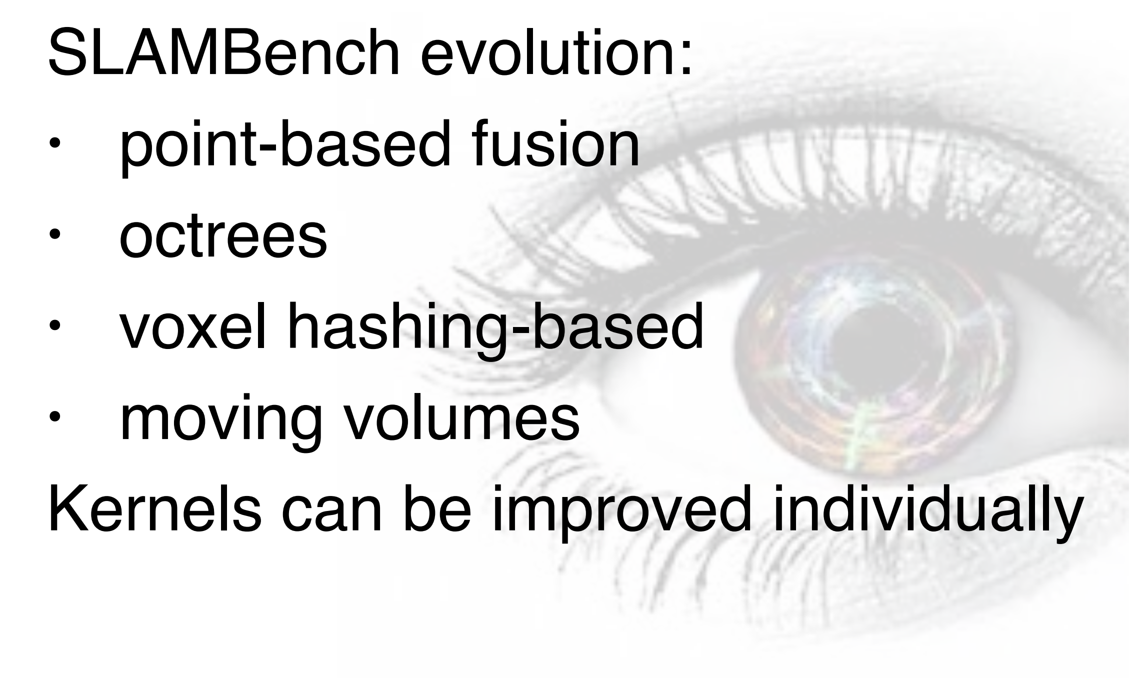

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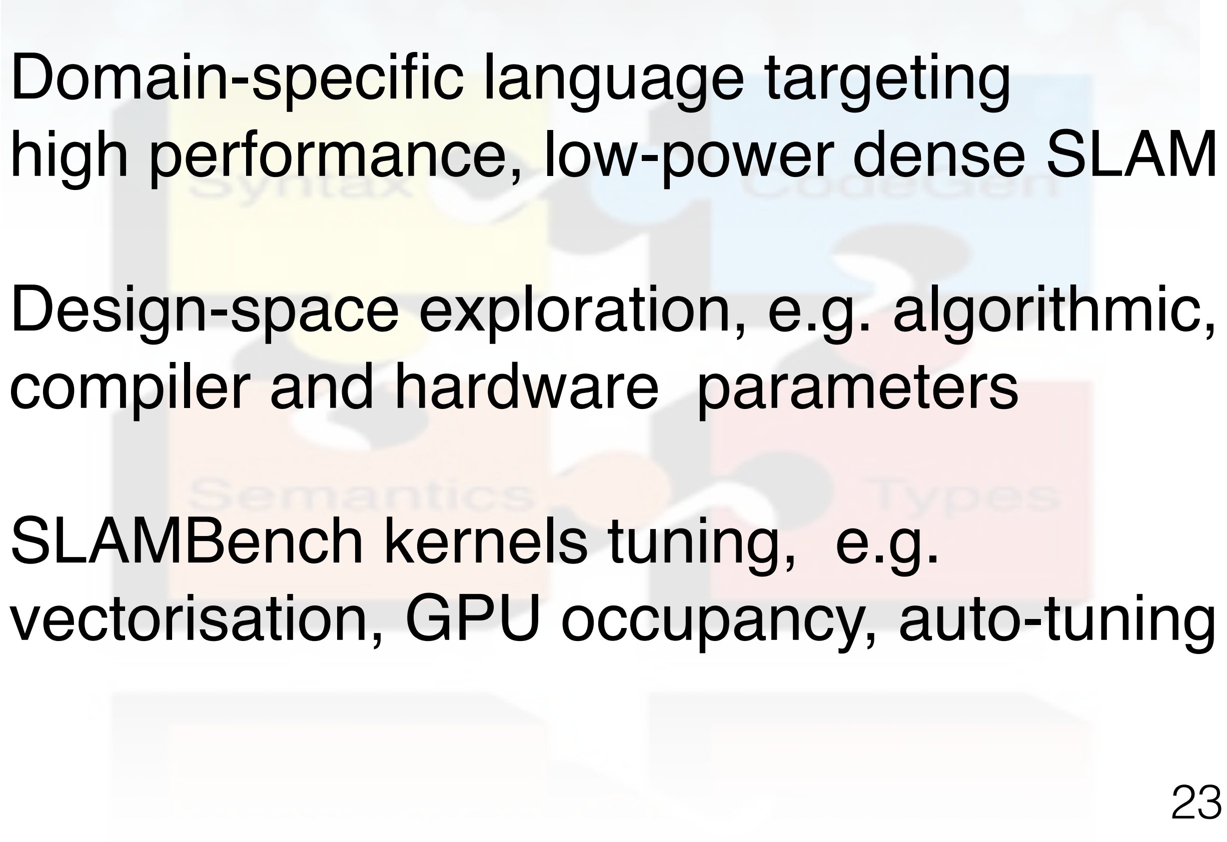

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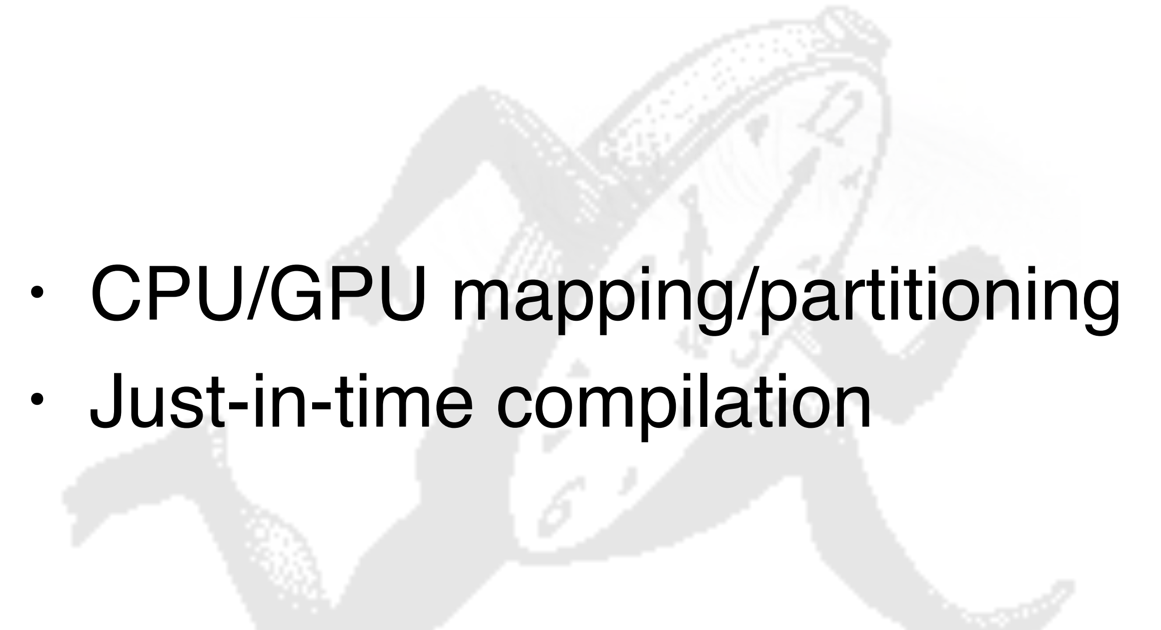

- CPU/GPU mapping/partitioning
- Just-in-time compilation

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3. [Rusinkiewicz and Levoy 2001] S. Rusinkiewicz, and M. Levoy. "Efficient variants of the ICP algorithm." 3-D Digital Imaging and Modeling, 2001. Proceedings. Third International Conference on. IEEE, 2001.
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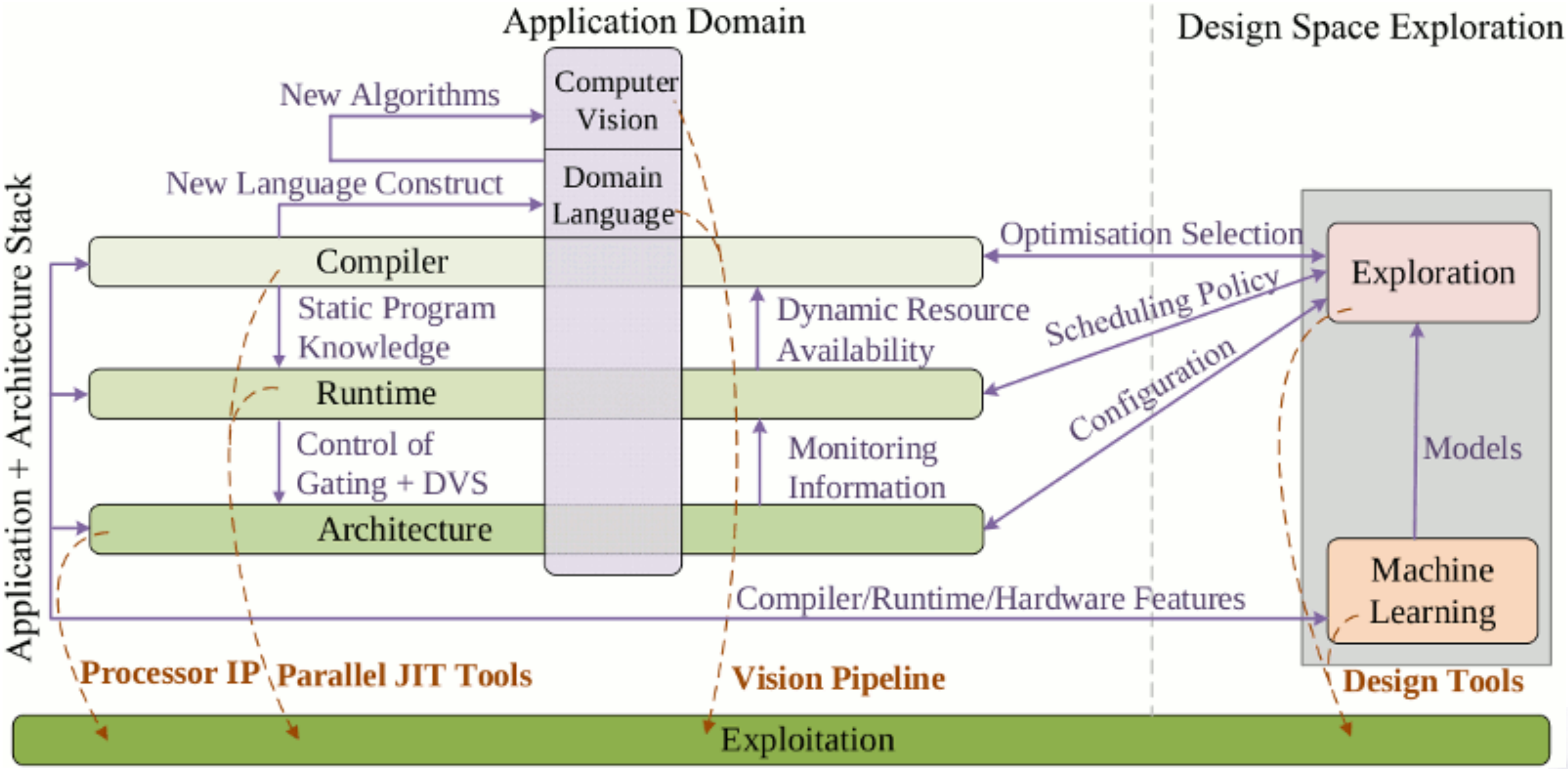
9. [Whelan et al. 2012] T. Whelan, M. Kaess, M. Fallon,H. Johannsson, J. Leonard, and J. McDonald. Kintinuous: Spatially extended kinectfusion. 2012.

Backup slides

PAMELA project

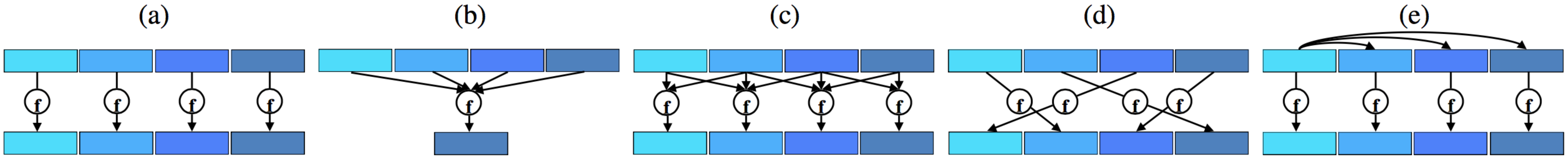
Panoramic Approach to the Many-corE LAndscape - from application to end-device: a holistic approach

5-year EPSRC grant: Imperial, Manchester and Edinburgh



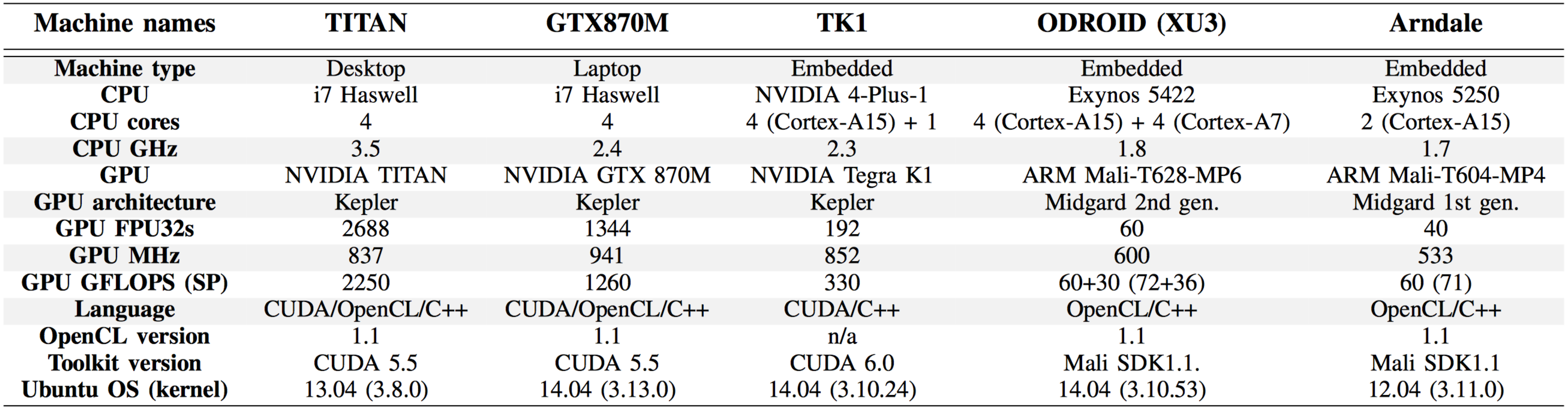
SLAMBench kernels

Kernels	Pipeline	Pattern	In	Out	%
acquire	Acquire	n/a	pointer	2D	0.03
mm2meters	Preprocess	Gather	2D	2D	0.06
bilateralFilter	Preprocess	Stencil	2D	2D	33.68
halfSample	Track	Stencil	2D	2D	0.05
depth2vertex	Track	Map	2D	2D	0.11
vertex2normal	Track	Stencil	2D	2D	0.27
track	Track	Map/Gather	2D	2D	4.72
reduce	Track	Reduction	2D	6x6	2.99
solve	Track	Sequential	6x6	6x1	0.02
integrate	Integrate	Map/Gather	2D/3D	3D	12.85
raycast	Raycast	Search/Stencil	2D/3D	2D	35.87
renderDepth	Rendering	Map	2D	2D	0.12
renderTrack	Rendering	Map	2D	2D	0.06
renderVolume	Rendering	Search/Stencil	3D	2D	9.18



Parallel patterns: (a) Map, (b) Reduction, (c) Stencil, (d) Gather and (e) Search.

Platforms



Machine names	TITAN	GTX870M	TK1	ODROID (XU3)	Arndale
Machine type	Desktop	Laptop	Embedded	Embedded	Embedded
CPU	i7 Haswell	i7 Haswell	NVIDIA 4-Plus-1	Exynos 5422	Exynos 5250
CPU cores	4	4	4 (Cortex-A15) + 1	4 (Cortex-A15) + 4 (Cortex-A7)	2 (Cortex-A15)
CPU GHz	3.5	2.4	2.3	1.8	1.7
GPU	NVIDIA TITAN	NVIDIA GTX 870M	NVIDIA Tegra K1	ARM Mali-T628-MP6	ARM Mali-T604-MP4
GPU architecture	Kepler	Kepler	Kepler	Midgard 2nd gen.	Midgard 1st gen.
GPU FPU32s	2688	1344	192	60	40
GPU MHz	837	941	852	600	533
GPU GFLOPS (SP)	2250	1260	330	60+30 (72+36)	60 (71)
Language	CUDA/OpenCL/C++	CUDA/OpenCL/C++	CUDA/C++	OpenCL/C++	OpenCL/C++
OpenCL version	1.1	1.1	n/a	1.1	1.1
Toolkit version	CUDA 5.5	CUDA 5.5	CUDA 6.0	Mali SDK1.1.	Mali SDK1.1
Ubuntu OS (kernel)	13.04 (3.8.0)	14.04 (3.13.0)	14.04 (3.10.24)	14.04 (3.10.53)	12.04 (3.11.0)

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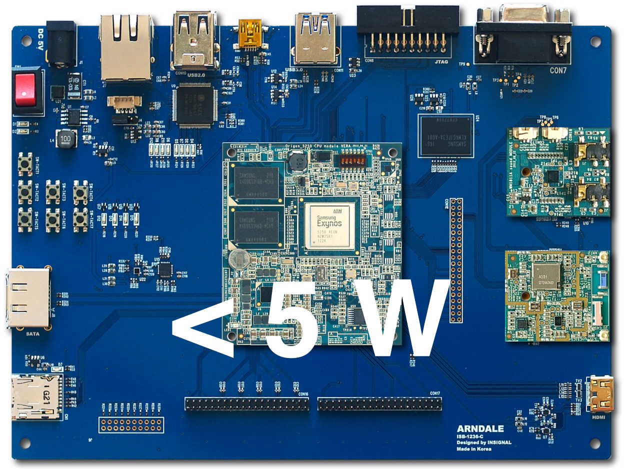
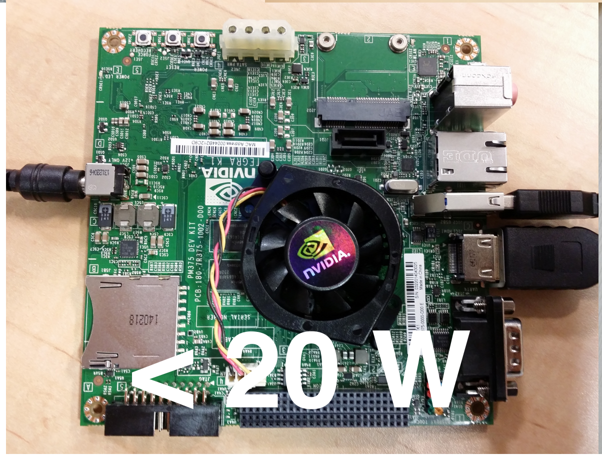
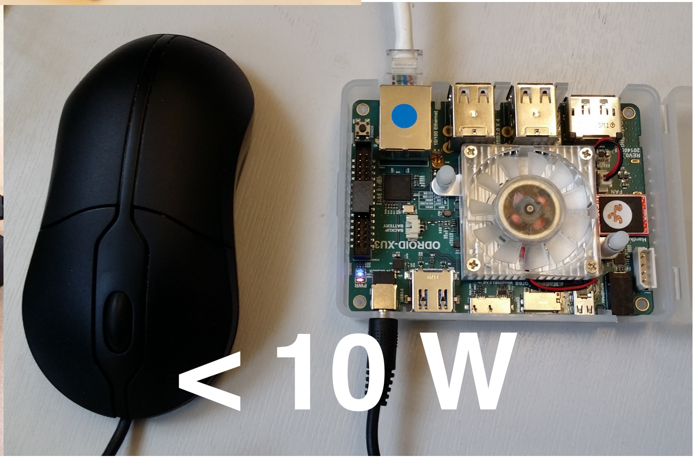
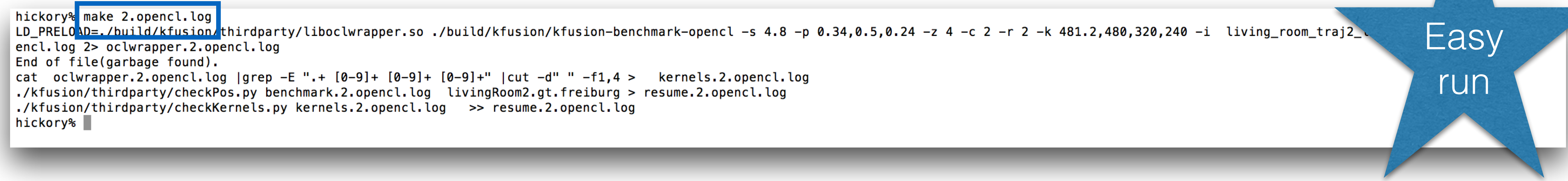






Textual User Interface

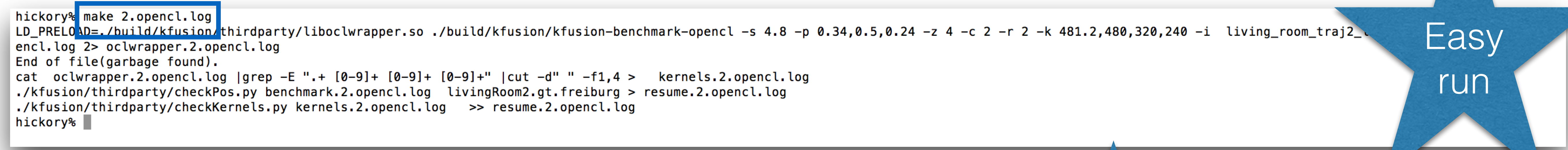


```
hickory% make 2.opencl.log
LD_PRELOAD=./build/kfusion/thirdparty/liboclwrapper.so ./build/kfusion/kfusion-benchmark-opencl -s 4.8 -p 0.34,0.5,0.24 -z 4 -c 2 -r 2 -k 481.2,480,320,240 -i  living_room_traj2_
encl.log 2> oclwrapper.2.opencl.log
End of file(garbage found).
cat  oclwrapper.2.opencl.log |grep -E ".+ [0-9]+ [0-9]+ [0-9]+" |cut -d" " -f1,4 >   kernels.2.opencl.log
./kfusion/thirdparty/checkPos.py benchmark.2.opencl.log  livingRoom2.gt.freiburg > resume.2.opencl.log
./kfusion/thirdparty/checkKernels.py kernels.2.opencl.log   >> resume.2.opencl.log
hickory% 
```

Easy run

For benchmarking purposes, SSH and post-processing tools friendly

Textual User Interface



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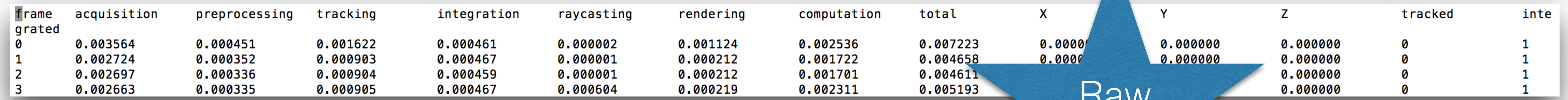


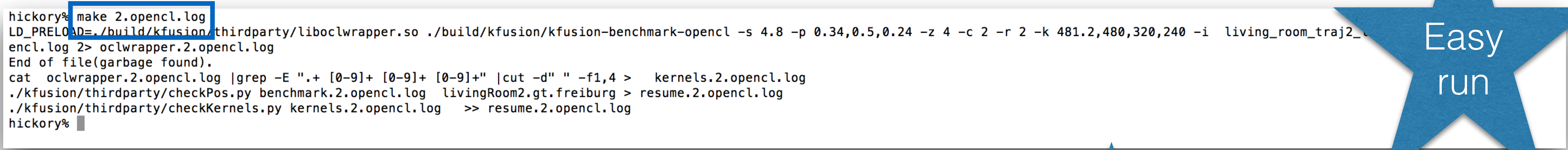
```
frame    acquisition    preprocessing   tracking       integration    raycasting     rendering      computation    total          X              Y              Z              tracked        inte
grated
0        0.003564       0.000451       0.001622       0.000461       0.000002       0.001124       0.002536       0.007223       0.0000         0.000000       0.000000       0              1
1        0.002724       0.000352       0.000903       0.000467       0.000001       0.000212       0.001722       0.004658       0.0000         0.000000       0.000000       0              1
2        0.002697       0.000336       0.000904       0.000459       0.000001       0.000212       0.001701       0.004611                                     0.000000       0              1
3        0.002663       0.000335       0.000905       0.000467       0.000604       0.000219       0.002311       0.005193                                     0.000000       0              1
```

Raw data

For benchmarking purposes, SSH and post-processing tools friendly

PAMELA

Textual User Interface



```
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LD_PRELOAD=./build/kfusion/thirdparty/liboclwrapper.so ./build/kfusion/kfusion-benchmark-opencl -s 4.8 -p 0.34,0.5,0.24 -z 4 -c 2 -r 2 -k 481.2,480,320,240 -i  living_room_traj2_
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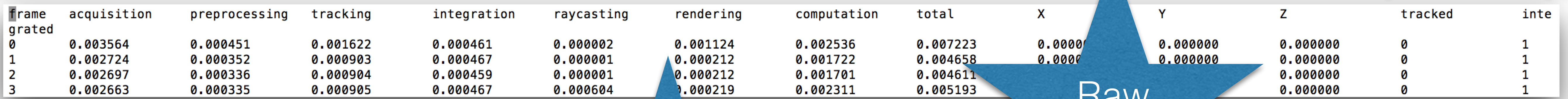
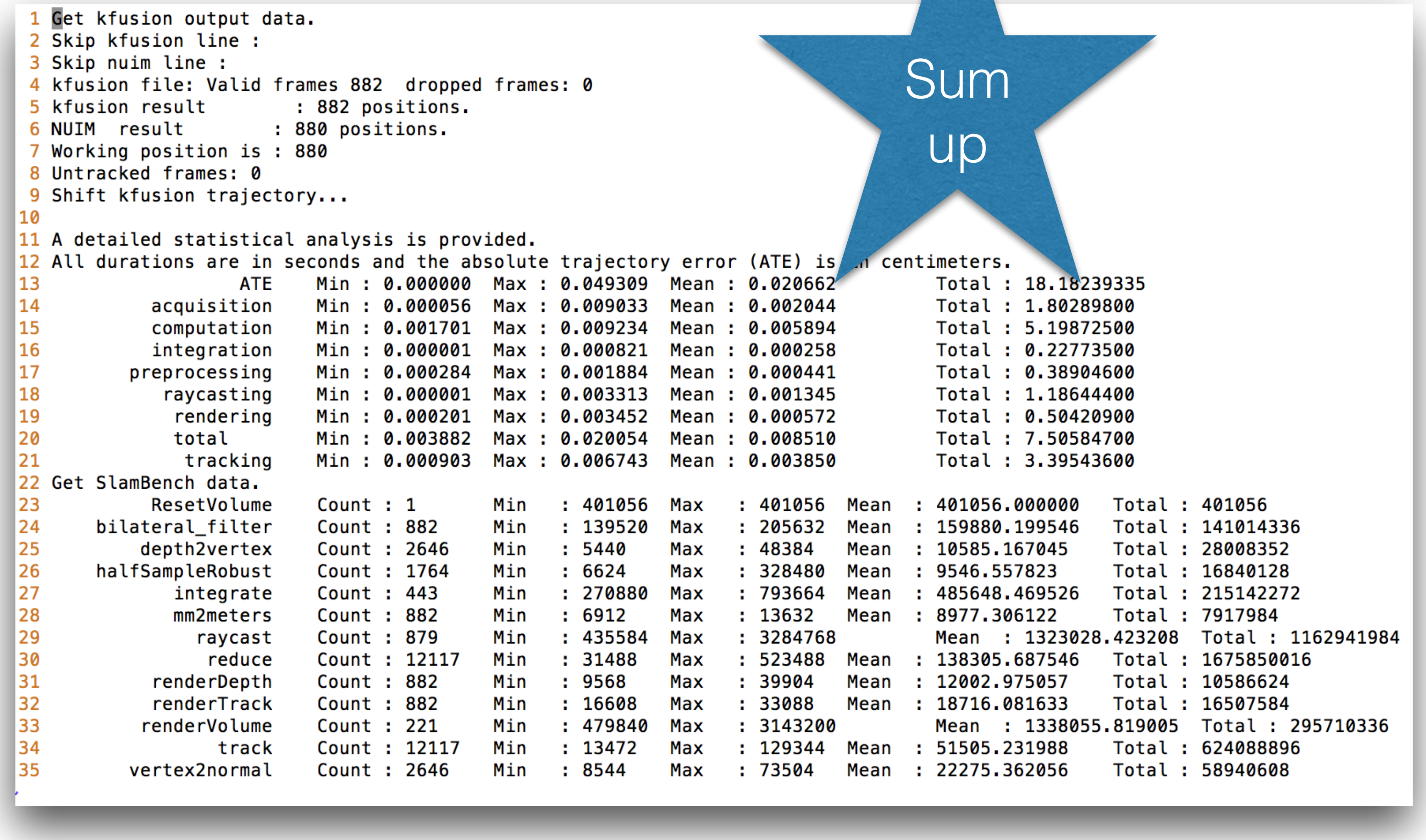


```
frame      acquisition      preprocessing    tracking         integration      raycasting       rendering        computation      total            X                Y                Z                tracked          inte
grated
0          0.003564         0.000451         0.001622         0.000461         0.000002         0.001124         0.002536         0.007223         0.0000           0.000000         0.000000         0                1
1          0.002724         0.000352         0.000903         0.000467         0.000001         0.000212         0.001722         0.004658         0.0000           0.000000         0.000000         0                1
2          0.002697         0.000336         0.000904         0.000459         0.000001         0.000212         0.001701         0.004611                                           0.000000         0                1
3          0.002663         0.000335         0.000905         0.000467         0.000604         .000219          0.002311         0.005193                                           0.000000         0                1
```

Raw data



```
Get kfusion output data.
Skip kfusion line :
Skip nuim line :
kfusion file: Valid frames 882  dropped frames: 0
kfusion result        : 882 positions.
NUIM  result        : 880 positions.
Working position is : 880
Untracked frames: 0
Shift kfusion trajectory...

A detailed statistical analysis is provided.
All durations are in seconds and the absolute trajectory error (ATE) is in centimeters.
                 ATE    Min : 0.000000  Max : 0.049309  Mean : 0.020662        Total : 18.18239335
         acquisition    Min : 0.000056  Max : 0.009033  Mean : 0.002044        Total : 1.80289800
         computation    Min : 0.001701  Max : 0.009234  Mean : 0.005894        Total : 5.19872500
         integration    Min : 0.000001  Max : 0.000821  Mean : 0.000258        Total : 0.22773500
       preprocessing    Min : 0.000284  Max : 0.001884  Mean : 0.000441        Total : 0.38904600
          raycasting    Min : 0.000001  Max : 0.003313  Mean : 0.001345        Total : 1.18644400
           rendering    Min : 0.000201  Max : 0.003452  Mean : 0.000572        Total : 0.50420900
               total    Min : 0.003882  Max : 0.020054  Mean : 0.008510        Total : 7.50584700
            tracking    Min : 0.000903  Max : 0.006743  Mean : 0.003850        Total : 3.39543600
Get SlamBench data.
         ResetVolume    Count : 1       Min    : 401056  Max    : 401056  Mean   : 401056.000000    Total : 401056
     bilateral_filter   Count : 882     Min    : 139520  Max    : 205632  Mean   : 159880.199546    Total : 141014336
        depth2vertex    Count : 2646    Min    : 5440    Max    : 48384   Mean   : 10585.167045     Total : 28008352
     halfSampleRobust   Count : 1764    Min    : 6624    Max    : 328480  Mean   : 9546.557823      Total : 16840128
           integrate    Count : 443     Min    : 270880  Max    : 793664  Mean   : 485648.469526    Total : 215142272
           mm2meters    Count : 882     Min    : 6912    Max    : 13632   Mean   : 8977.306122      Total : 7917984
             raycast    Count : 879     Min    : 435584  Max    : 3284768         Mean   : 1323028.423208  Total : 1162941984
              reduce    Count : 12117   Min    : 31488   Max    : 523488  Mean   : 138305.687546    Total : 1675850016
         renderDepth    Count : 882     Min    : 9568    Max    : 39904   Mean   : 12002.975057     Total : 10586624
         renderTrack    Count : 882     Min    : 16608   Max    : 33088   Mean   : 18716.081633     Total : 16507584
        renderVolume    Count : 221     Min    : 479840  Max    : 3143200         Mean   : 1338055.819005  Total : 295710336
               track    Count : 12117   Min    : 13472   Max    : 129344  Mean   : 51505.231988     Total : 624088896
       vertex2normal    Count : 2646    Min    : 8544    Max    : 73504   Mean   : 22275.362056     Total : 58940608
```

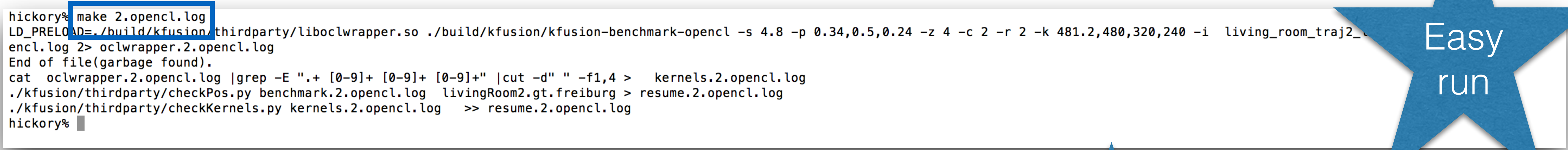
Sum up

For benchmarking purposes, SSH and post-processing tools friendly

PAMELA

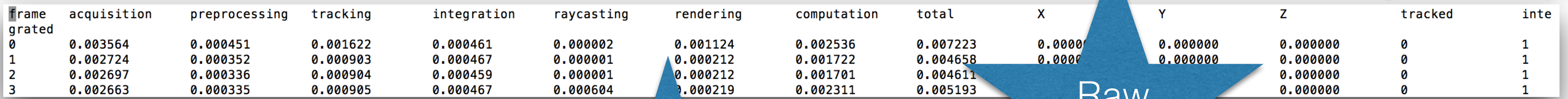
Luigi Nardi - Imperial College London

Textual User Interface



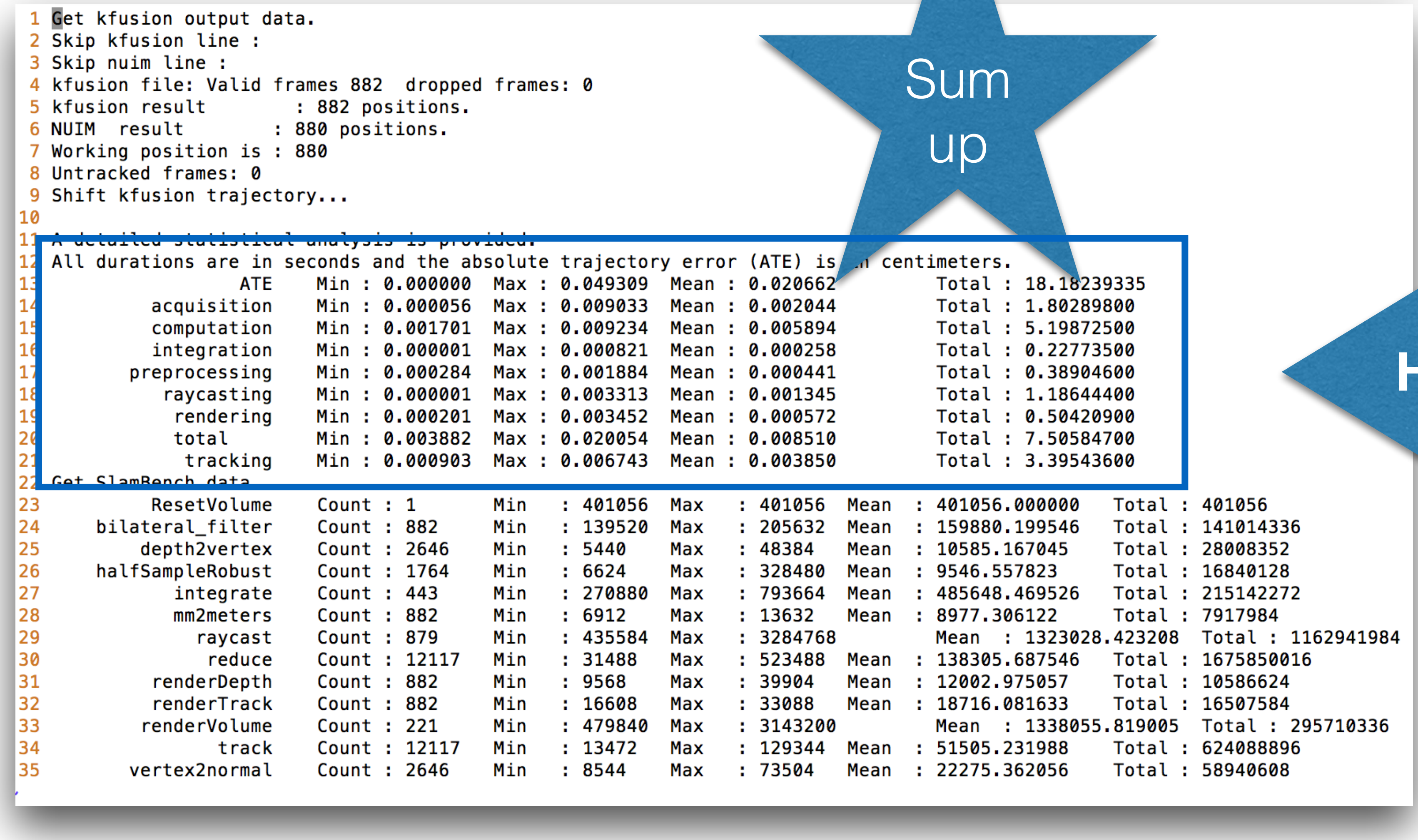
```
hickory% make 2.opencl.log
LD_PRELOAD=./build/kfusion/thirdparty/liboclwrapper.so ./build/kfusion/kfusion-benchmark-opencl -s 4.8 -p 0.34,0.5,0.24 -z 4 -c 2 -r 2 -k 481.2,480,320,240 -i  living_room_traj2_
encl.log 2> oclwrapper.2.opencl.log
End of file(garbage found).
cat  oclwrapper.2.opencl.log |grep -E ".+ [0-9]+ [0-9]+ [0-9]+" |cut -d" " -f1,4 >   kernels.2.opencl.log
./kfusion/thirdparty/checkPos.py benchmark.2.opencl.log  livingRoom2.gt.freiburg > resume.2.opencl.log
./kfusion/thirdparty/checkKernels.py kernels.2.opencl.log   >> resume.2.opencl.log
hickory%
```

Easy run



```
frame    acquisition      preprocessing    tracking         integration      raycasting       rendering        computation      total            X                Y                Z                tracked          inte
grated
0        0.003564         0.000451         0.001622         0.000461         0.000002         0.001124         0.002536         0.007223         0.0000           0.000000         0.000000         0                1
1        0.002724         0.000352         0.000903         0.000467         0.000001         0.000212         0.001722         0.004658         0.0000           0.000000         0.000000         0                1
2        0.002697         0.000336         0.000904         0.000459         0.000001         0.000212         0.001701         0.004611                                           0.000000         0                1
3        0.002663         0.000335         0.000905         0.000467         0.000604         .000219          0.002311         0.005193                                           0.000000         0                1
```

Raw data



```
Get kfusion output data.
Skip kfusion line :
Skip nuim line :
kfusion file: Valid frames 882  dropped frames: 0
kfusion result       : 882 positions.
NUIM  result       : 880 positions.
Working position is : 880
Untracked frames: 0
Shift kfusion trajectory...

A detailed statistical analysis is provided.
All durations are in seconds and the absolute trajectory error (ATE) is in centimeters.
                ATE    Min : 0.000000  Max : 0.049309  Mean : 0.020662         Total : 18.18239335
        acquisition    Min : 0.000056  Max : 0.009033  Mean : 0.002044         Total : 1.80289800
        computation    Min : 0.001701  Max : 0.009234  Mean : 0.005894         Total : 5.19872500
        integration    Min : 0.000001  Max : 0.000821  Mean : 0.000258         Total : 0.22773500
      preprocessing    Min : 0.000284  Max : 0.001884  Mean : 0.000441         Total : 0.38904600
         raycasting    Min : 0.000001  Max : 0.003313  Mean : 0.001345         Total : 1.18644400
          rendering    Min : 0.000201  Max : 0.003452  Mean : 0.000572         Total : 0.50420900
          total        Min : 0.003882  Max : 0.020054  Mean : 0.008510         Total : 7.50584700
           tracking    Min : 0.000903  Max : 0.006743  Mean : 0.003850         Total : 3.39543600
Get SlamBench data
        ResetVolume    Count : 1       Min   : 401056  Max   : 401056  Mean  : 401056.000000    Total : 401056
    bilateral_filter   Count : 882     Min   : 139520  Max   : 205632  Mean  : 159880.199546    Total : 141014336
       depth2vertex    Count : 2646    Min   : 5440    Max   : 48384   Mean  : 10585.167045     Total : 28008352
    halfSampleRobust   Count : 1764    Min   : 6624    Max   : 328480  Mean  : 9546.557823      Total : 16840128
          integrate    Count : 443     Min   : 270880  Max   : 793664  Mean  : 485648.469526    Total : 215142272
          mm2meters    Count : 882     Min   : 6912    Max   : 13632   Mean  : 8977.306122      Total : 7917984
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             reduce    Count : 12117   Min   : 31488   Max   : 523488  Mean  : 138305.687546    Total : 1675850016
        renderDepth    Count : 882     Min   : 9568    Max   : 39904   Mean  : 12002.975057     Total : 10586624
        renderTrack    Count : 882     Min   : 16608   Max   : 33088   Mean  : 18716.081633     Total : 16507584
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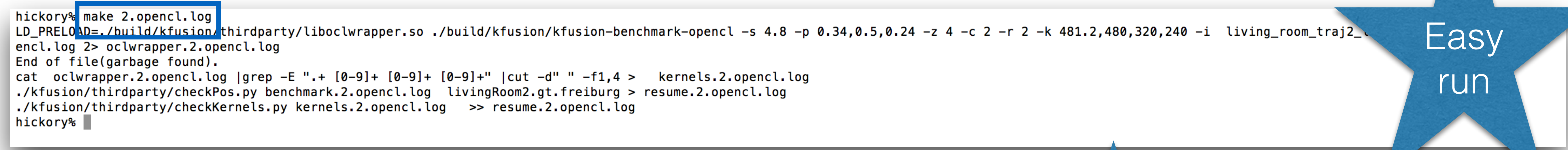
              track    Count : 12117   Min   : 13472   Max   : 129344  Mean  : 51505.231988     Total : 624088896
      vertex2normal    Count : 2646    Min   : 8544    Max   : 73504   Mean  : 22275.362056     Total : 58940608
```

Sum up

High-level blocks statistics

Textual User Interface



```
hickory% make 2.opencl.log
LD_PRELOAD=./build/kfusion/thirdparty/liboclwrapper.so ./build/kfusion/kfusion-benchmark-opencl -s 4.8 -p 0.34,0.5,0.24 -z 4 -c 2 -r 2 -k 481.2,480,320,240 -i  living_room_traj2_
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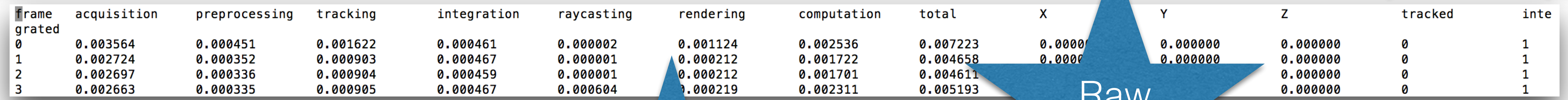
./kfusion/thirdparty/checkKernels.py kernels.2.opencl.log   >> resume.2.opencl.log
hickory%
```

Easy run



```
frame    acquisition      preprocessing    tracking         integration      raycasting       rendering        computation      total            X                Y                Z                tracked          inte
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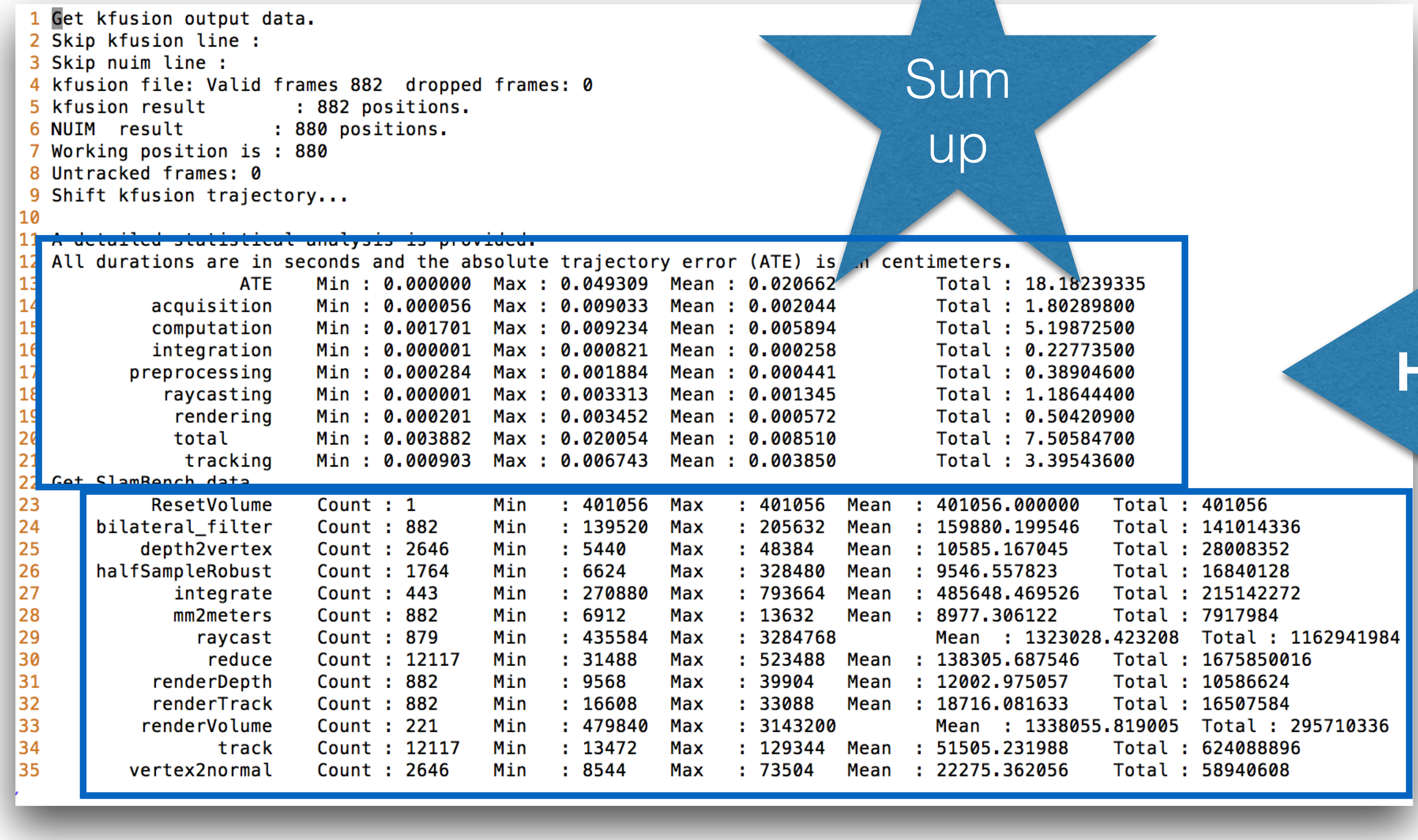
0        0.003564         0.000451         0.001622         0.000461         0.000002         0.001124         0.002536         0.007223         0.0000           0.000000         0.000000         0                1
1        0.002724         0.000352         0.000903         0.000467         0.000001         0.000212         0.001722         0.004658         0.0000           0.000000         0.000000         0                1
2        0.002697         0.000336         0.000904         0.000459         0.000001         0.000212         0.001701         0.004611                                           0.000000         0                1
3        0.002663         0.000335         0.000905         0.000467         0.000604         .000219          0.002311         0.005193                                           0.000000         0                1
```

Raw data



```
Get kfusion output data.
Skip kfusion line :
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                total     Min : 0.003882  Max : 0.020054  Mean : 0.008510         Total : 7.50584700
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               raycast    Count : 879     Min    : 435584  Max    : 3284768         Mean   : 1323028.423208  Total : 1162941984
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           renderDepth    Count : 882     Min    : 9568    Max    : 39904   Mean   : 12002.975057     Total : 10586624
           renderTrack    Count : 882     Min    : 16608   Max    : 33088   Mean   : 18716.081633     Total : 16507584
          renderVolume    Count : 221     Min    : 479840  Max    : 3143200         Mean   : 1338055.819005  Total : 295710336
                 track    Count : 12117   Min    : 13472   Max    : 129344  Mean   : 51505.231988     Total : 624088896
          vertex2normal   Count : 2646    Min    : 8544    Max    : 73504   Mean   : 22275.362056     Total : 58940608
```

Sum up

High-level blocks statistics

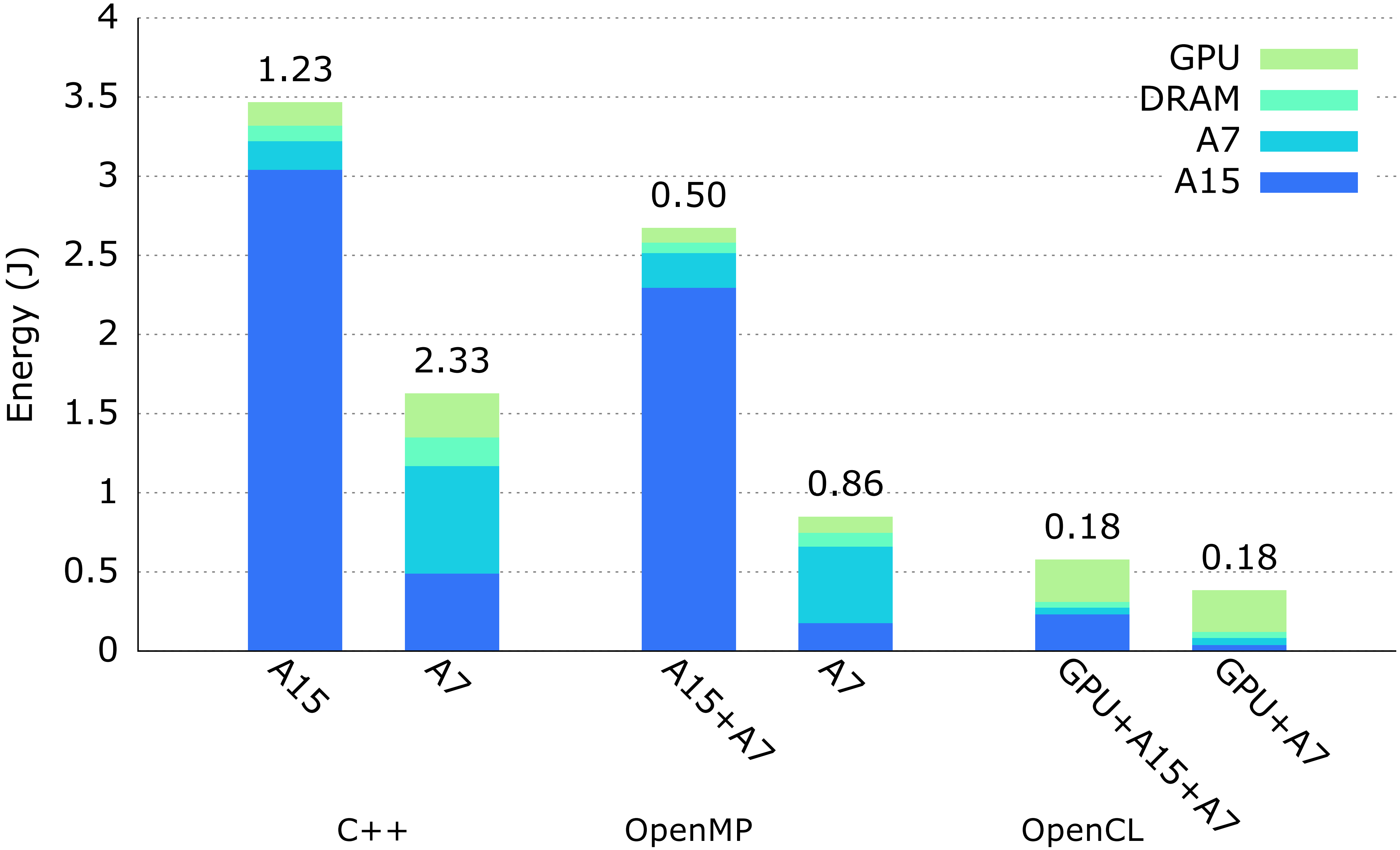
Kernels statistics

“Performance”: energy (ODROID)

On-board voltage/current sensors and split power rails:
power measured individually on big (A15), LITTLE (A7), GPU and DRAM

"Performance": energy (ODROID)

On-board voltage/current sensors and split power rails:
power measured individually on big (A15), LITTLE (A7), GPU and DRAM



Energy usage per frame, mean time as marked

Copyrights

- Author: unknown. Microsoft Kinect camera. [Image]. Retrieved from http://channel9.msdn.com/Series/KinectSDKQuickstarts/Understanding-Kinect-Hardware
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