

Introducing SLAMBench, a performance and accuracy benchmarking methodology for SLAM

Luigi Nardi, Ph.D.
Imperial College London
@ICRA, May 29th 2015

In collaboration with:

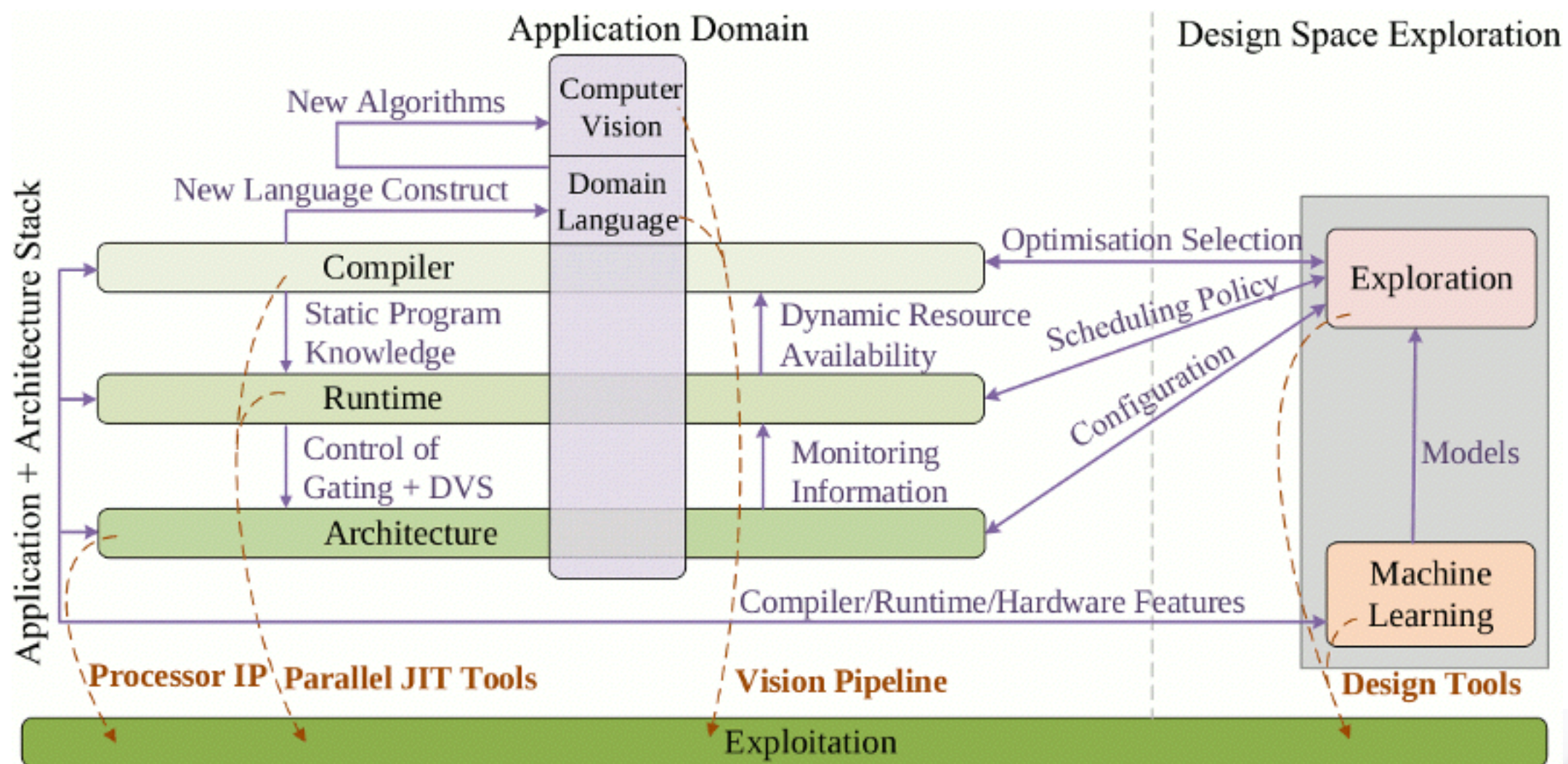
Bruno Bodin, M Zeeshan Zia, John Mawer, Andy Nisbet, Paul H J Kelly, Andrew J Davison, Mikel Luján, Michael F P O'Boyle, Graham Riley, Nigel Topham, Steve Furber



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

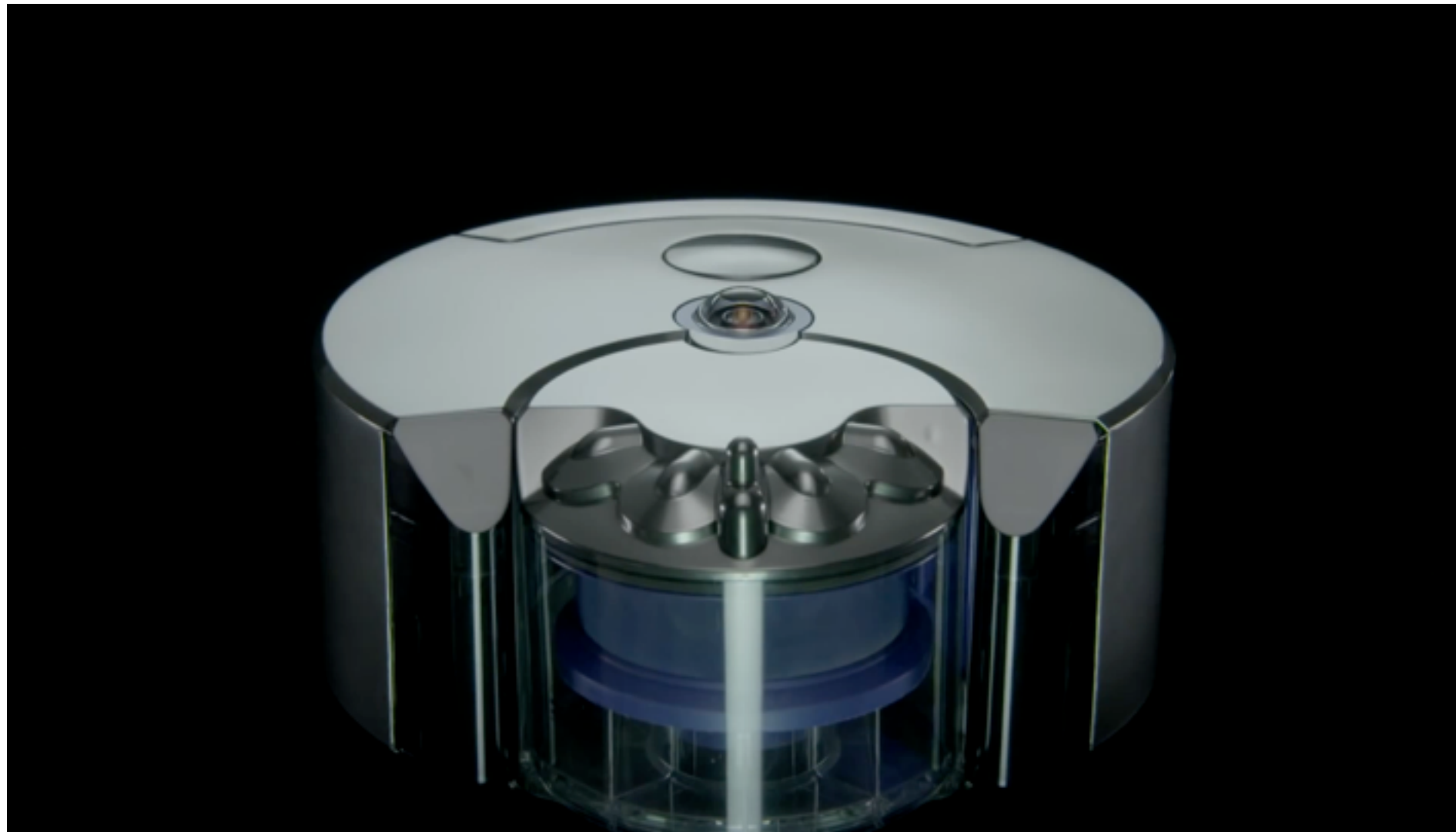
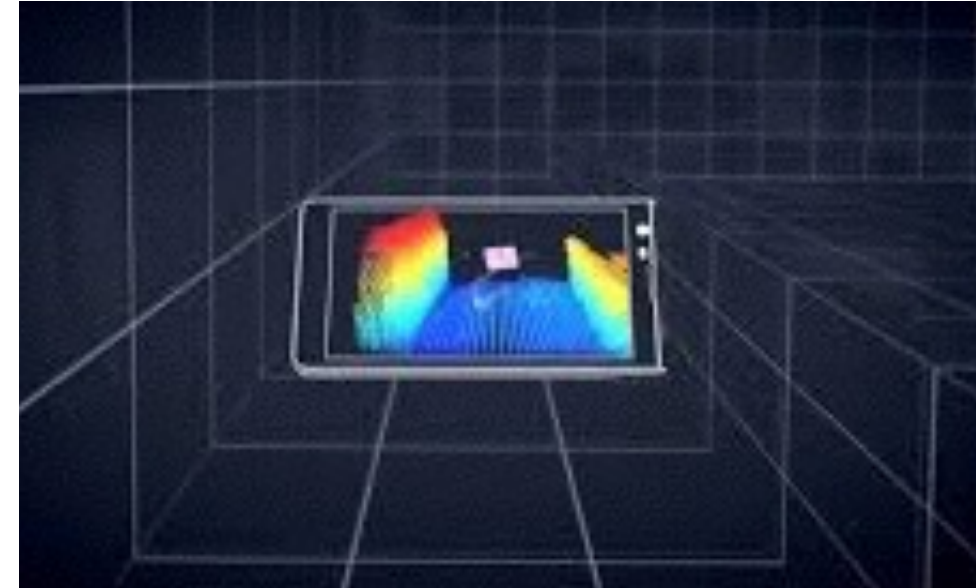


Simultaneous localisation and mapping (SLAM)

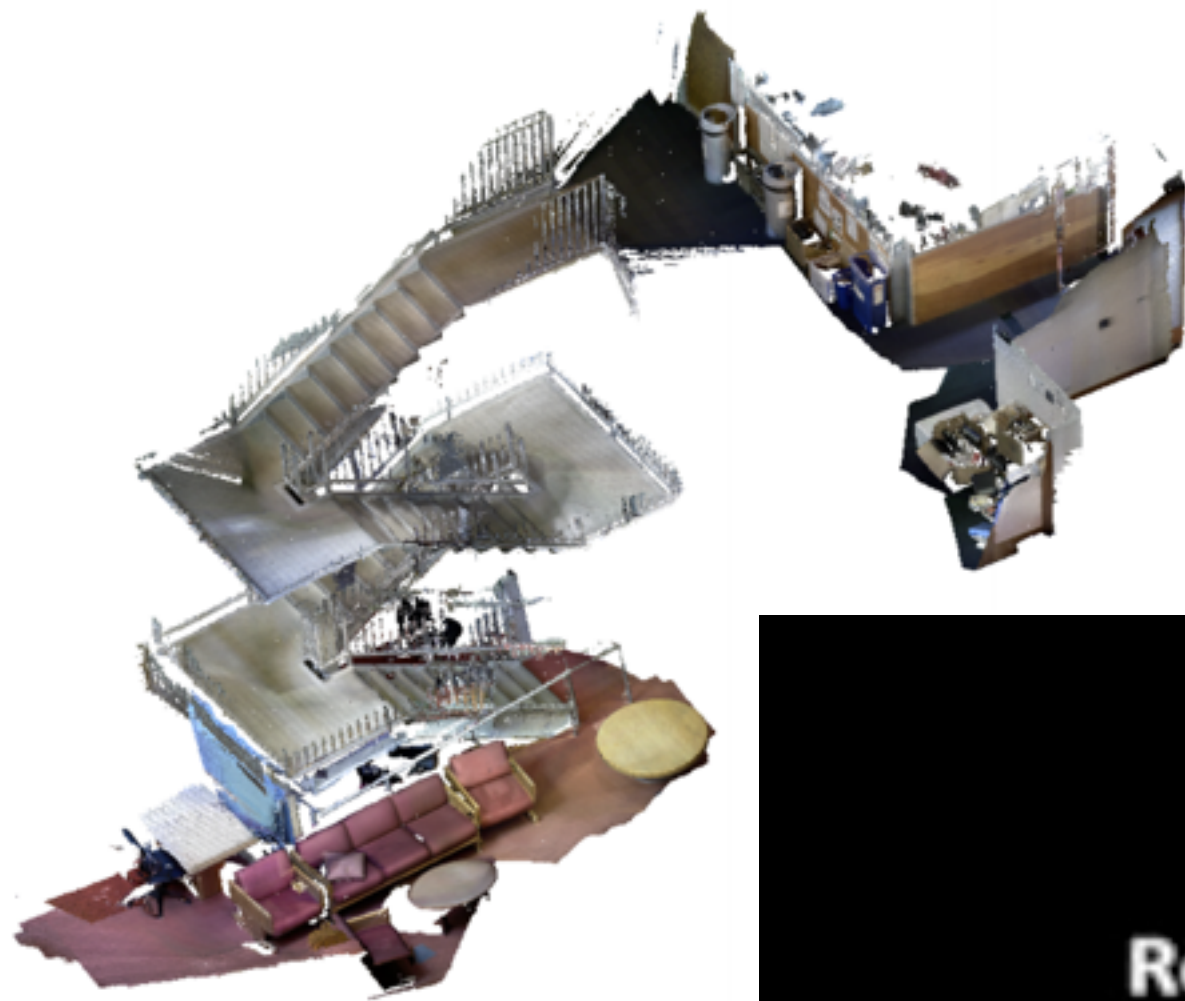
Build a coherent world representation and localise the camera in real-time



Video:
[Dyson 360 Eye](#)



Simultaneous localisation and mapping (SLAM)



[Whelan et al. 2012]



SIGGRAPH Talks 2011 KinectFusion: Real-Time Dynamic 3D Surface Reconstruction and Interaction

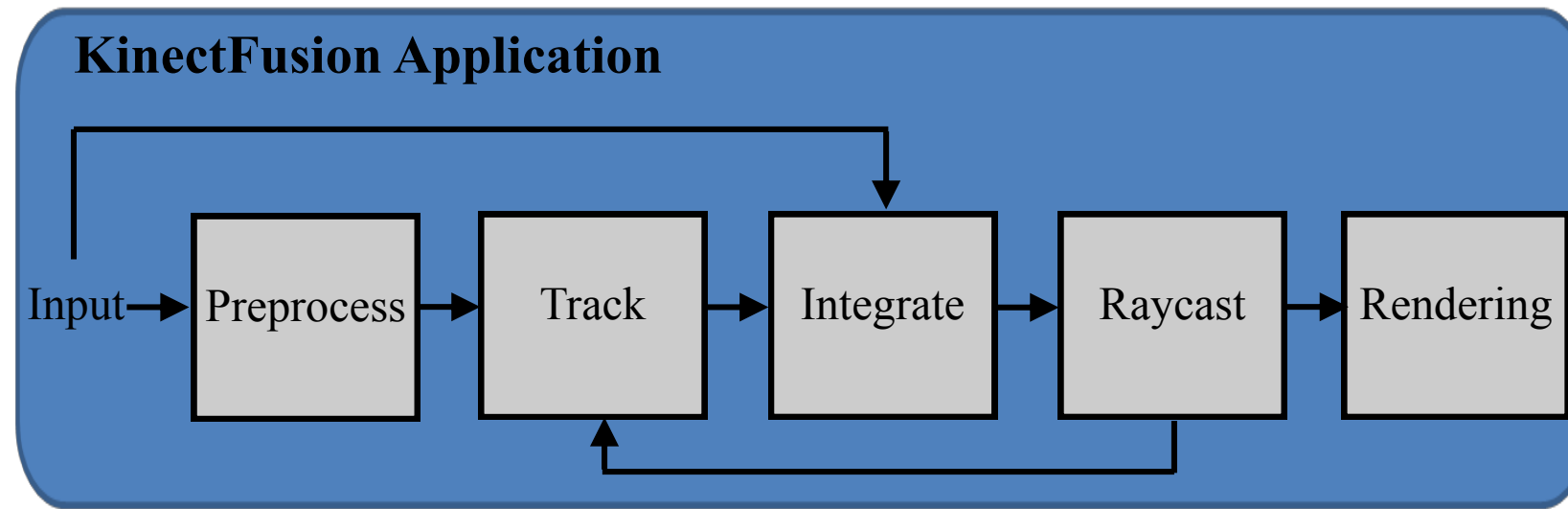
Shahram Izadi 1, Richard Newcombe 2, David Kim 1,3, Otmar Hilliges 1,
David Molyneaux 1,4, Pushmeet Kohli 1, Jamie Shotton 1,
Steve Hodges 1, Dustin Freeman 5, Andrew Davison 2, Andrew Fitzgibbon 1

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

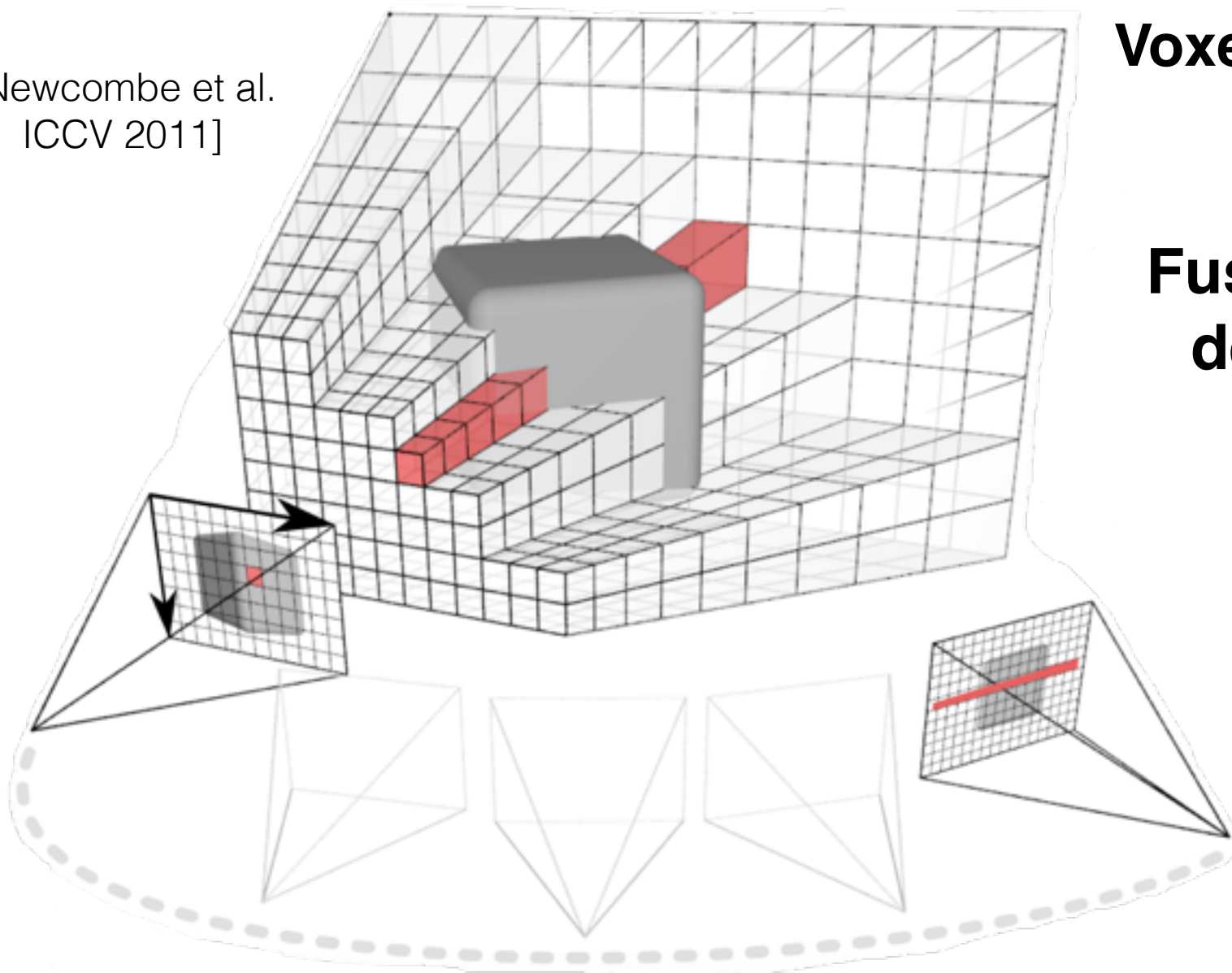
Video:

[Newcombe et al. ISMAR 2011]

KinectFusion SLAM implementation



[Newcombe et al.
ICCV 2011]



Voxel grid represents **3D surfaces**
[Curless and Levoy 1996]

Fuses (or integrate) the stream
depth frames into a **3D map**

3D surfaces recovered
by **raycasting**

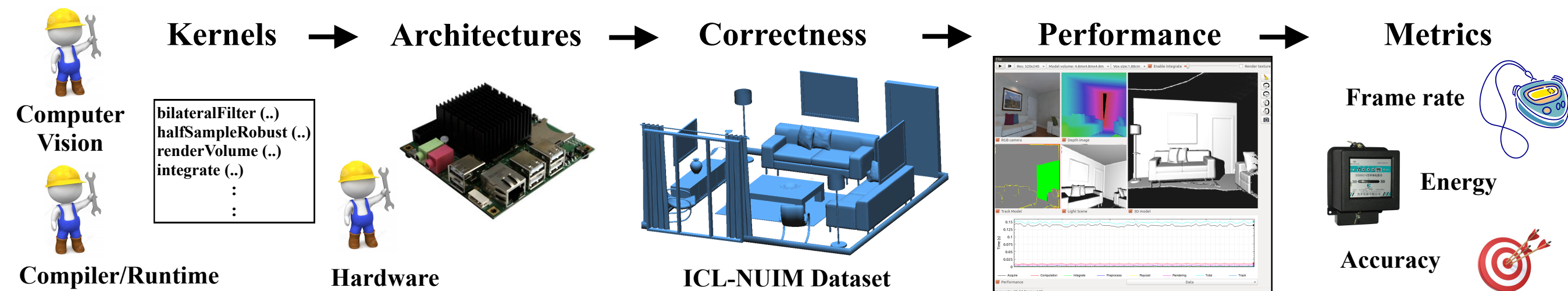
Localisation (or tracking):
estimates the camera pose



Three “Performance” metrics

1. In computer vision (CV) benchmarks target **accuracy**
2. Benchmarks in other fields are about **execution time**
3. Is somebody targeting **energy**?

Holistic approach to SLAM “performance”: SLAMBench



How to measure SLAM “Performance”?

SLAM computation depends on:

- Images acquired
- Way the camera is moved
- Numerical approximations
- Processing frame rate
(depends on hardware capability)

**Need for reproducibility
and accuracy check**

Pre-recorded scenes

Process-every-frame mode

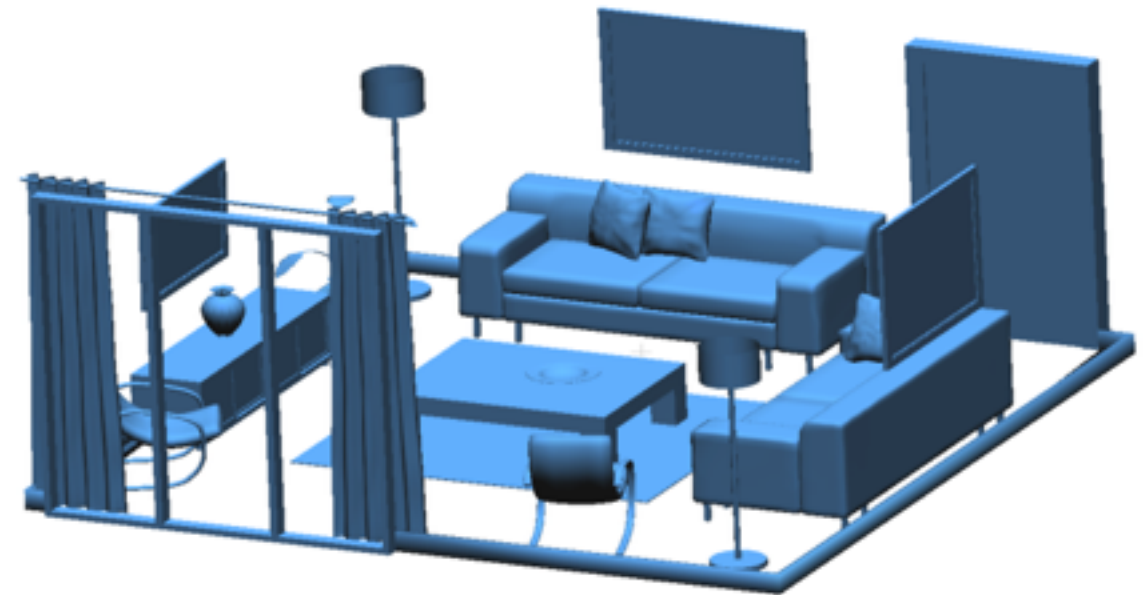
*ICL-NUIM dataset
(frames and ground truth)*



ICL-NUIM dataset



- ICL-NUIM synthetic dataset [Handa et al. 2014]
- 880 RGB-D frames at 30 FPS
- Absolute trajectory error (ATE) based on ground truth



SLAMBench framework vision

SLAM benchmarks

KinectFusion ...**Dense SLAM****LSD-SLAM** ...**Semi-dense SLAM****ORB-SLAM** ...**Sparse SLAM**

high-level blocks,
KFusion based on
[Reitmayr 2011]

Implementation languages

C++**OpenMP****OpenCL****CUDA** ...

wide range
of languages

Desktop to embedded platforms

ARM**Intel****NVIDIA** ...

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

Datasets

ICL-NUIM**TUM** ...

integrated
verification

Performance evaluation

Frame rate**Energy****Accuracy**

3 metrics:
execution time,
energy and accuracy

Machines	TITAN	GTX870M	TK1	ODROID	Arndale
CPU	Intel	Intel	ARM	ARM	ARM
CPU name	i7 Haswell	i7 Haswell	NVIDIA 4-Plus-1	Exynos 5422	Exynos 5250
CPU GFLOPS	448	307	74	80	27
CPU cores	4	4	4 + 1	4 + 4	2
GPU	NVIDIA	NVIDIA	NVIDIA	ARM	ARM
GPU name	TITAN	GTX 870M	Tegra K1	Mali-T628	Mali-T604
GPU GFLOPS	4500	2520	330	60 + 30	60

Platforms



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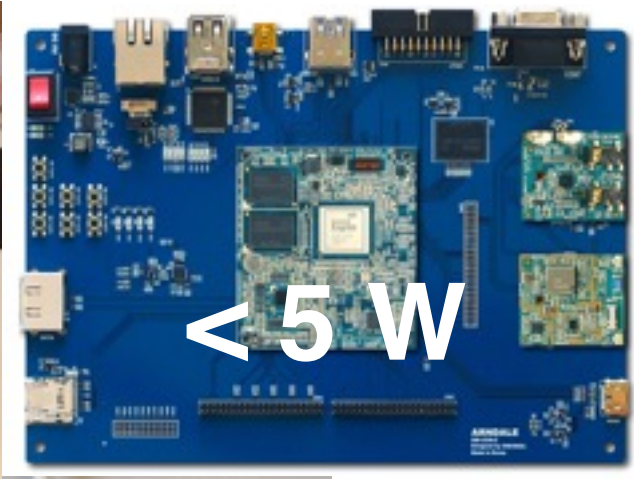
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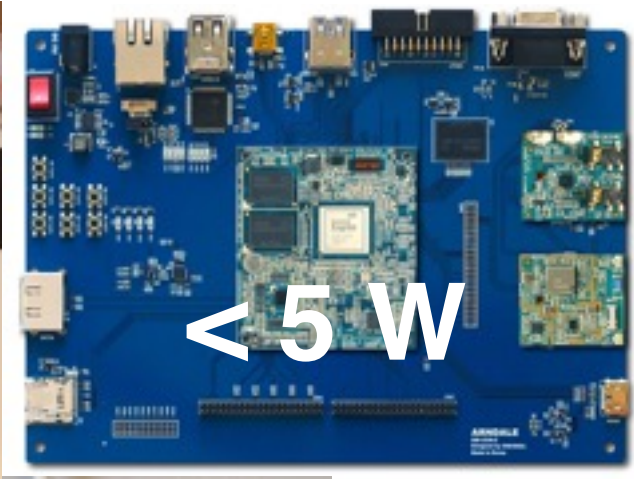
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Platforms



“Performance”: accuracy

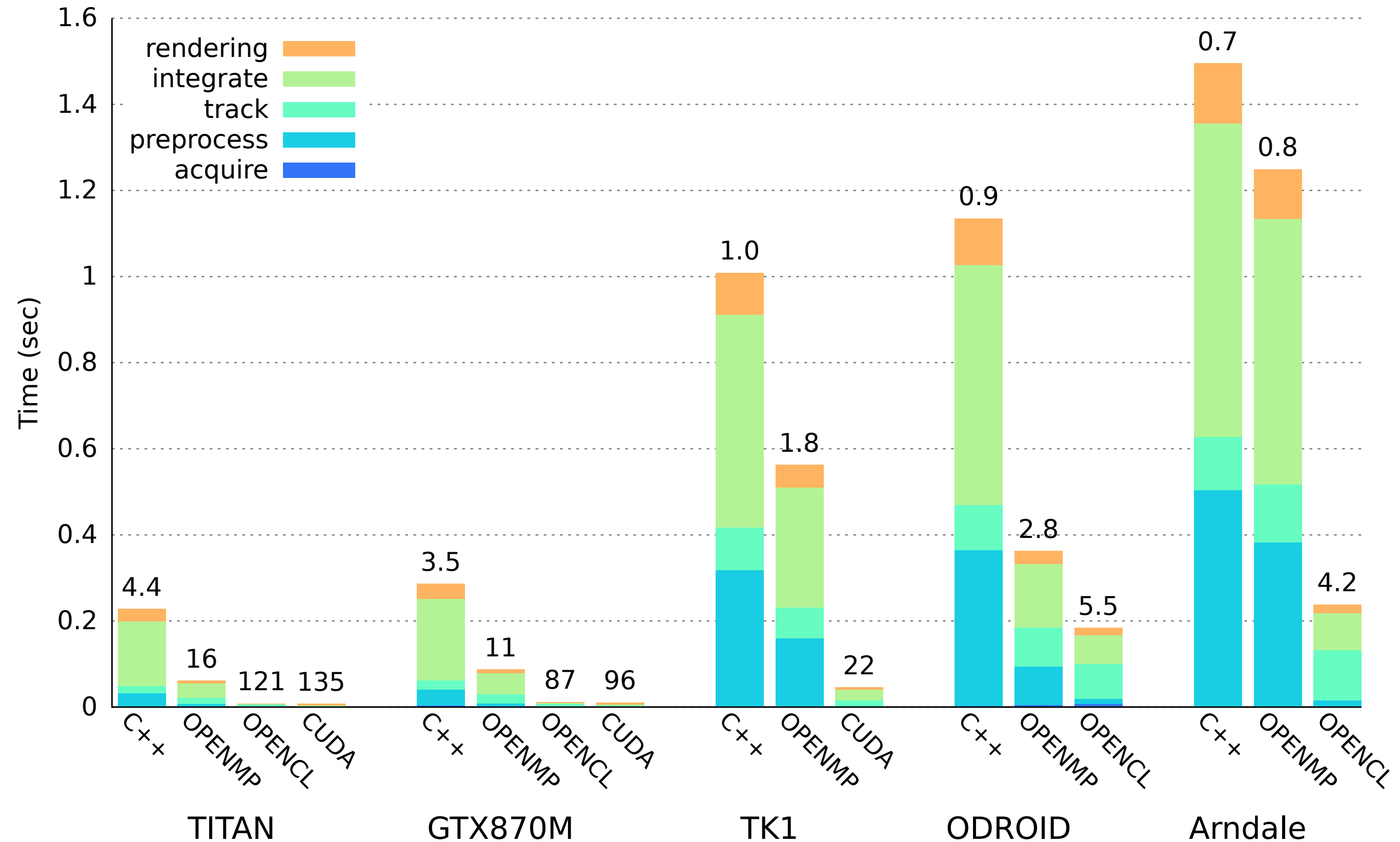
Absolute trajectory error (ATE) in cm - default algorithmic configuration

ATE in cm	TITAN	GTX870M	TK1	ODROID	Arndale
C++	2.07	2.07	2.06	2.06	2.06
OpenMP	2.07	2.07	2.06	2.06	2.06
OpenCL	2.07	2.07	n/a	2.01	2.07
CUDA	2.07	2.07	2.07	n/a	n/a

- ATE easy-to-use tool for non computer vision experts
- Semantic validation instead than bitwise accuracy

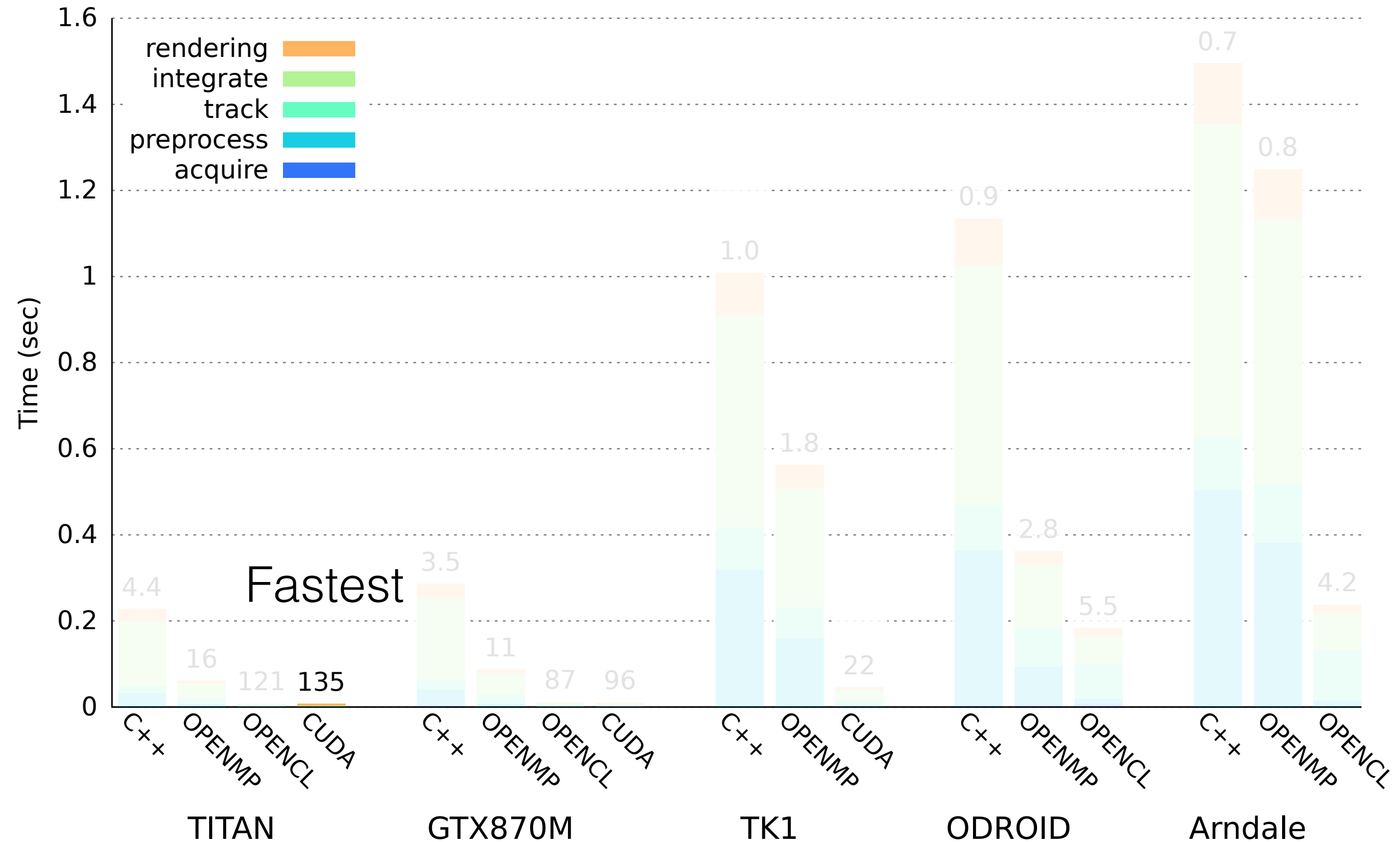
“Performance”: execution time

Mean time per frame (lower is better)



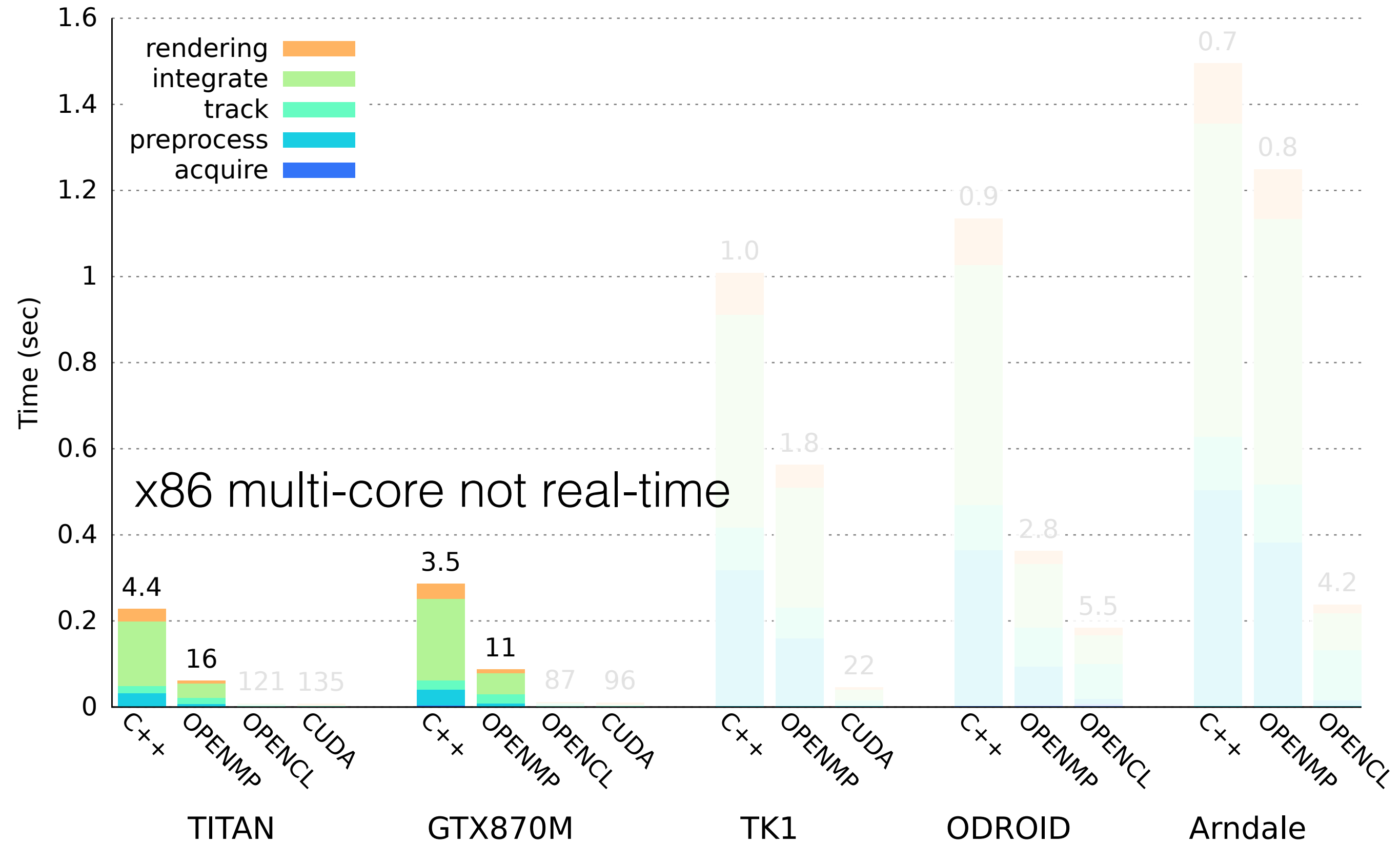
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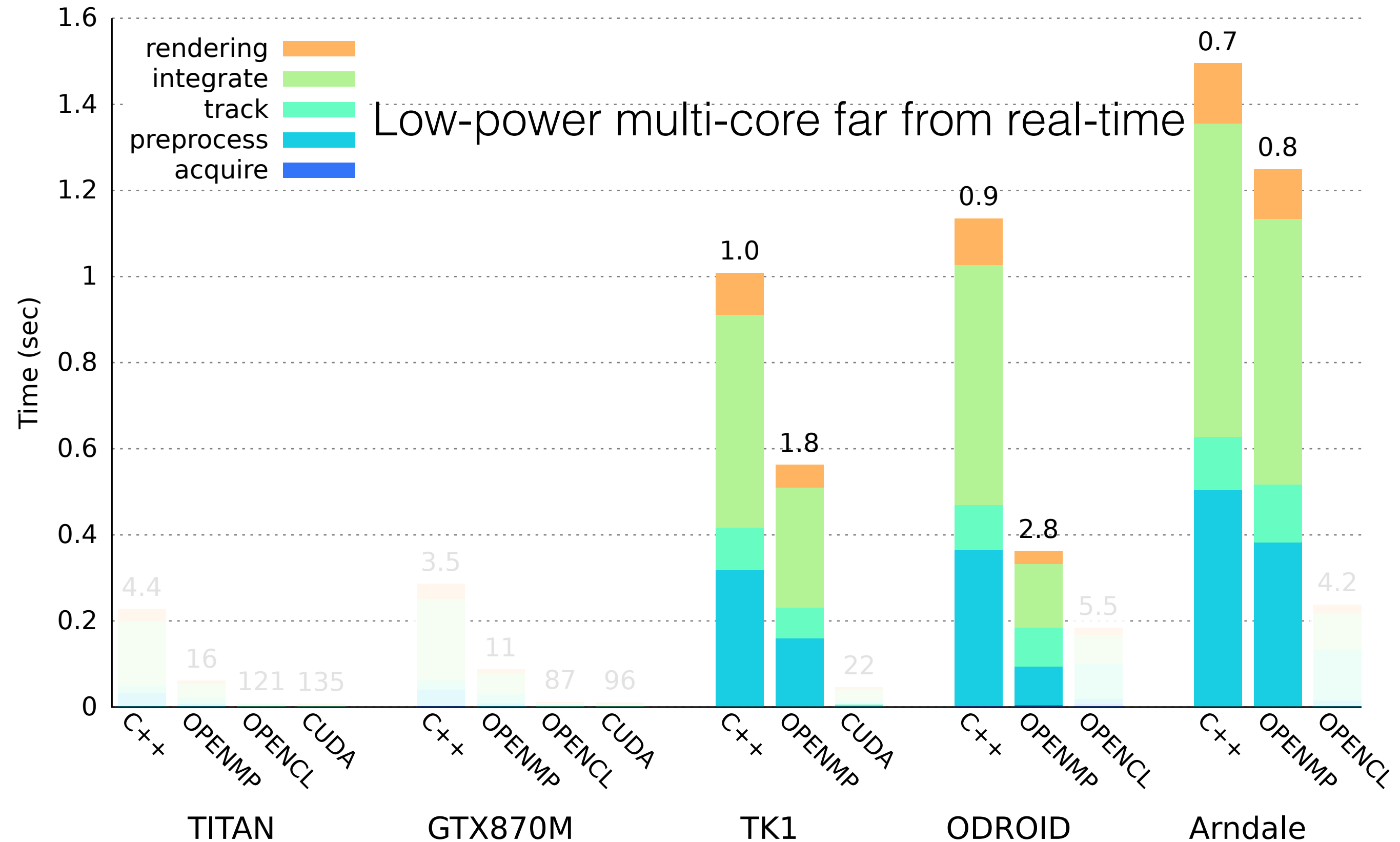
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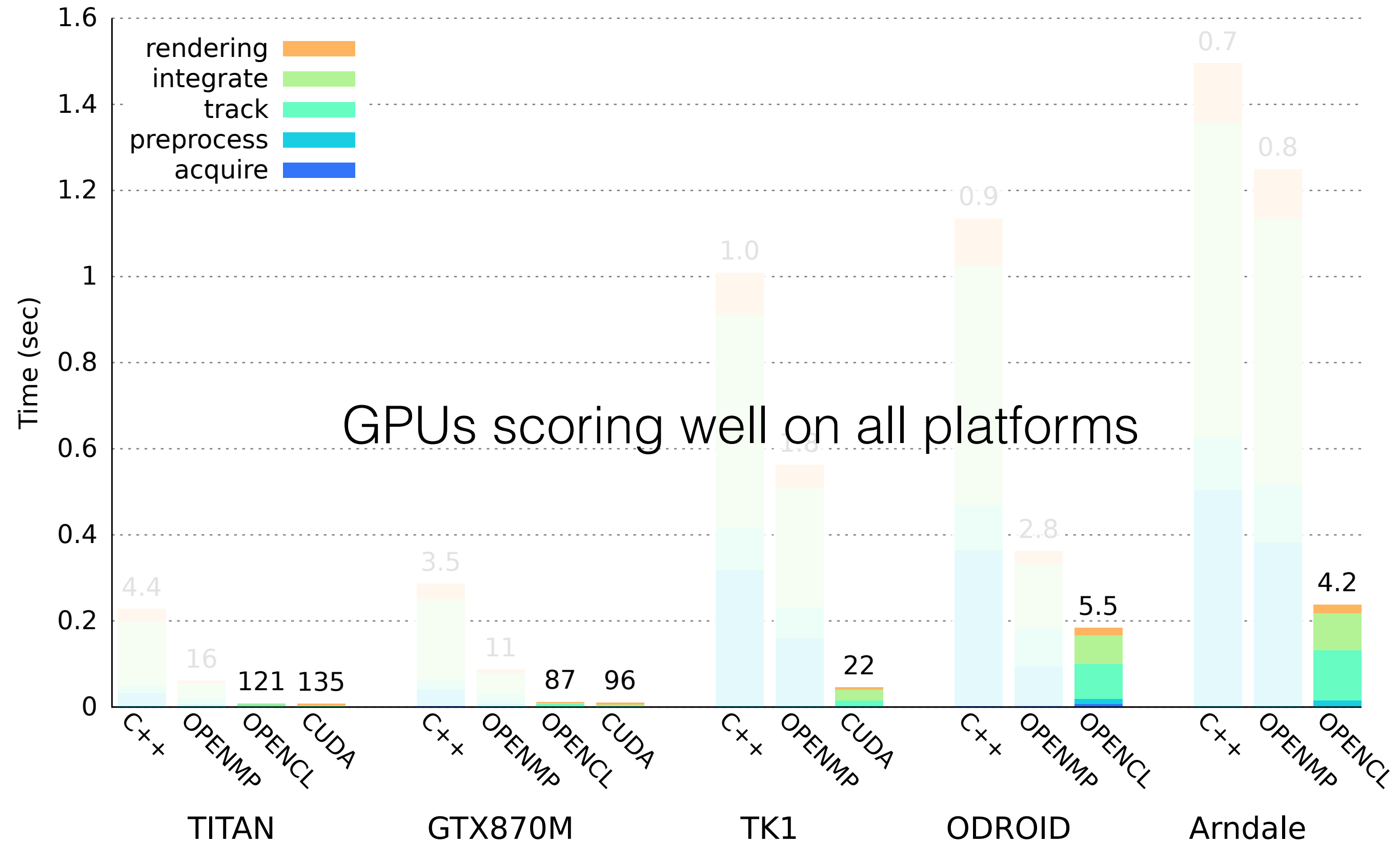
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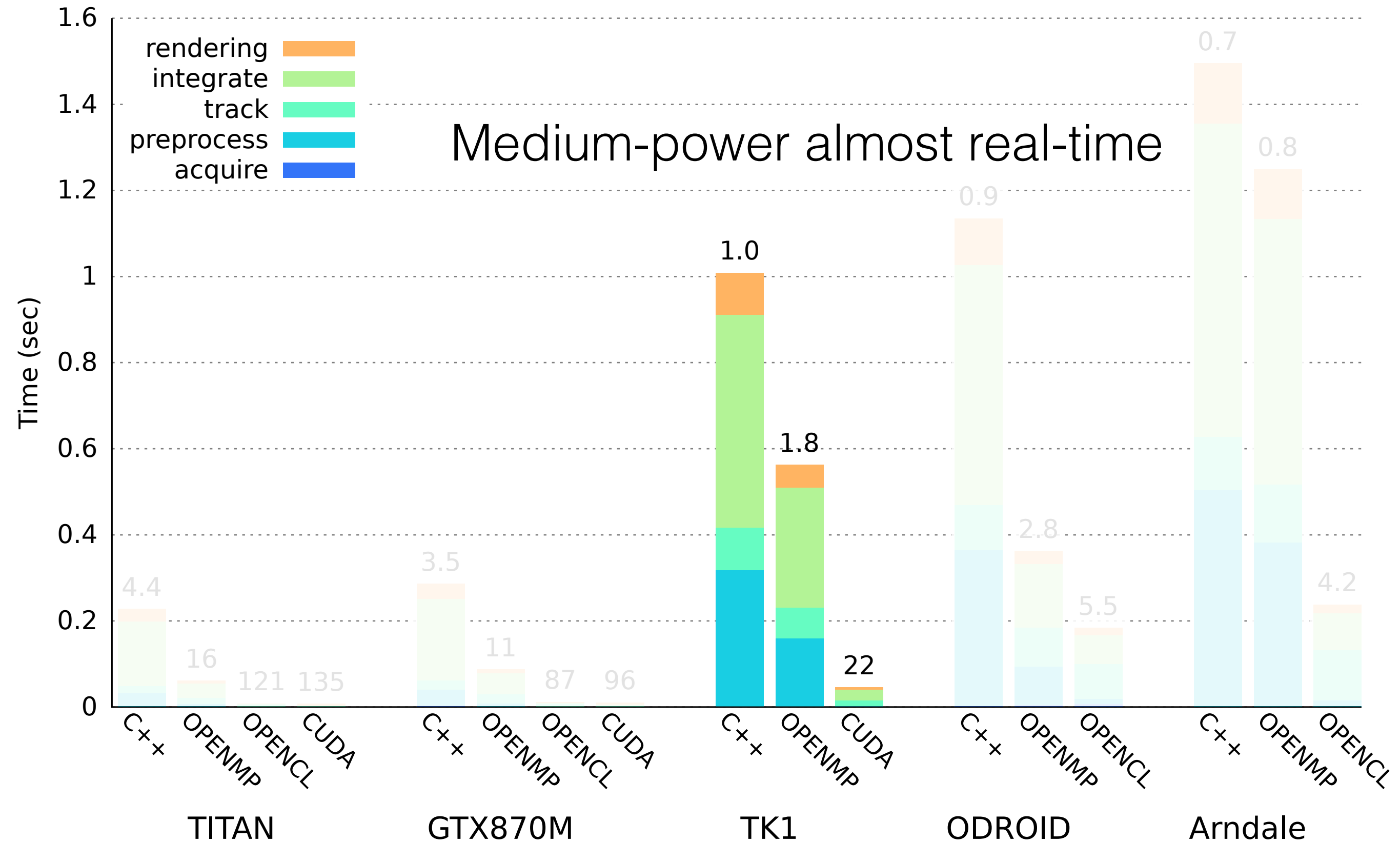
“Performance”: execution time

Mean time per frame (lower is better)



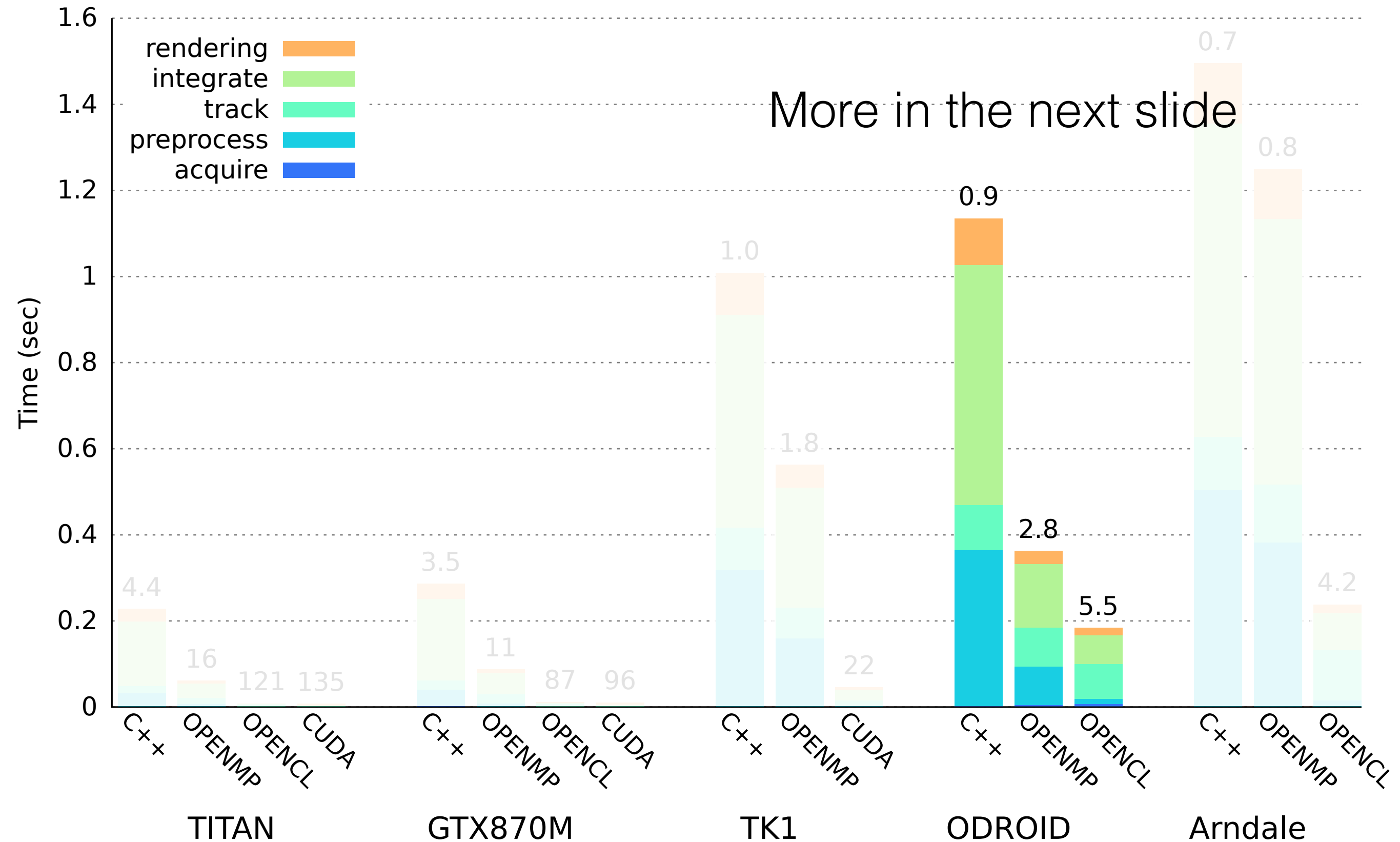
“Performance”: execution time

Mean time per frame (lower is better)



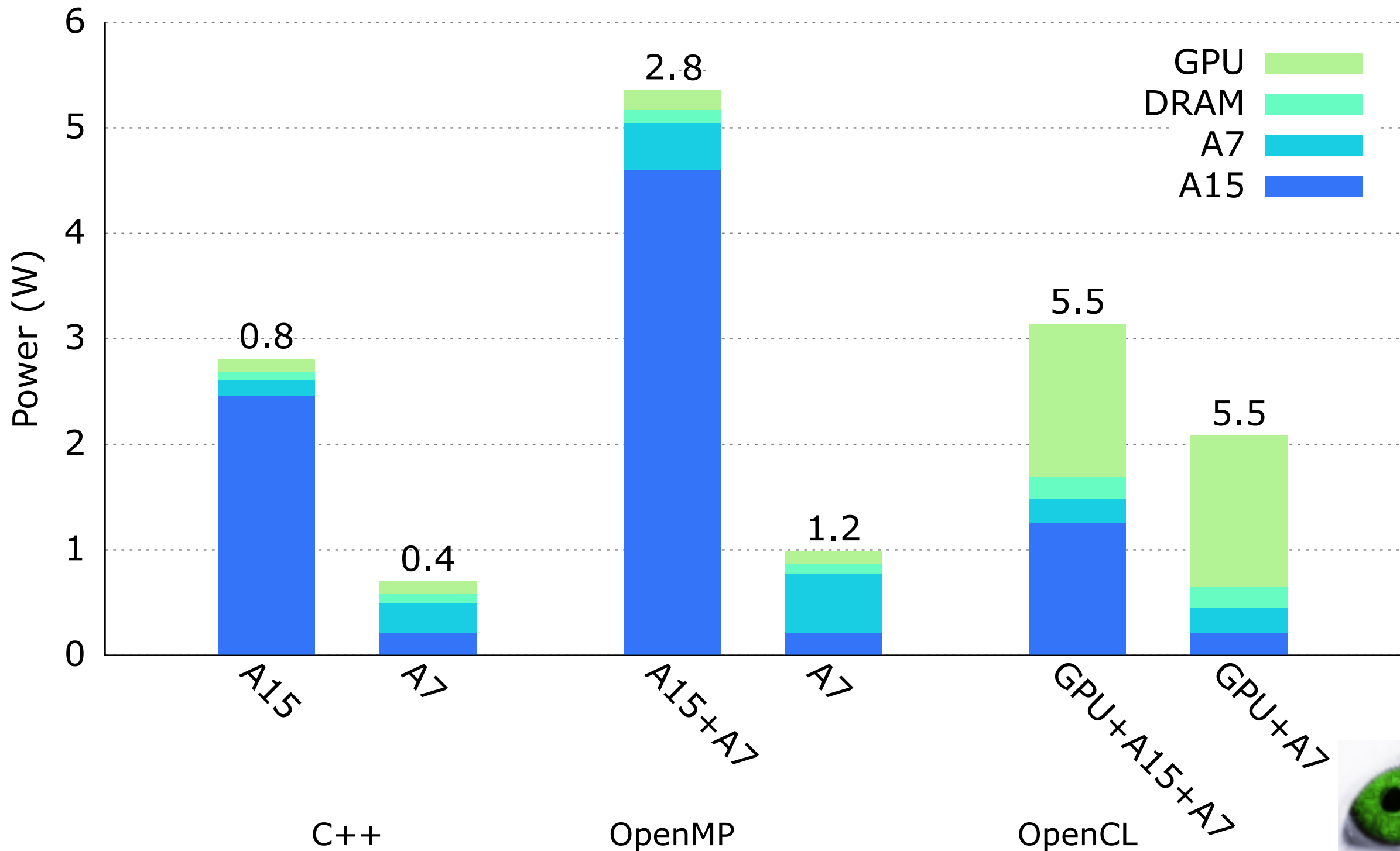
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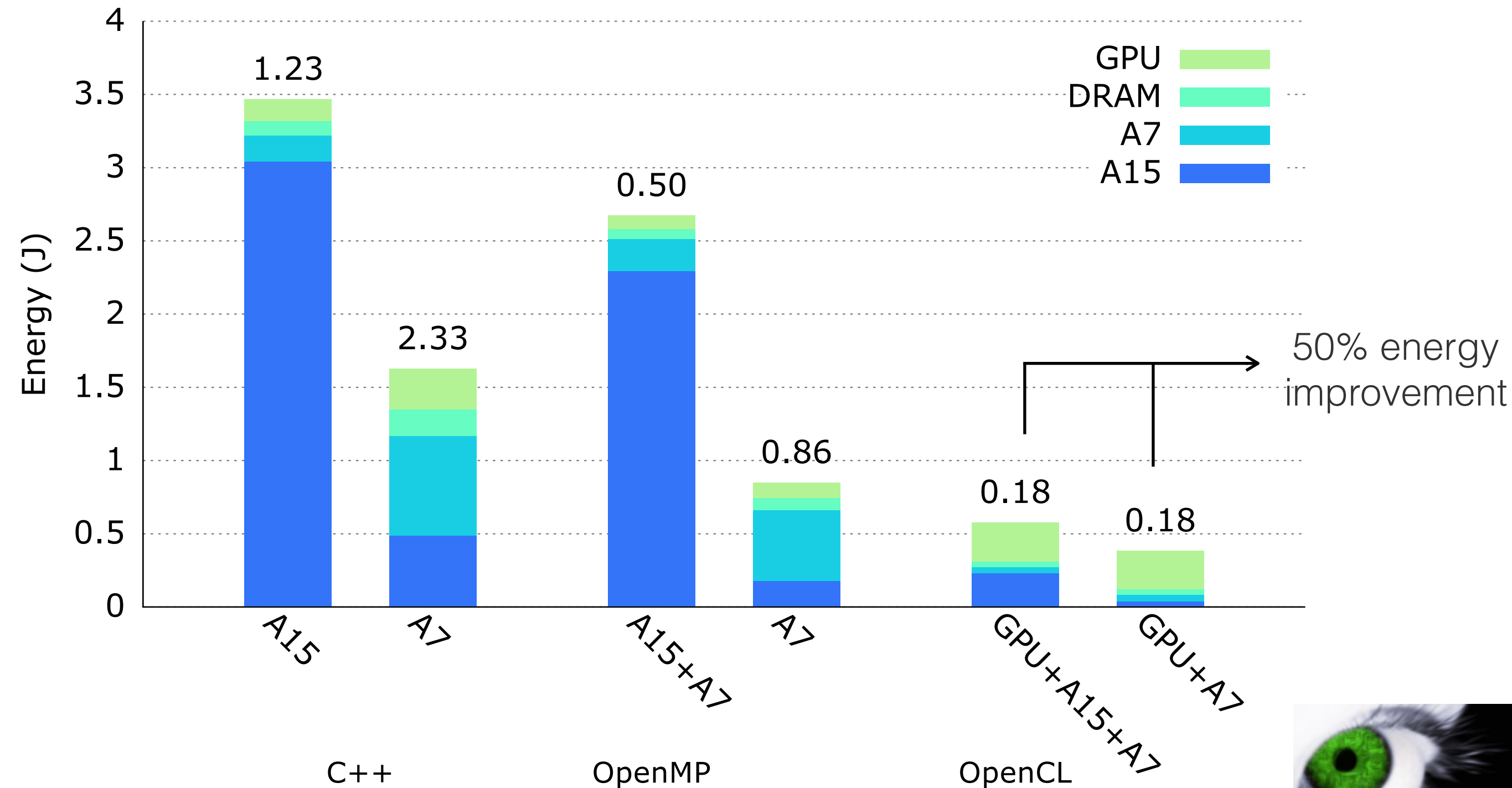
“Performance” power (ODROID-XU3)

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



“Performance”: energy (ODROID-XU3)

Energy usage per frame, mean time as marked



SLAMBench today

- Publicly released
13/11/2014
(500 downloads)
- Early adopters:
 - Computer Vision
 - Compiler/runtime
 - Architecture

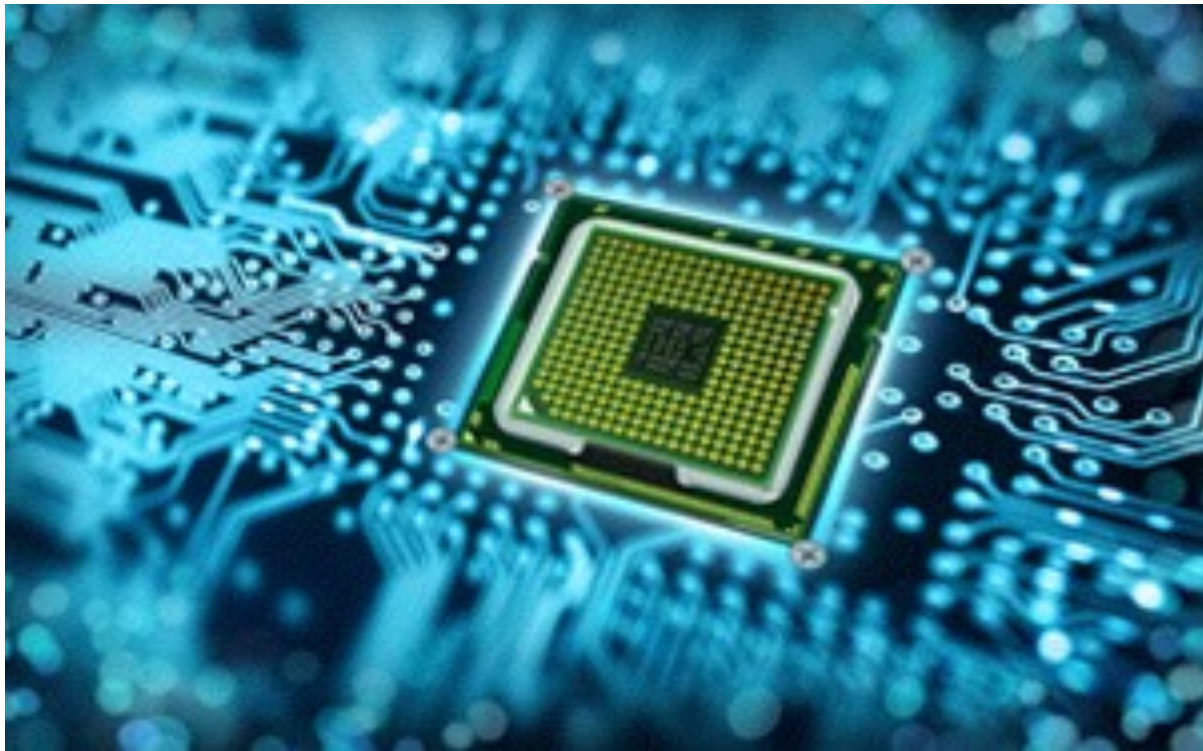


apt.cs.manchester.ac.uk/projects/PAMELA/tools/SLAMBench/

Web



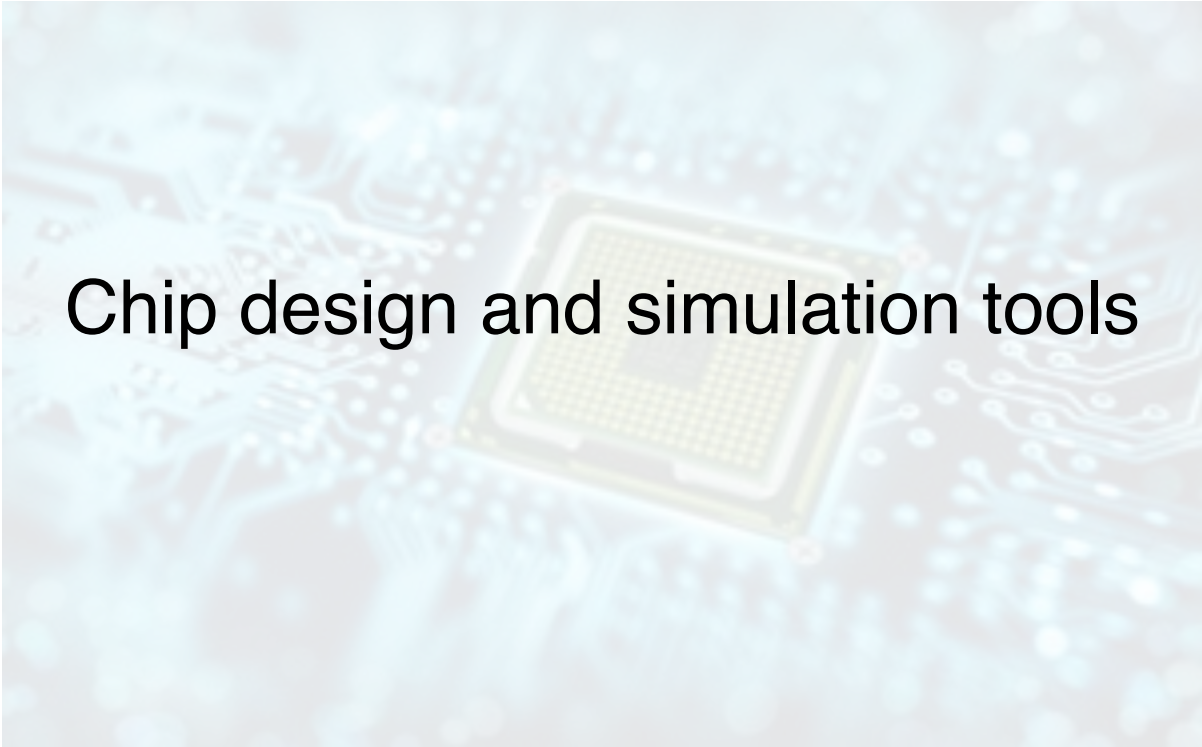
SLAMBench opportunities



Chip design and simulation tools



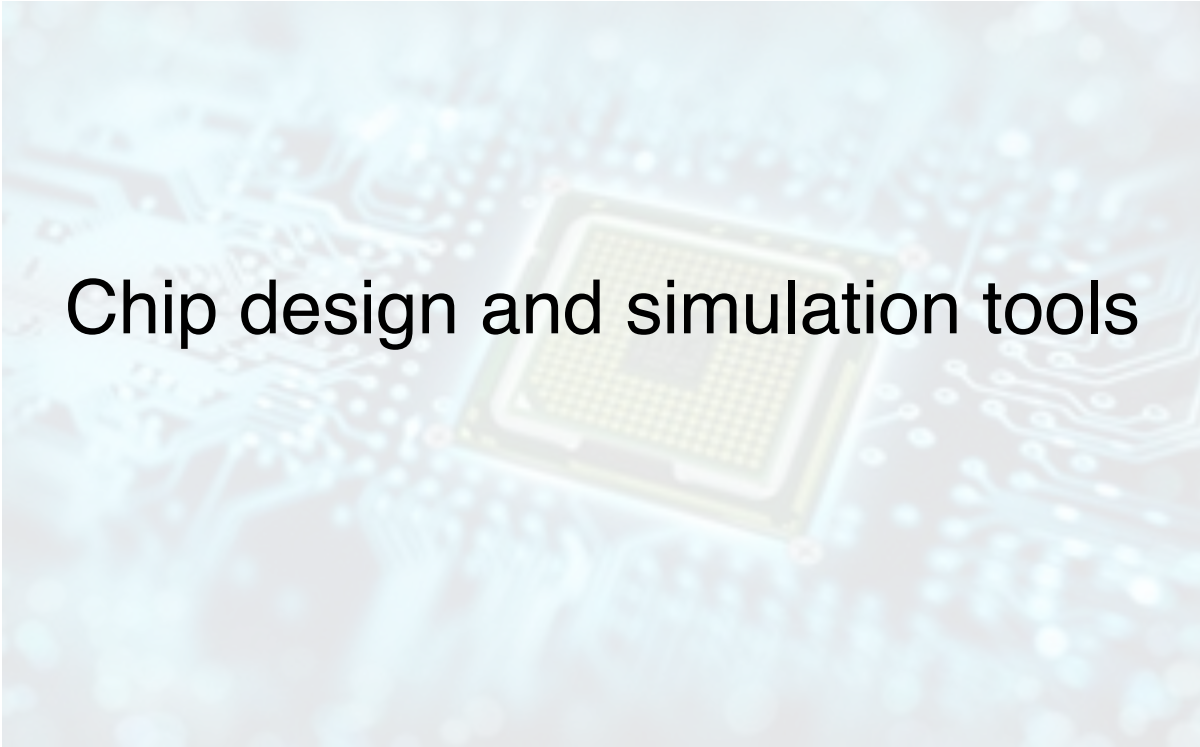
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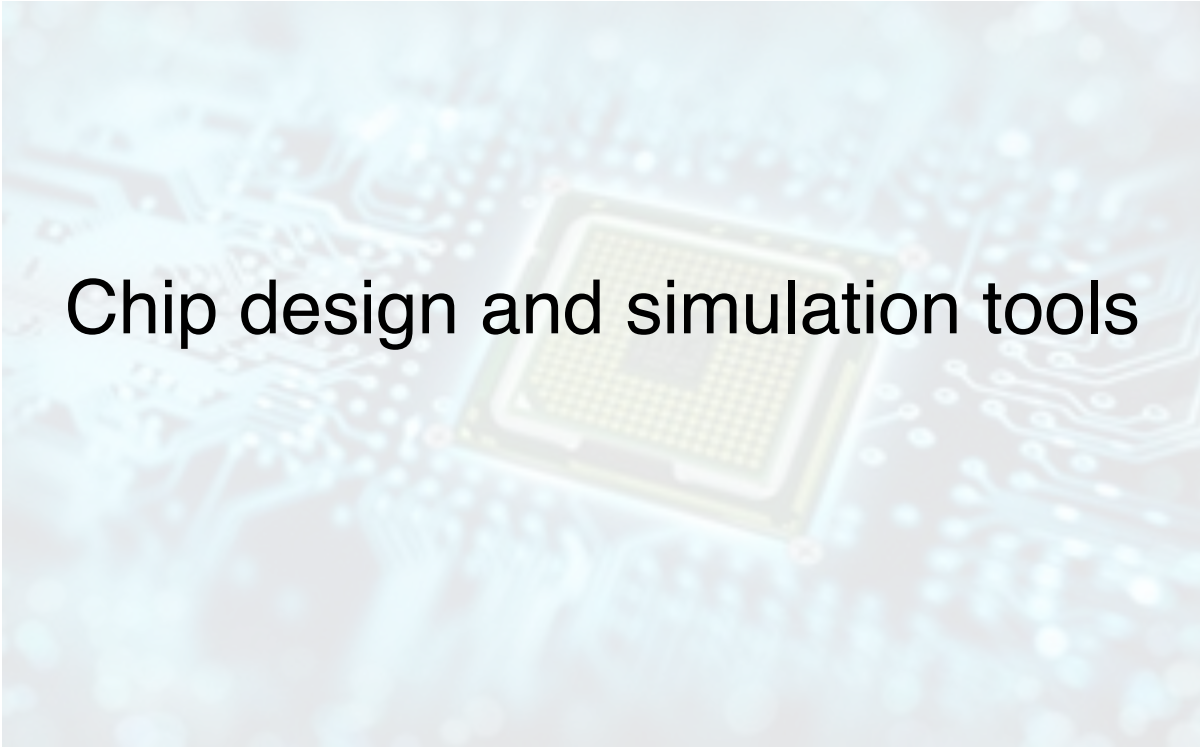
SLAMBench evolution:

- Point fusion
- Octrees
- Semi-dense SLAM
- Feature-based SLAM

Kernels can be improved individually



SLAMBench opportunities



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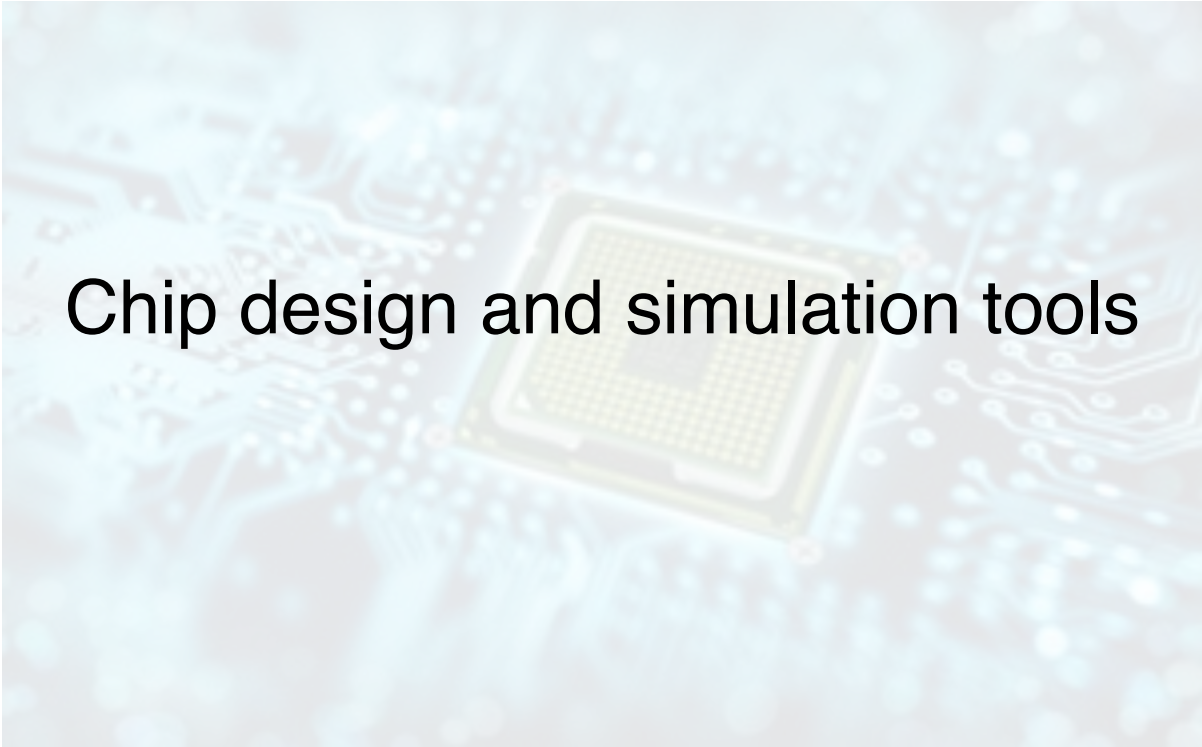
Domain-specific language (DSL) targeting high performance, low-power solutions

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

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



SLAMBench opportunities



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SLAMBench evolution:

- Point fusion
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Kernels can be improved individually

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

What is the optimisation space?

Configuration parameters:

Space 1

1. Algorithmic:

- Minimisation methods
- Early exit condition value
- Application-specific parameters

What is the optimisation space?

Configuration parameters:

Space 1	1. Algorithmic: • Minimisation methods • Early exit condition value • Application-specific parameters
Space 2	2. Compilation: • opencl-params: -cl-mad-enable, -cl-fast-relaxed-math, etc. • Local work group size • Kernel partitioning ratio • Thread coarsening

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Configuration parameters:

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Space 2	2. Compilation: • opencl-params: -cl-mad-enable, -cl-fast-relaxed-math, etc. • Local work group size • Kernel partitioning ratio • Thread coarsening
Space 3	3. Hardware: • CPU frequency • # of active big cores • # of active LITTLE cores

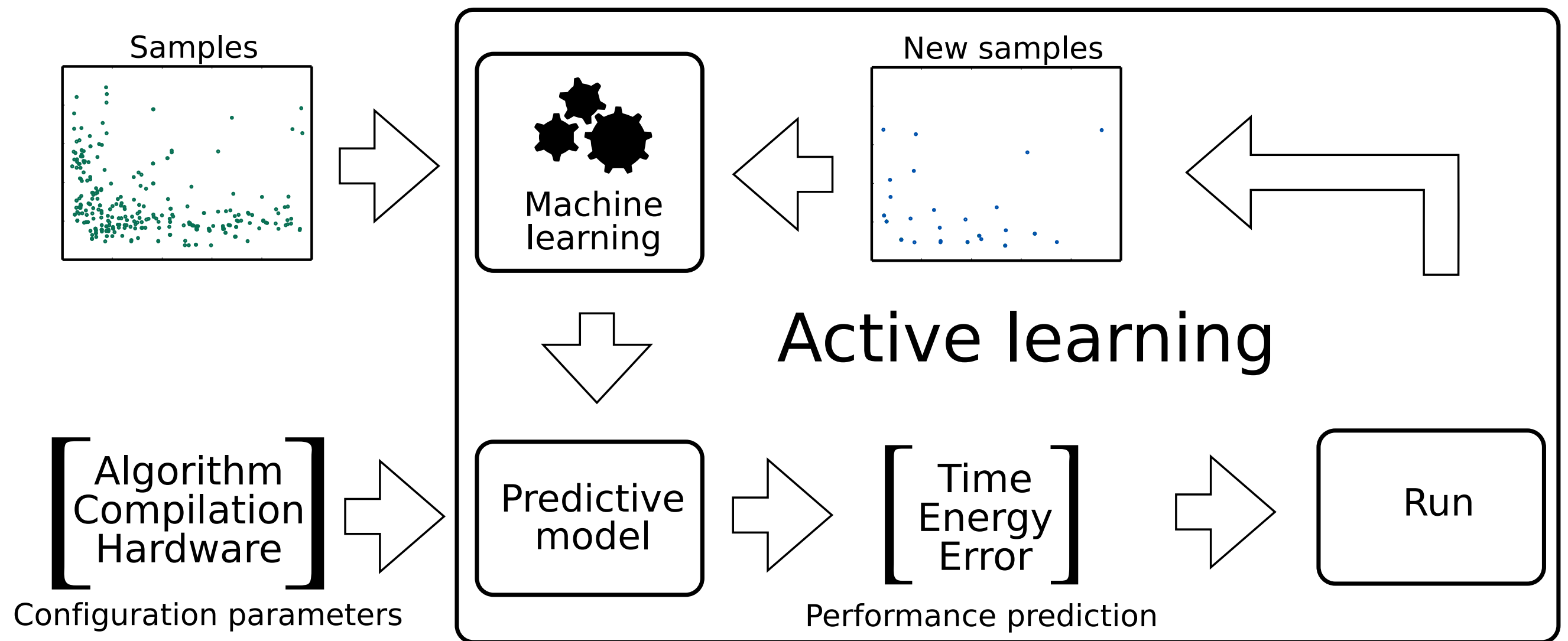
What is the optimisation space?

Configuration parameters:

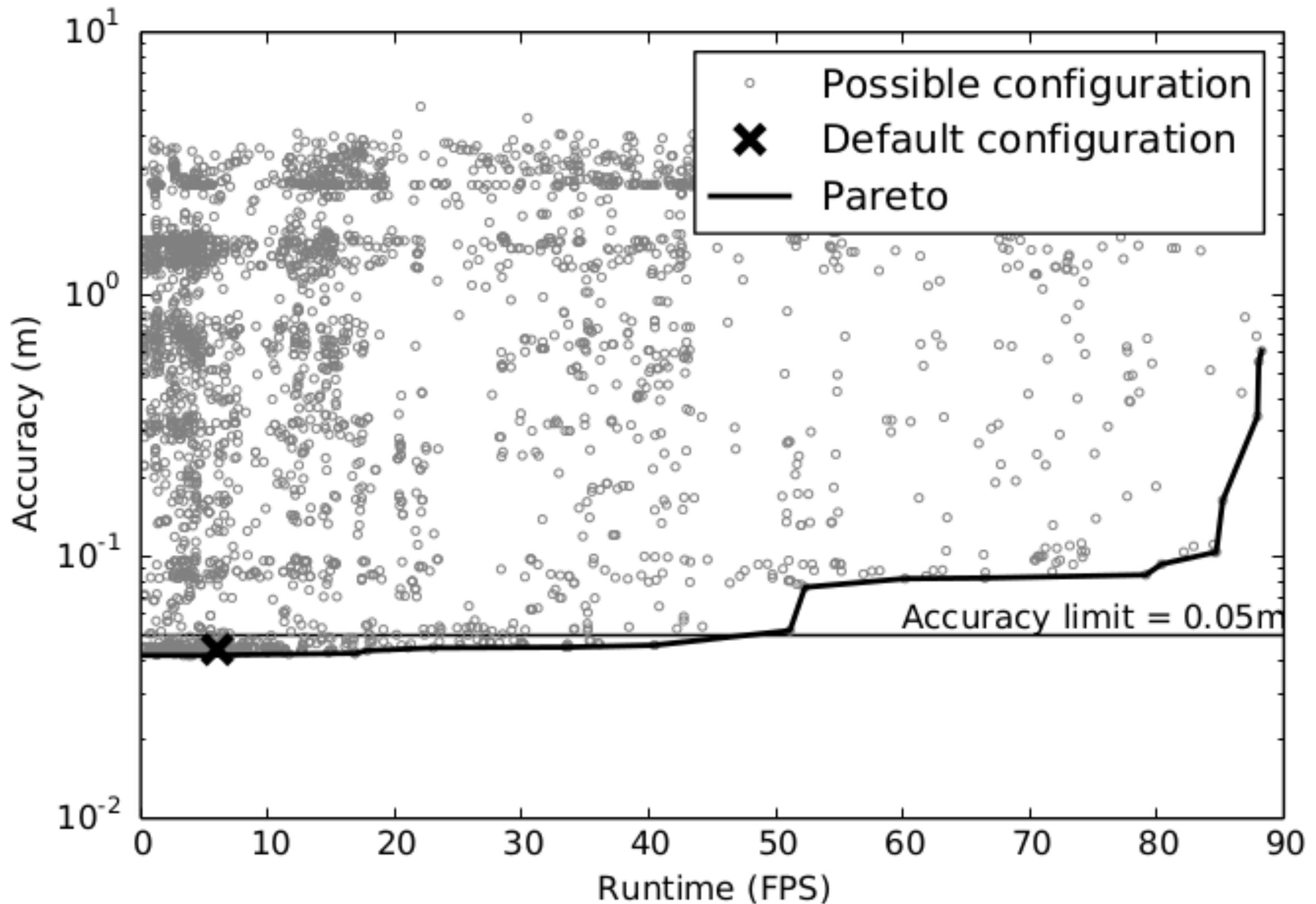
Joint space	Space 1	1. Algorithmic: • Minimisation methods • Early exit condition value • Application-specific parameters
	Space 2	2. Compilation: • openccl-params: -cl-mad-enable, -cl-fast-relaxed-math, etc. • Local work group size • Kernel partitioning ratio • Thread coarsening
	Space 3	3. Hardware: • CPU frequency • # of active big cores • # of active LITTLE cores

Warning: huge space, impossible to run exhaustively

Joint design-space exploration (DSE)



DSE on SLAMBench algorithmic parameters



References

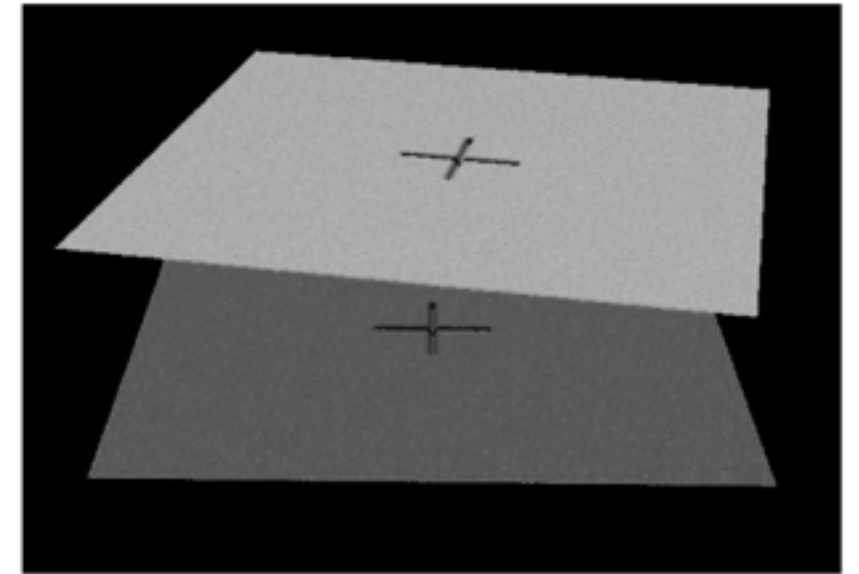
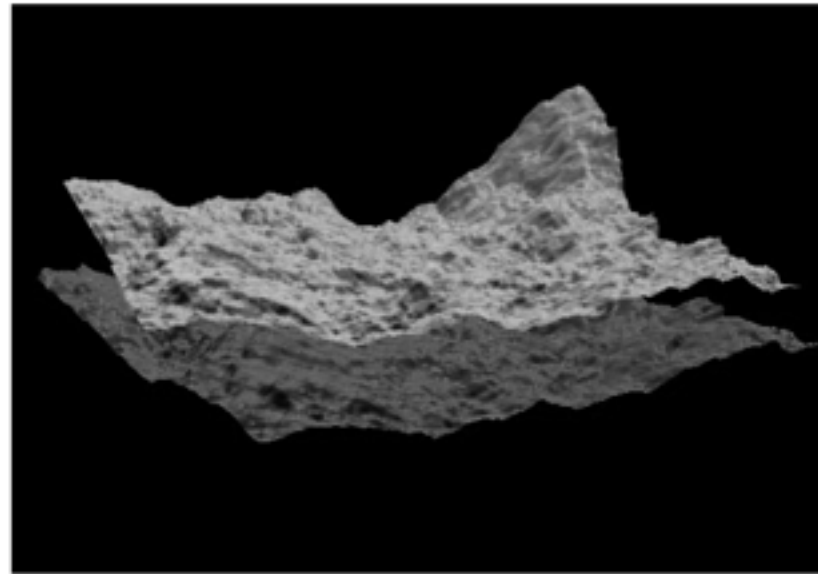
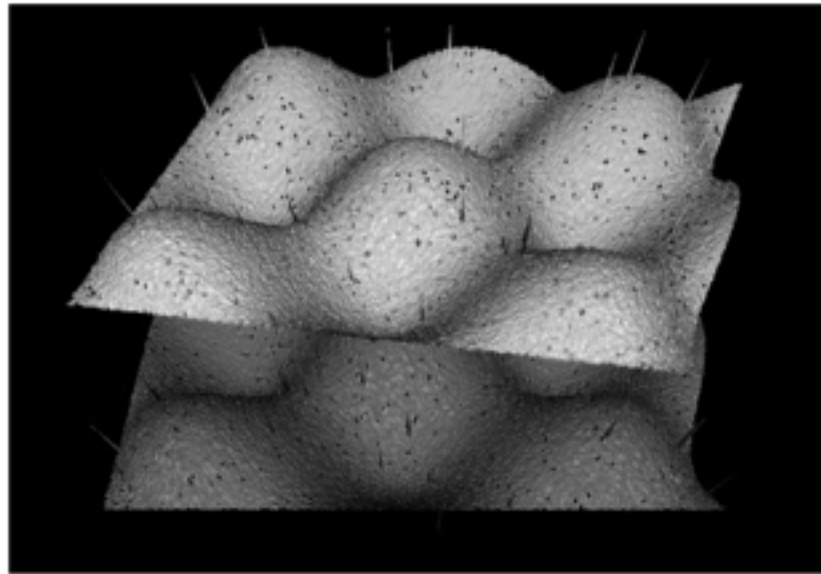
1. [Nardi et al. 2015] L. Nardi, B. Bodin, M. Z. Zia, J. Mawer, A. Nisbet, P. H. J. Kelly, A. J. Davison, M. Luján, M. F. P. O'Boyle, G. Riley, N. Topham, and S. Furber. "Introducing SLAMBench, a performance and accuracy benchmarking methodology for SLAM." Submitted, arXiv:1410.2167, 2015.
2. [Newcombe et al. ICCV 2011] R. A. Newcombe, S. J. Lovegrove and A. J. Davison. "DTAM: Dense tracking and mapping in real-time." Computer Vision (ICCV), 2011 IEEE International Conference on. IEEE, 2011.
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.
4. [Chen et al. 2013] J. Chen, D. Bautembach, and S. Izadi, Scalable real-time volumetric surface reconstruction, in ACM Trans. Graph., 2013.
5. [Newcombe et al. ISMAR 2011] R. A. Newcombe, S. Izadi, O. Hilliges, D. Molyneaux, D. Kim, A. J. Davison, P. Kohi, J. Shotton, S. Hodges, and A. Fitzgibbon. "KinectFusion: Real-time dense surface mapping and tracking." 10th IEEE Int. Symp. on Mixed and augmented reality (ISMAR), 2011.
6. [Handa et al. 2014] A. Handa, T. Whelan, J. McDonald, and A. J. Davison. A Benchmark for RGB-D Visual Odometry, 3D Reconstruction and SLAM. IEEE Int. Conf. on Robotics and Automation, ICRA 2014.
7. [Reitmayr] G. Reitmayr. KFusion github 2011. <https://github.com/GerhardR/kfusion>
8. [Curless and Levoy 1996] B. Curless and M. Levoy. A volumetric method for building complex models from range images. In Proc. Computer graphics and interactive technique. ACM, 1996.
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



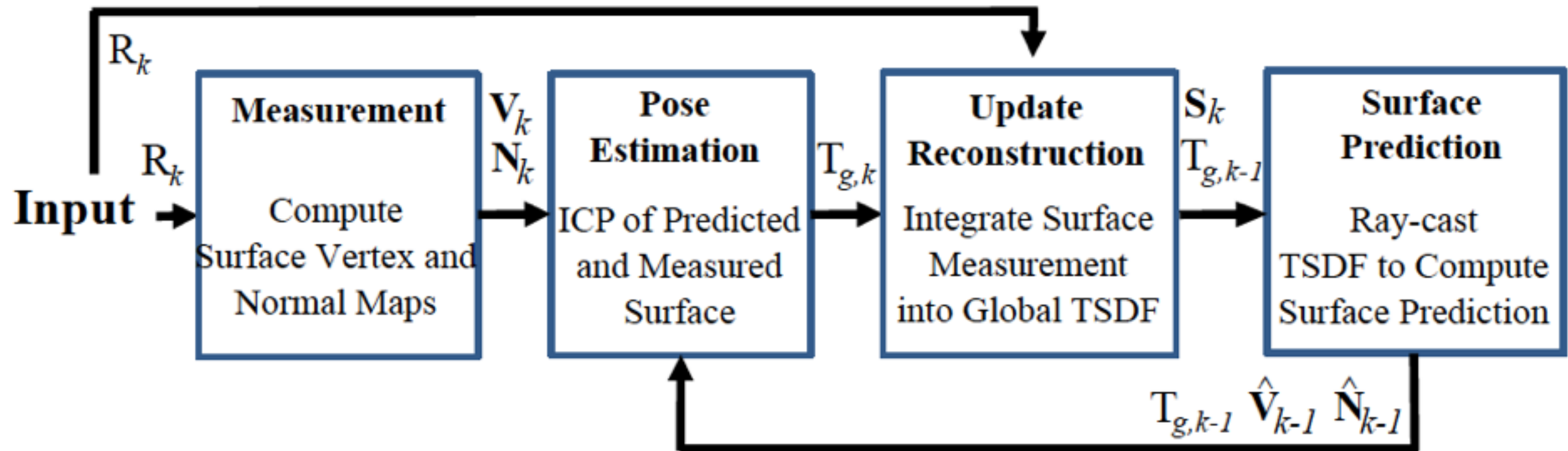
ICP registration



[Rusinkiewicz and Levoy 2001]

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





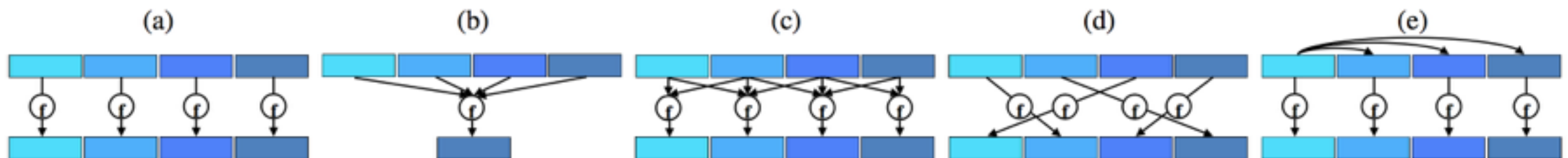
KinectFusion pipeline

- 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



SLAMBench kernels

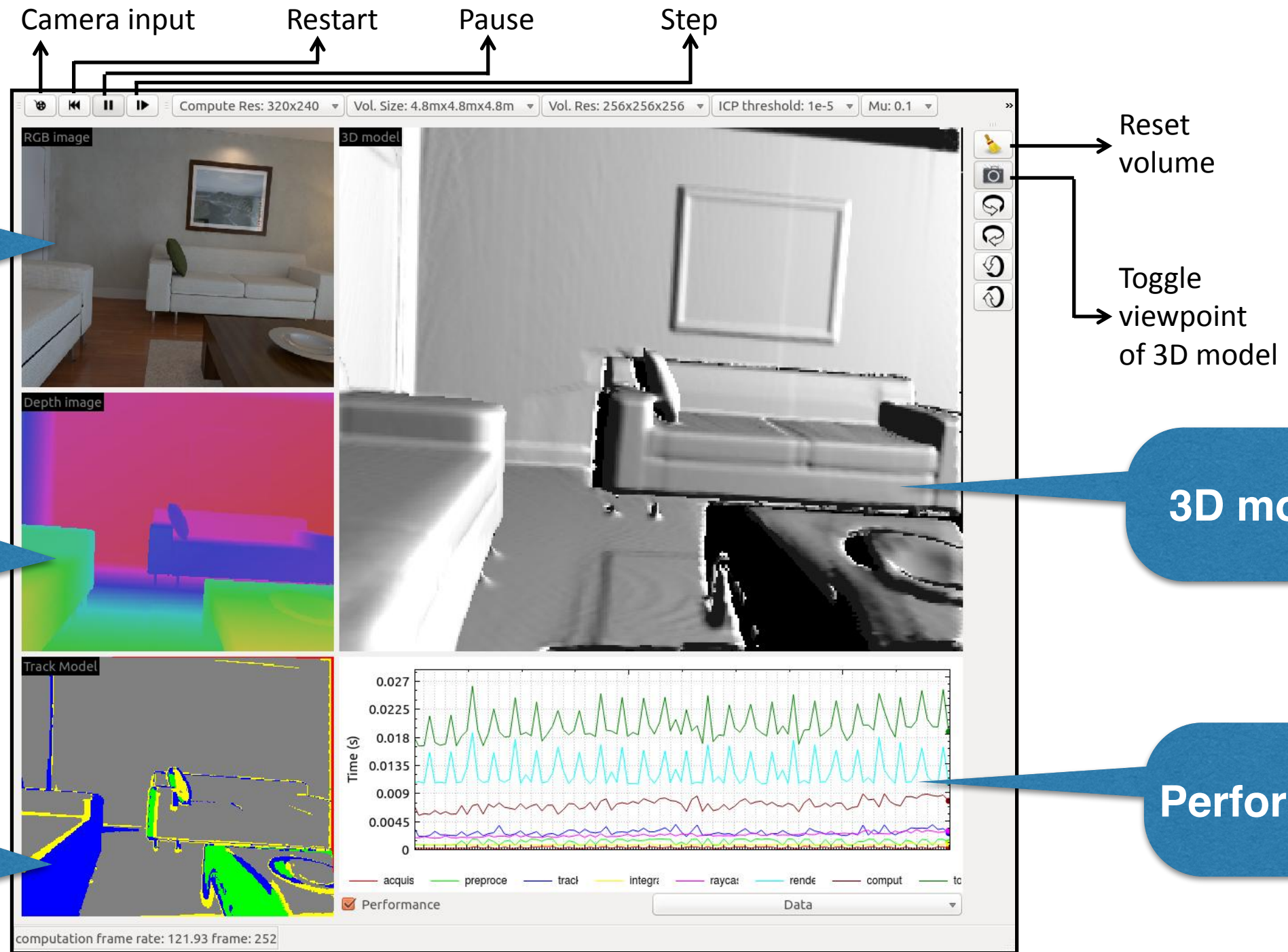
Kernels	Pipeline	Pattern	In	Out	%
acquire	Acquire	n/a	pointer	2D	0.03
mm2meters	Preprocess	Gather	2D	2D	0.06
bilateralFilter	Preprocess	Stencil	2D	2D	33.68
halfSample	Track	Stencil	2D	2D	0.05
depth2vertex	Track	Map	2D	2D	0.11
vertex2normal	Track	Stencil	2D	2D	0.27
track	Track	Map/Gather	2D	2D	4.72
reduce	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.



SLAMBench GUI



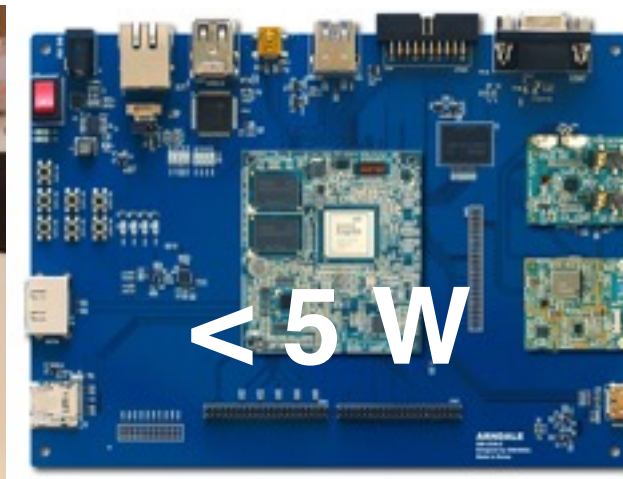
Platforms

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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)	4500	2520	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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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)	4500	2520	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)



Textual User Interface



Easy
run

```
hickory% make 2.openc1.log
LD_PRELOAD=./build/kfusion/thirdparty/liboclwrapper.so ./build/kfusion/kfusion-benchmark-openc1 -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_
enc1.log 2> oclwrapper.2.openc1.log
End of file(garbage found).
cat oclwrapper.2.openc1.log |grep -E ".+ [0-9]+ [0-9]+ [0-9]+" |cut -d" " -f1,4 > kernels.2.openc1.log
./kfusion/thirdparty/checkPos.py benchmark.2.openc1.log livingRoom2.gt.freiburg > resume.2.openc1.log
./kfusion/thirdparty/checkKernels.py kernels.2.openc1.log >> resume.2.openc1.log
hickory%
```

For benchmarking purposes,
SSH and post-processing
tools friendly



Textual User Interface

Easy
run

Raw
data

For benchmarking purposes,
SSH and post-processing
tools friendly



Textual User Interface

Easy
run

Raw
data

Sum
up

For benchmarking purposes,
SSH and post-processing
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hickory%
```

frame	acquisition	preprocessing	tracking	integration	raycasting	rendering	computation	total	X	Y	Z	tracked	inte
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	0.0000	0.000000	0.000000	0	1
3	0.002663	0.000335	0.000905	0.000467	0.000604	0.000219	0.002311	0.005193	0.0000	0.000000	0.000000	0	1

```
1 Get kfusion output data.
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7 Working position is : 880
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9 Shift kfusion trajectory...
10
11 A detailed statistical analysis is provided.
12 All durations are in seconds and the absolute trajectory error (ATE) is in centimeters.
13 ATE Min : 0.000000 Max : 0.049309 Mean : 0.020662 Total : 18.18239335
14 acquisition Min : 0.000056 Max : 0.009033 Mean : 0.002044 Total : 1.80289800
15 computation Min : 0.001701 Max : 0.009234 Mean : 0.005894 Total : 5.19872500
16 integration Min : 0.000001 Max : 0.000821 Mean : 0.000258 Total : 0.22773500
17 preprocessing Min : 0.000284 Max : 0.001884 Mean : 0.000441 Total : 0.38904600
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19 rendering Min : 0.000201 Max : 0.003452 Mean : 0.000572 Total : 0.50420900
20 total Min : 0.003882 Max : 0.020054 Mean : 0.008510 Total : 7.50584700
21 tracking Min : 0.000903 Max : 0.006743 Mean : 0.003850 Total : 3.39543600
22 Get SlamBench data.
23 ResetVolume Count : 1 Min : 401056 Max : 401056 Mean : 401056.000000 Total : 401056
24 bilateral_filter Count : 882 Min : 139520 Max : 205632 Mean : 159880.199546 Total : 141014336
25 depth2vertex Count : 2646 Min : 5440 Max : 48384 Mean : 10585.167045 Total : 28008352
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29 raycast Count : 879 Min : 435584 Max : 3284768 Mean : 1323028.423208 Total : 1162941984
30 reduce Count : 12117 Min : 31488 Max : 523488 Mean : 138305.687546 Total : 1675850016
31 renderDepth Count : 882 Min : 9568 Max : 39904 Mean : 12002.975057 Total : 10586624
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33 renderVolume Count : 221 Min : 479840 Max : 3143200 Mean : 1338055.819005 Total : 295710336
34 track Count : 12117 Min : 13472 Max : 129344 Mean : 51505.231988 Total : 624088896
35 vertex2normal Count : 2646 Min : 8544 Max : 73504 Mean : 22275.362056 Total : 58940608
```

Textual User Interface

Easy
run

Raw
data

Sum
up

High-level blocks statistics

ses,
g



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hickory% make 2.openc1.log
LD_PRELOAD=./build/kfusion/thirdparty/liboc1wrapper.so ./build/kfusion/kfusion-benchmark-openc1 -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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hickory%
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3	0.002663	0.000335	0.000905	0.000467	0.000004	0.000219	0.002311	0.005193	0.0000	0.000000	0.000000	0	1

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Textual User Interface

Easy
run

Raw
data

Sum
up

High-level blocks statistics

Kernels statistics

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35 vertex2normal Count : 2646 Min : 8544 Max : 73504 Mean : 22275.362056 Total : 58940608
```



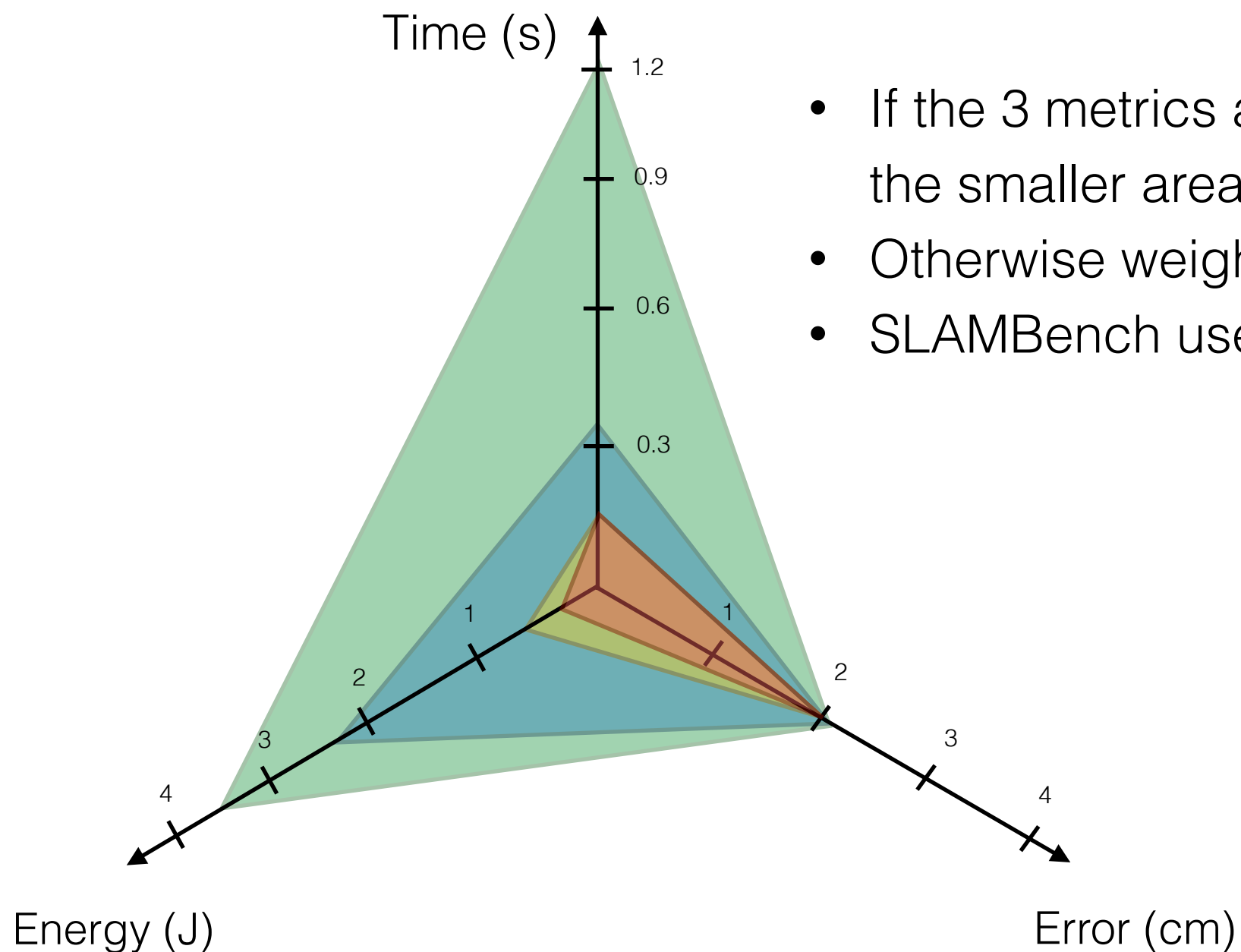
Conclusions

- **First vision benchmark** for performance, energy and accuracy
- **Fair comparison** of accelerators, tools and novel algorithms in SLAM
- "Performance" results on state-of-the-art desktop, laptop and embedded:
 - 4 configurations super real-time FPS (**135 FPS** on TITAN)
 - Tegra K1 achieves **22 FPS**
 - GPGPU for SLAM leads to high-efficiency
 - ODROID-XU3 achieves **5.5 FPS** for **2.1 Watts**
- This research paves the way for **systematic holistic evaluation**



“Performance” trade-off

Language	Configuration	Error (cm)	Time (s)	Time (FPS)	Energy (J)	Area	Colour
C++ OpenMP OpenCL OpenCL	A15	2.06	1.23	0.81	3.47	4.4	
	A15 + A7	2.06	0.35	2.8	2.67	2.8	
	GPU + A15 + A7	2.01	0.18	5.5	0.58	0.6	
	GPU + A7	2.01	0.18	5.5	0.38	0.4	



- If the 3 metrics are equally important:
the smaller area the better: $4.4 > 2.8 > 0.6 > 0.4$
- Otherwise weighted area
- SLAMBench use case: 52% energy improvement

Copyrights

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