A performance, energy and accuracy aware benchmarking methodology for robot vision

- SLAMBench -

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In collaboration with:
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Imperial College London

EPSRC
Engineering and Physical Sciences Research Council

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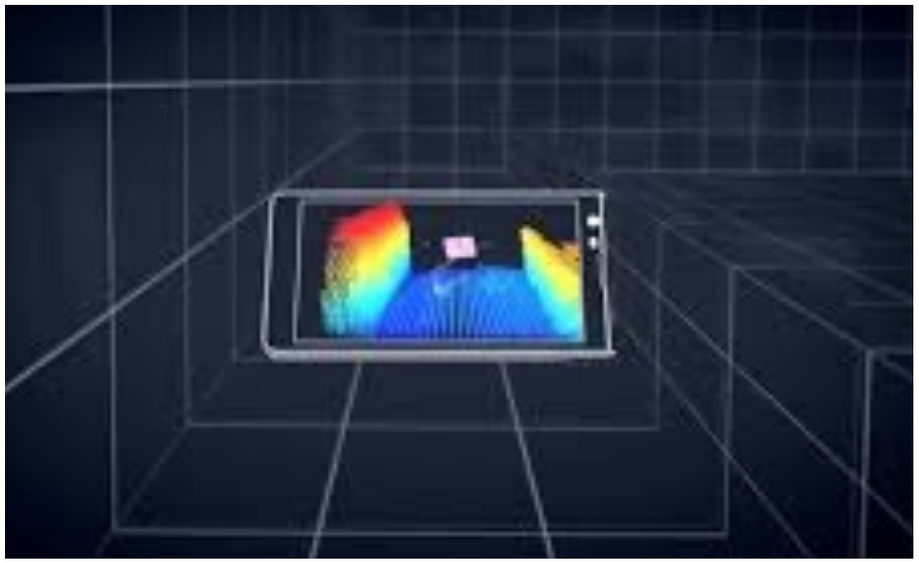
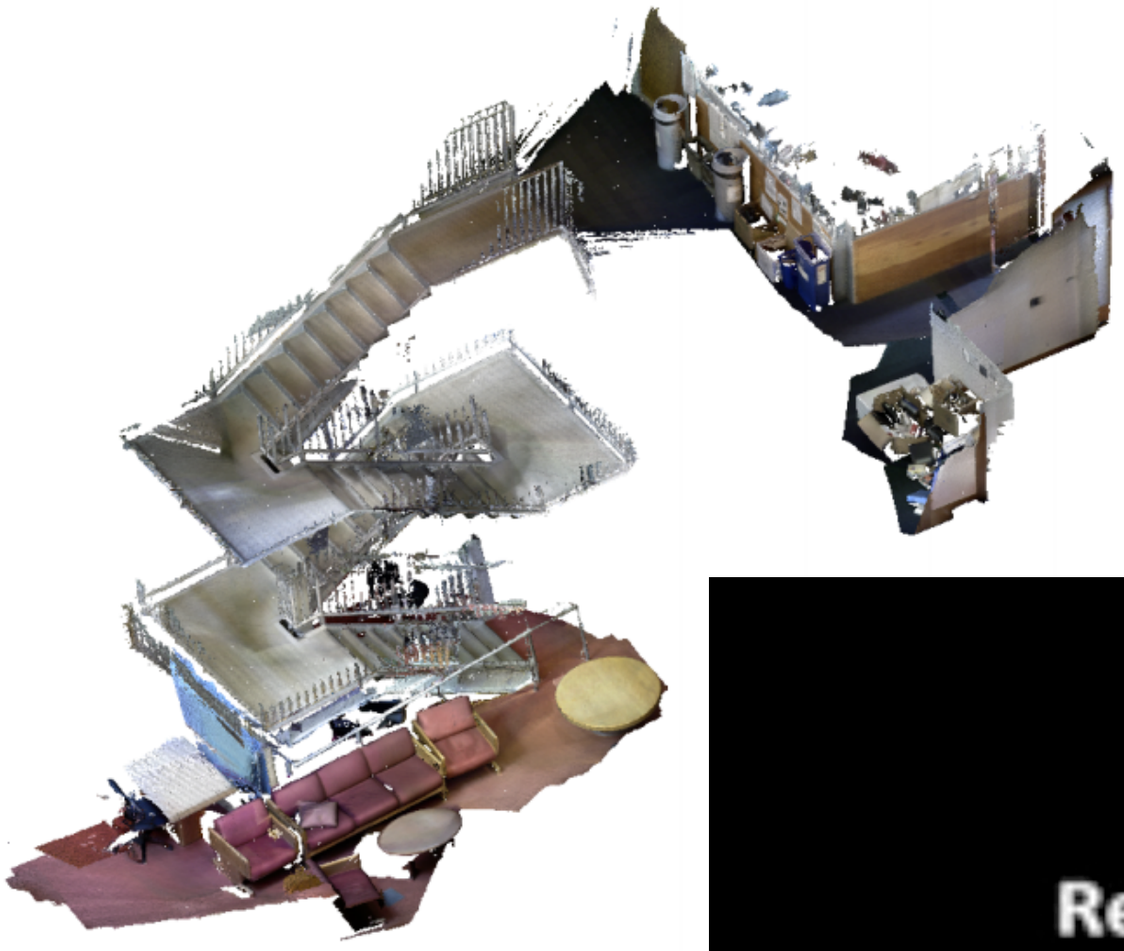
Simultaneous localisation and mapping (SLAM)

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

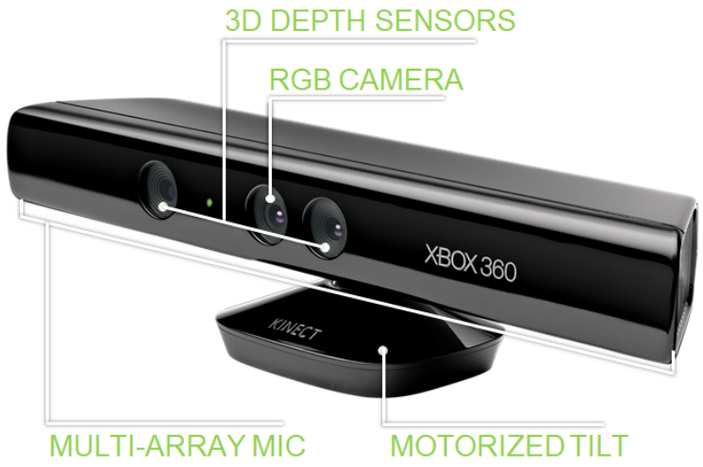


Video:
Dyson 360 Eye

Simultaneous localisation and mapping (SLAM)

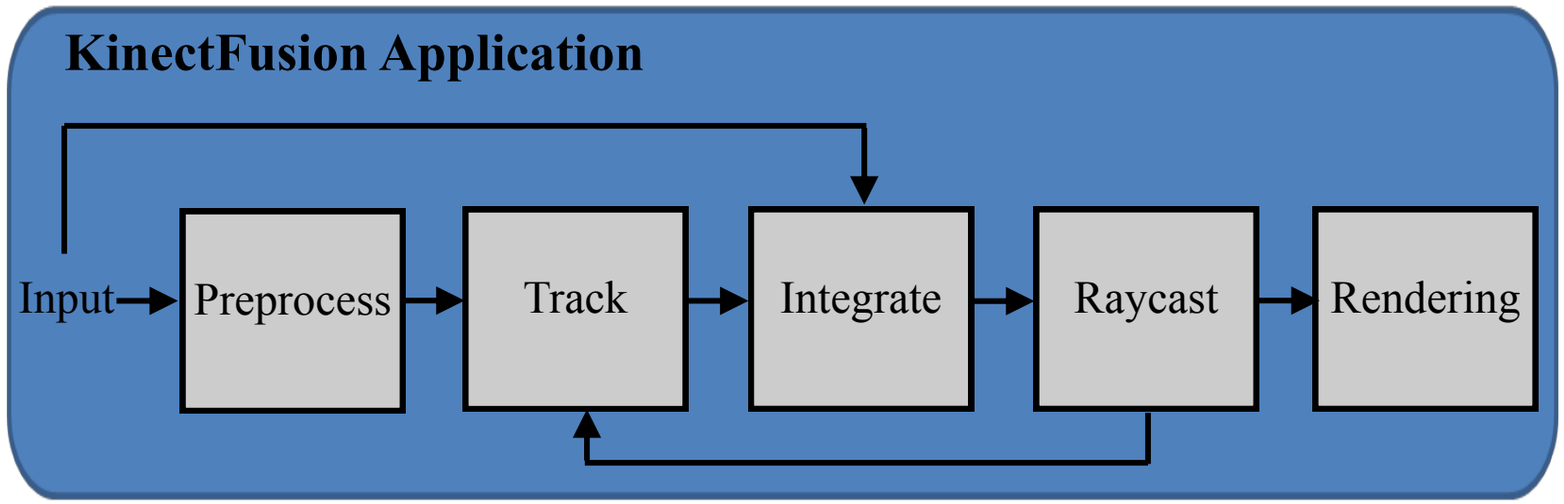


[Whelan et al. 2012]



Video:
[Newcombe et al. ISMAR 2011]

KinectFusion SLAM implementation



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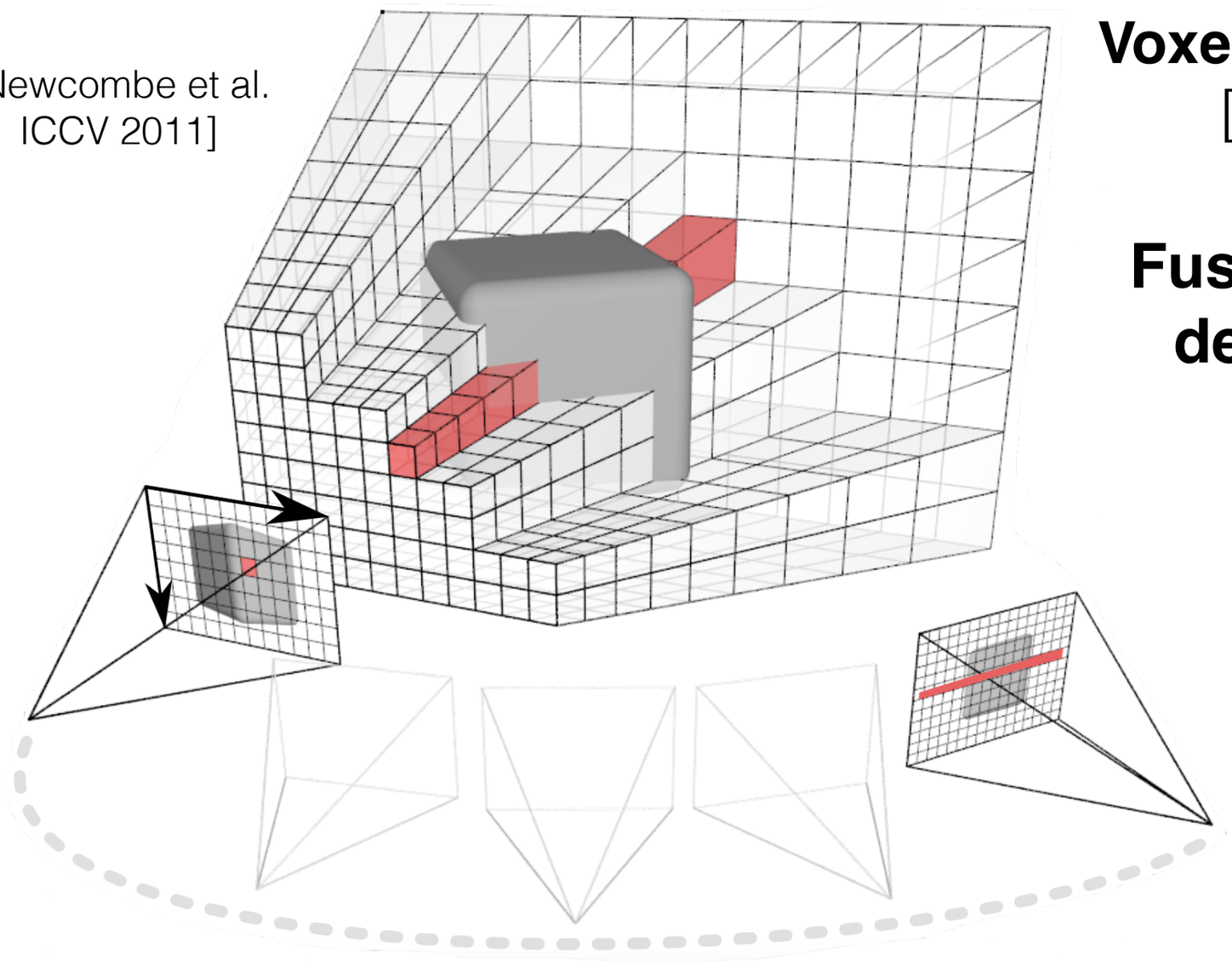


Voxel grid represents **3D surfaces**
[Curless and Levoy 1996]

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

3D surfaces recovered by **raycasting**

Localisation (or tracking): estimates the camera pose

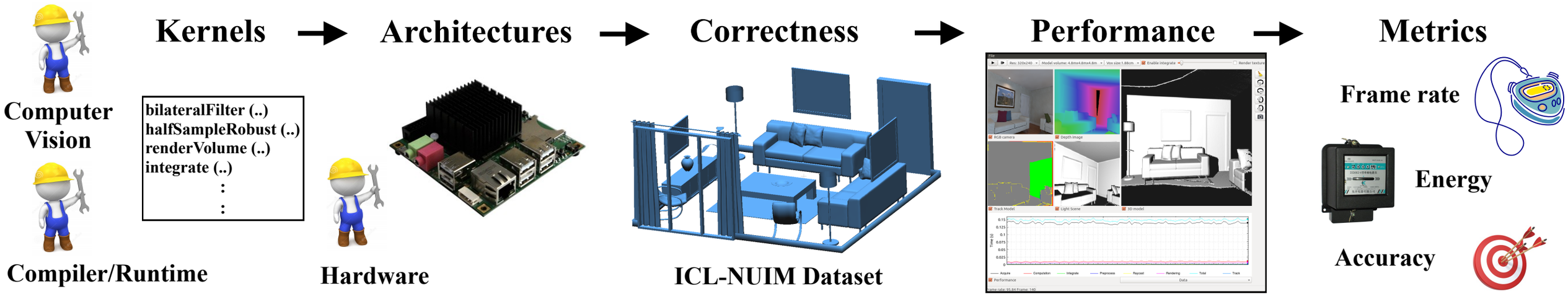
Outline

- Simultaneous localisation and mapping (SLAM) application
- **Performance metrics in SLAM**
- From desktop to embedded
- SLAMBench

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)

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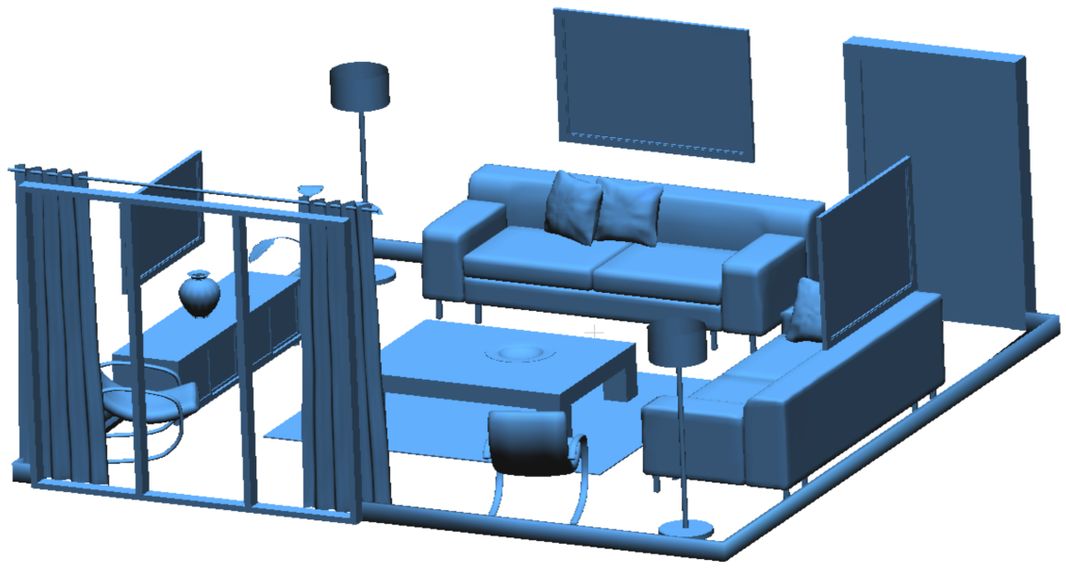
Need for reproducibility and accuracy check
Pre-recorded scenes
Process-every-frame mode
ICL-NUIM dataset (*frames and* ground truth)

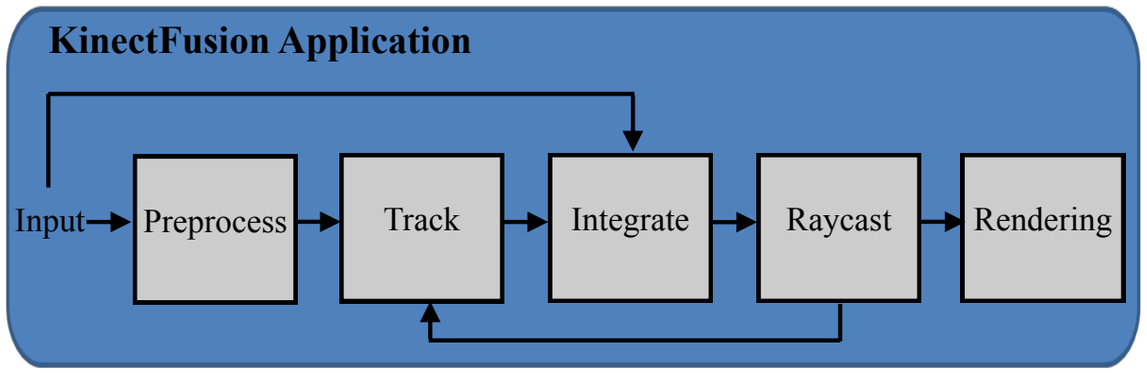
ICL-NUIM dataset

- 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



high-level blocks composed by 14 lower level kernels based on [Reitmayr 2011]

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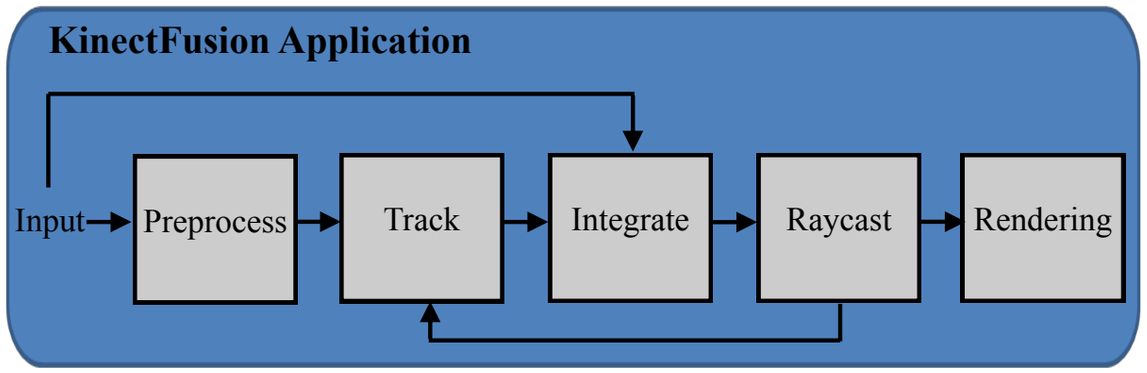

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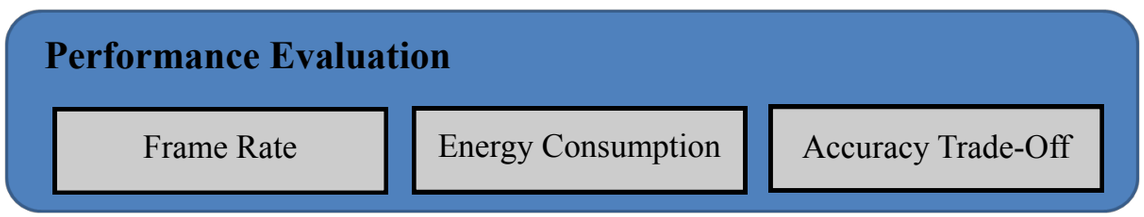
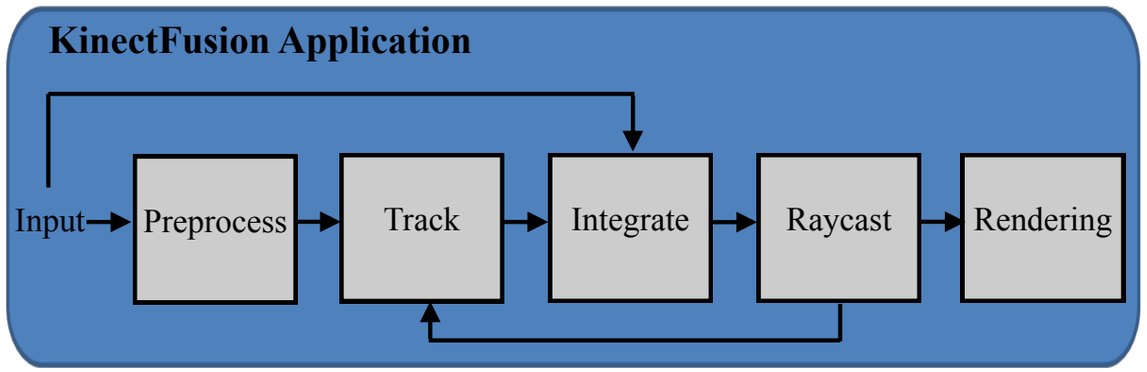


3 metrics:
execution time/energy/accuracy

SLAMBench framework



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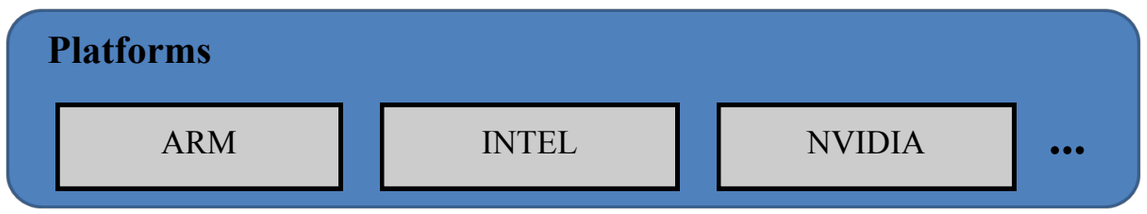
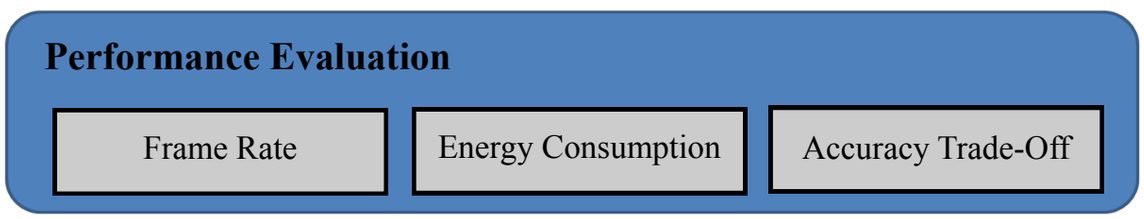


desktop, mobile, embedded: multi-core and many-core



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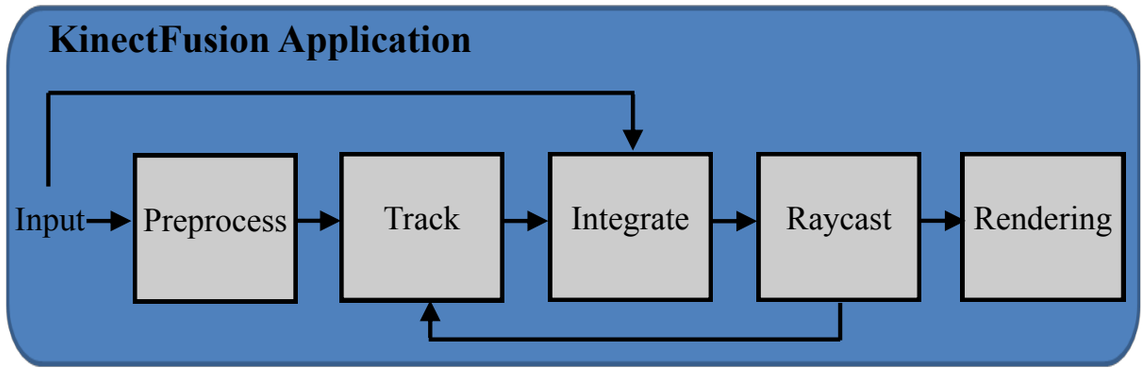

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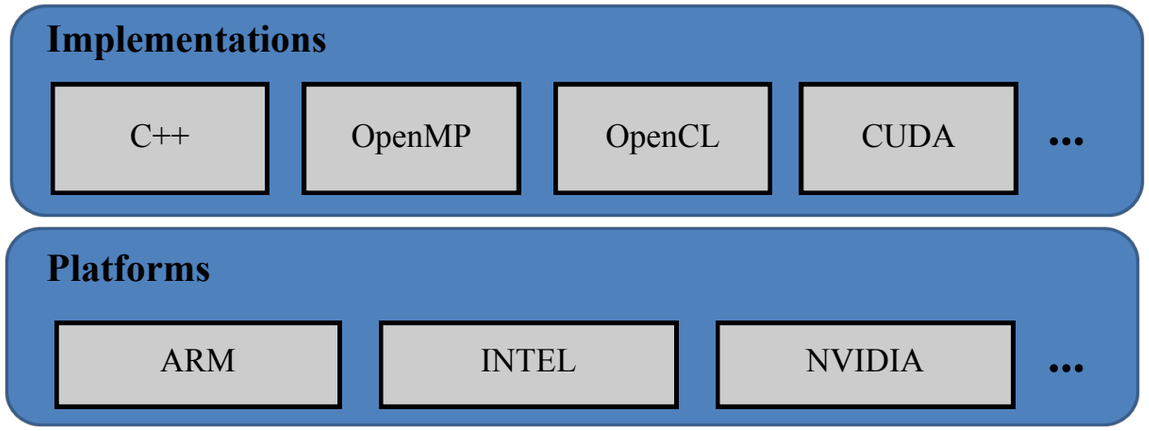
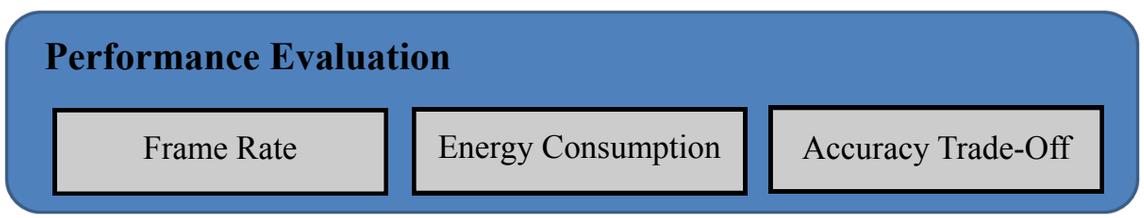


wide range of languages

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



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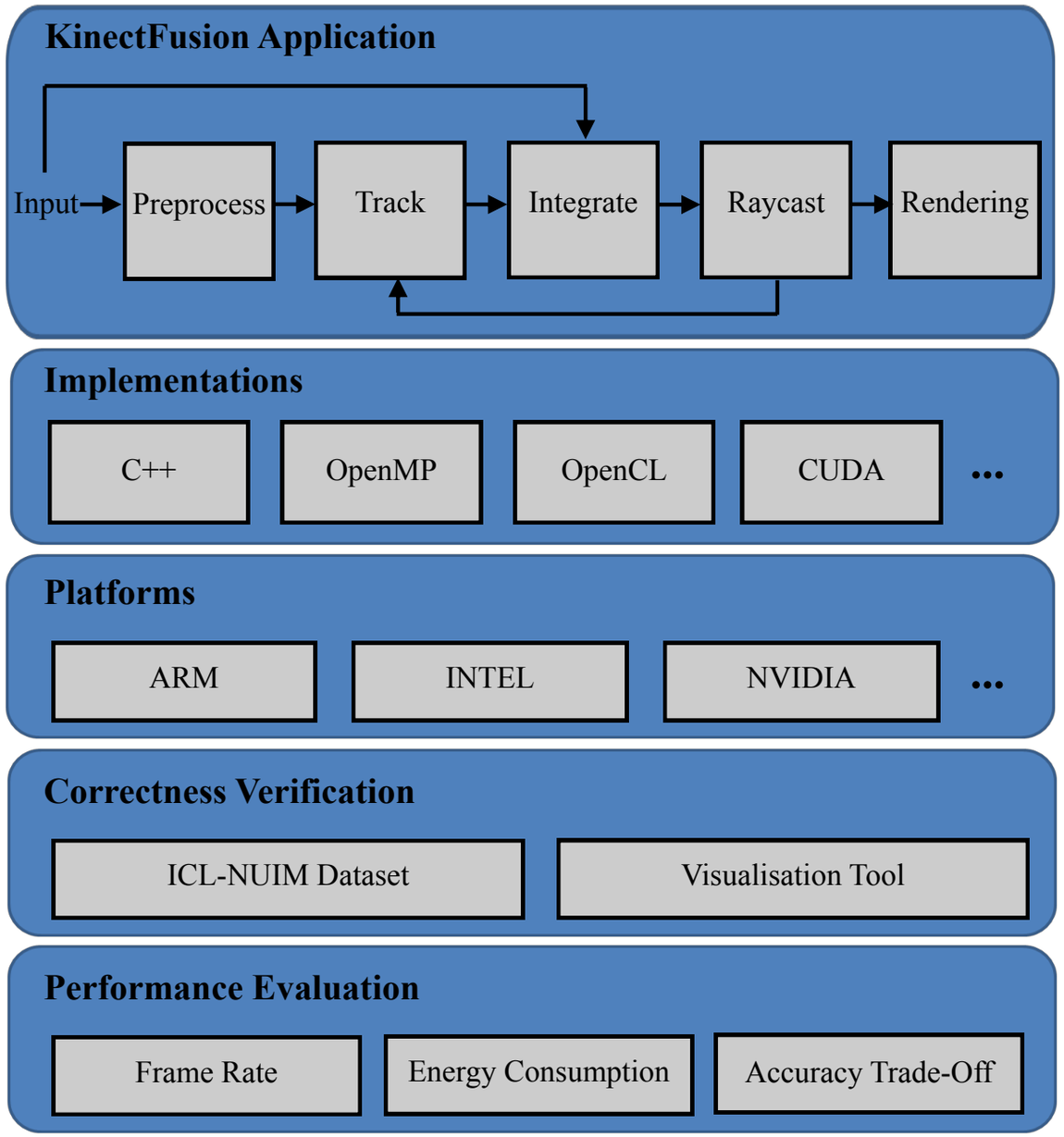

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wide range of languages

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

integrated verification/visualisation

3 metrics: execution time/energy/accuracy

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- Simultaneous localisation and mapping (SLAM) application
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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

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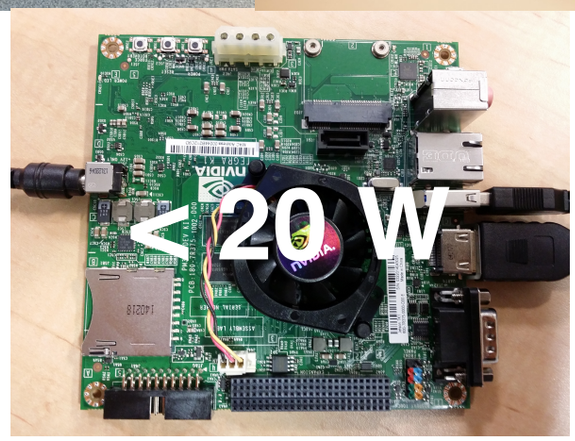

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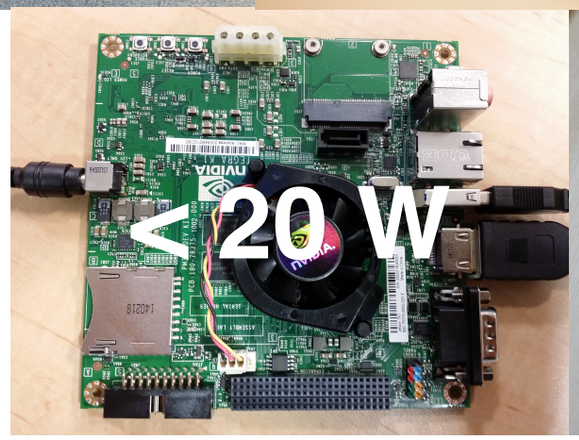

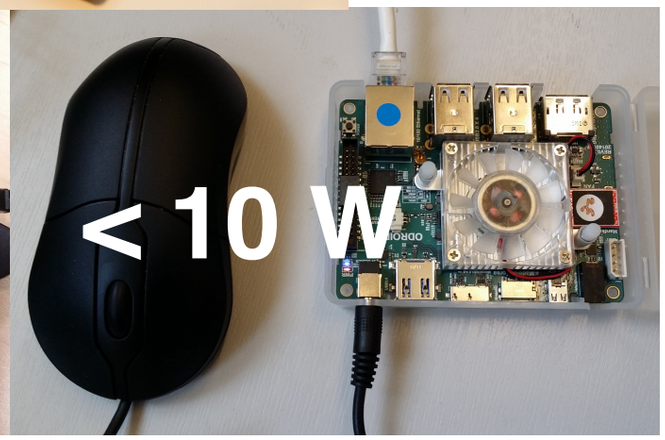

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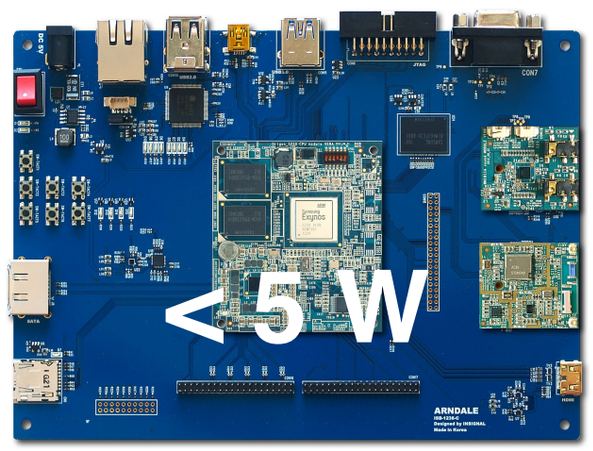

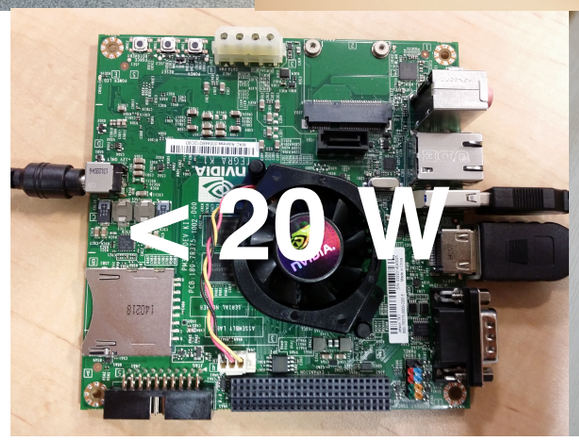

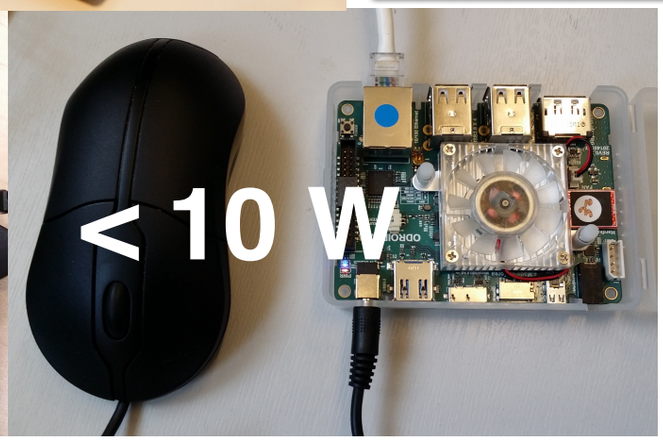

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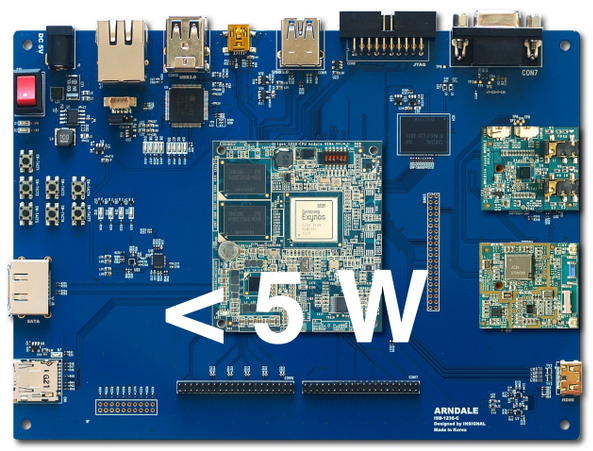

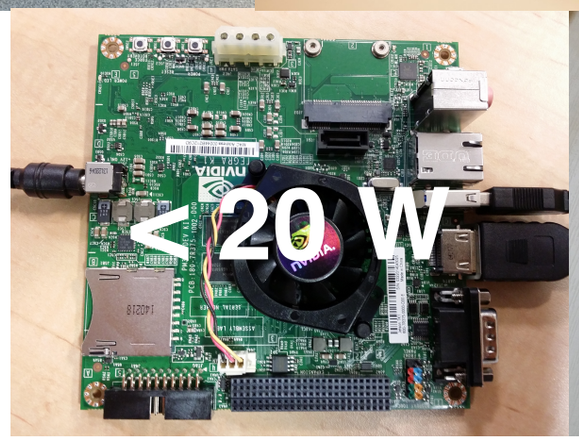

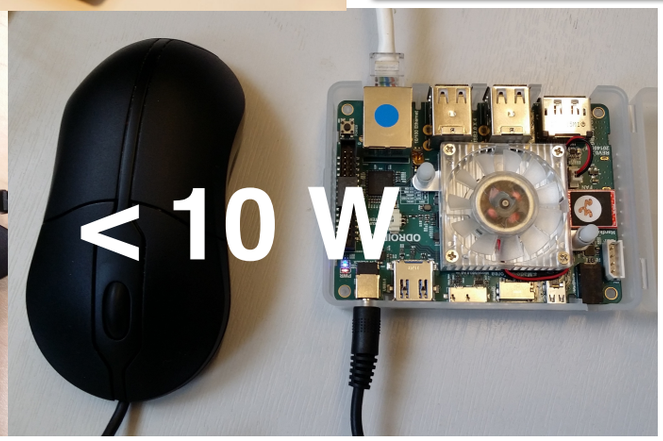

“Performance”: accuracy

Absolute trajectory error (ATE) - 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

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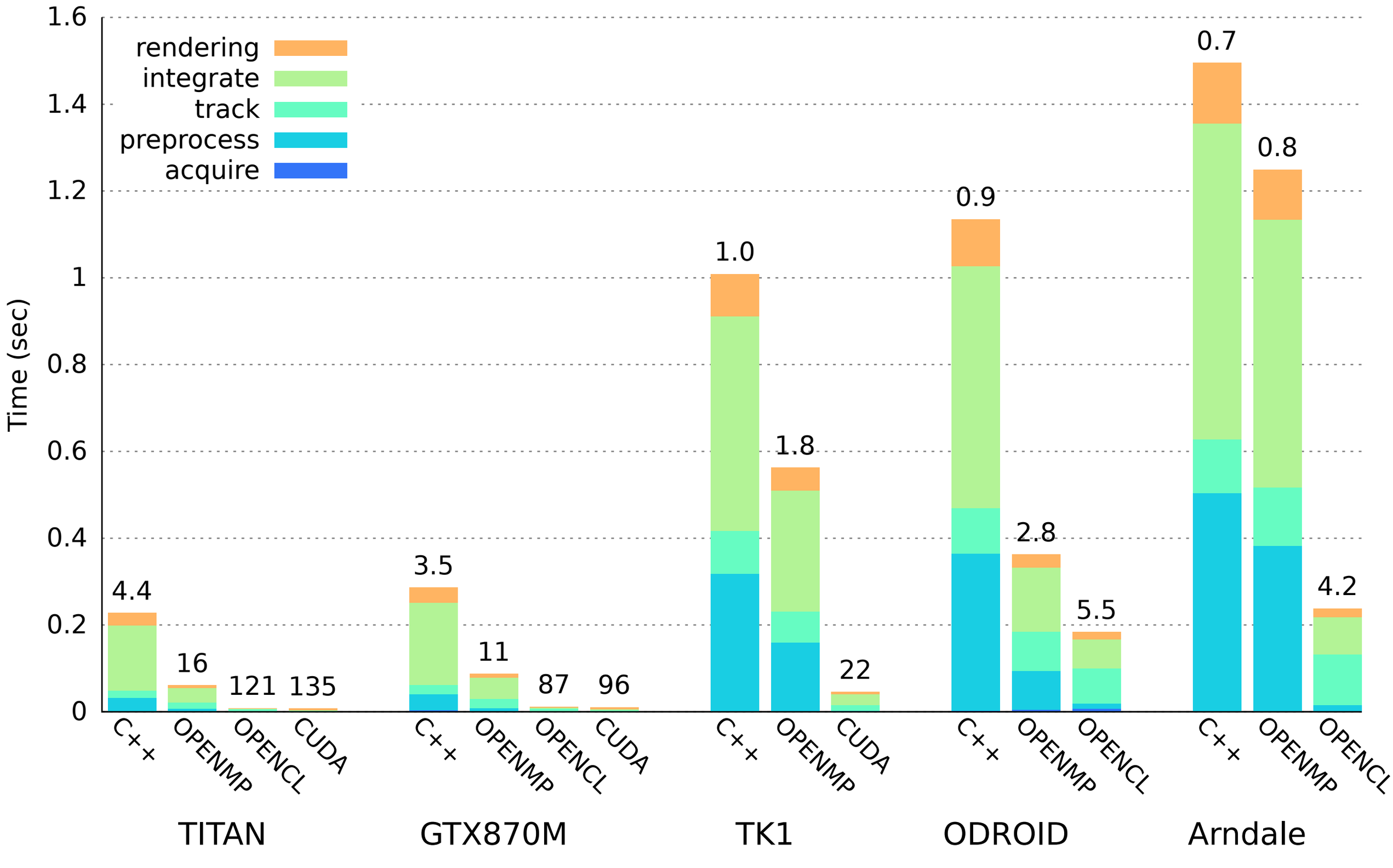
“Performance”: execution time

Mean time per frame (lower is better)



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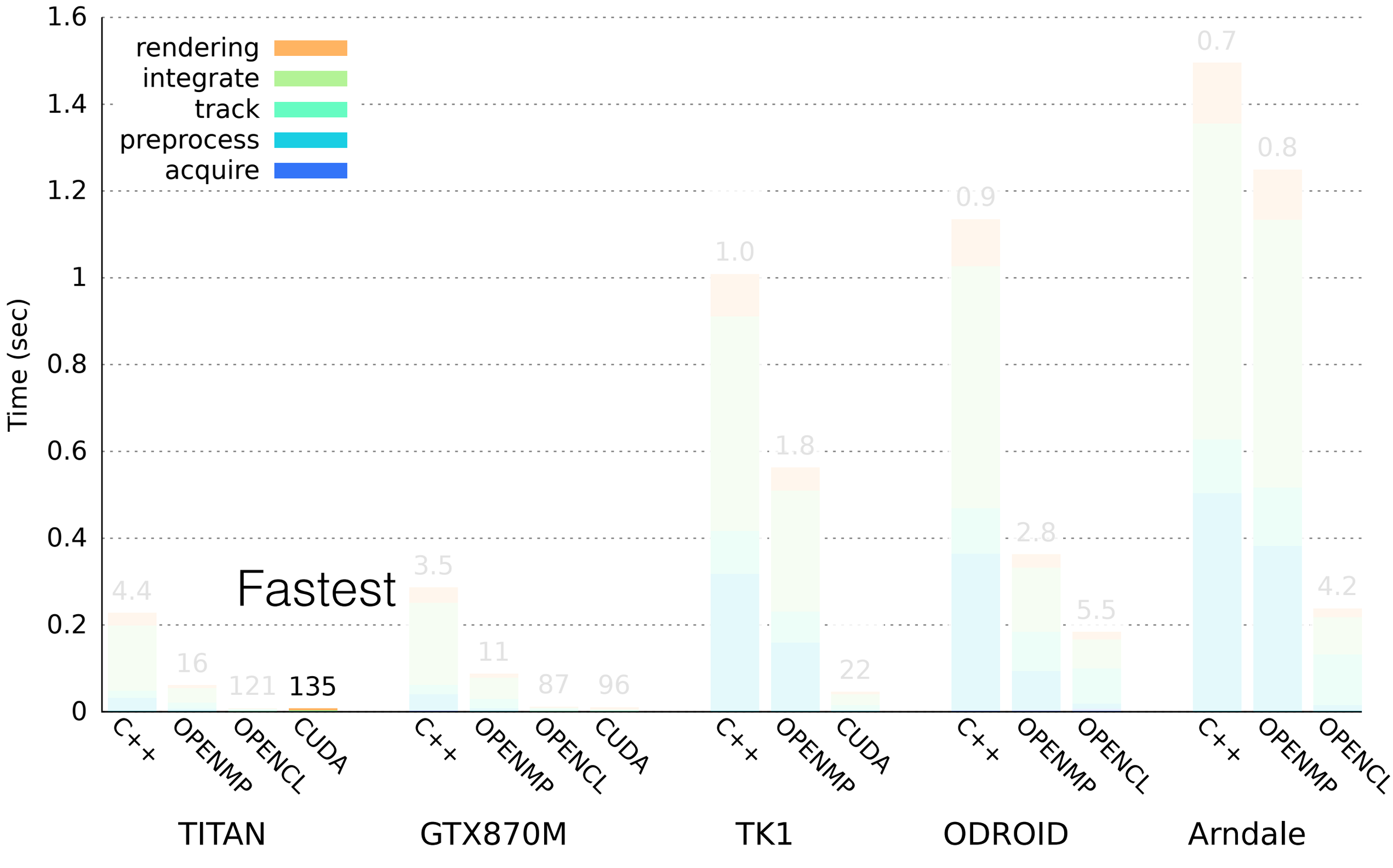

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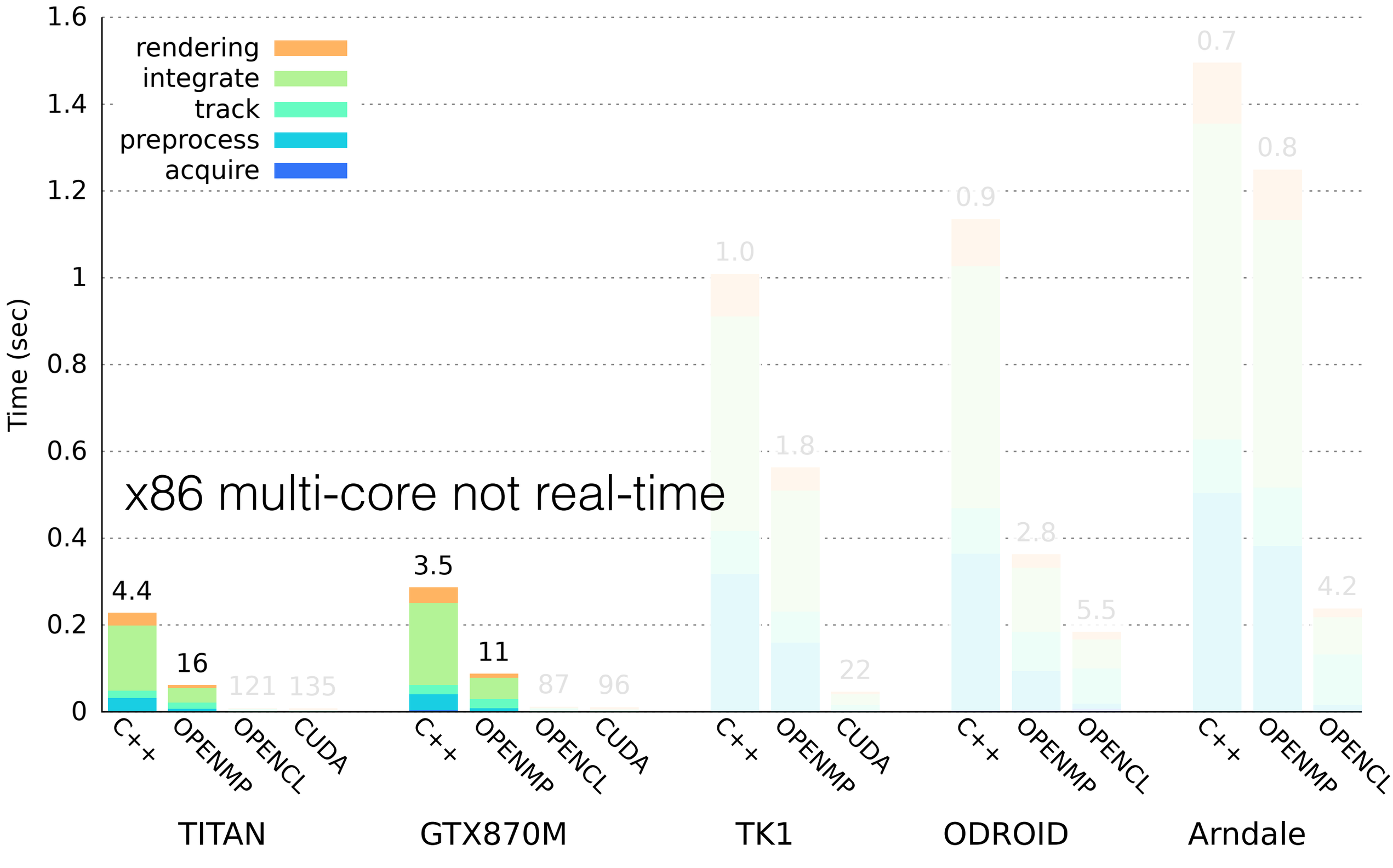

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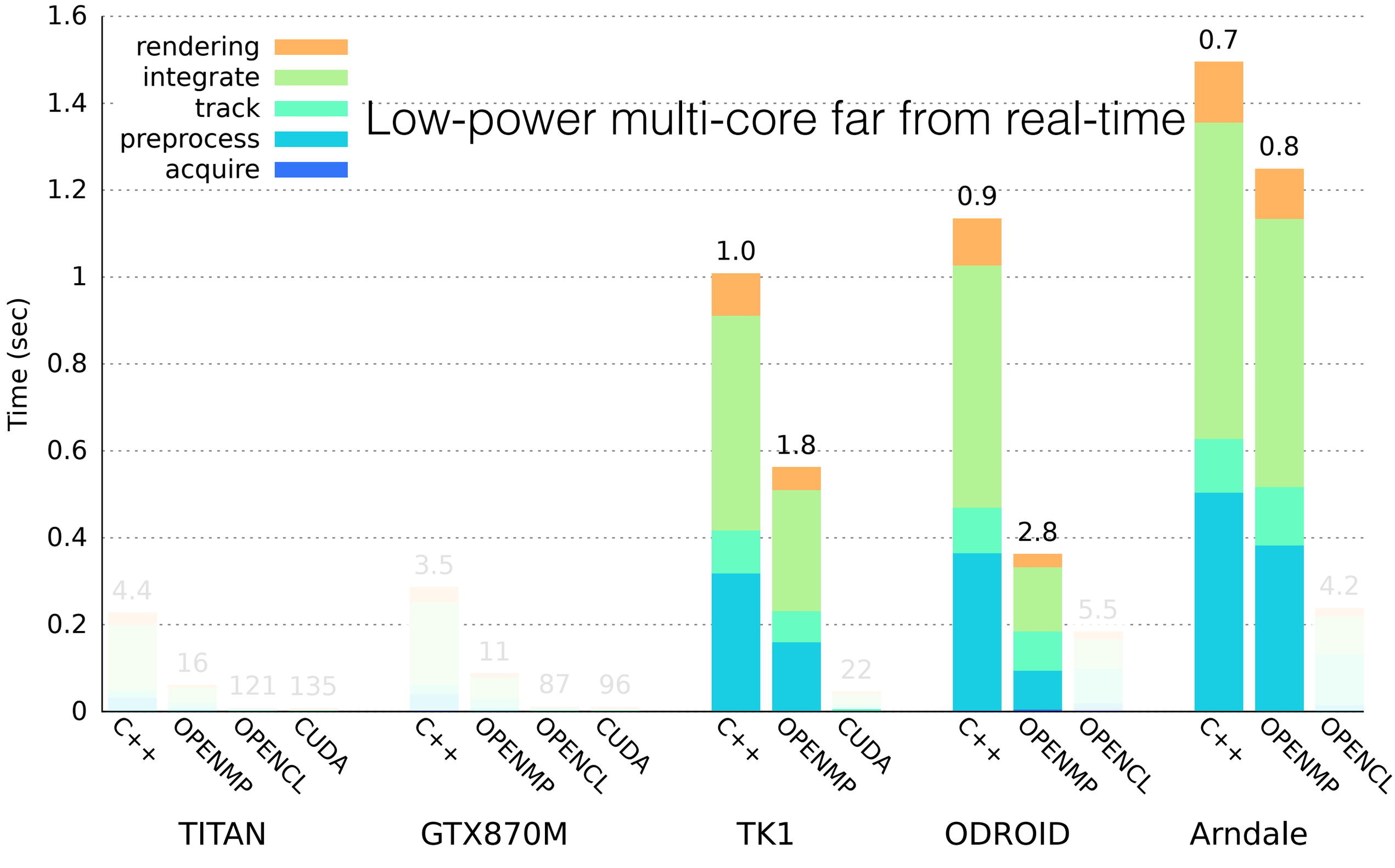

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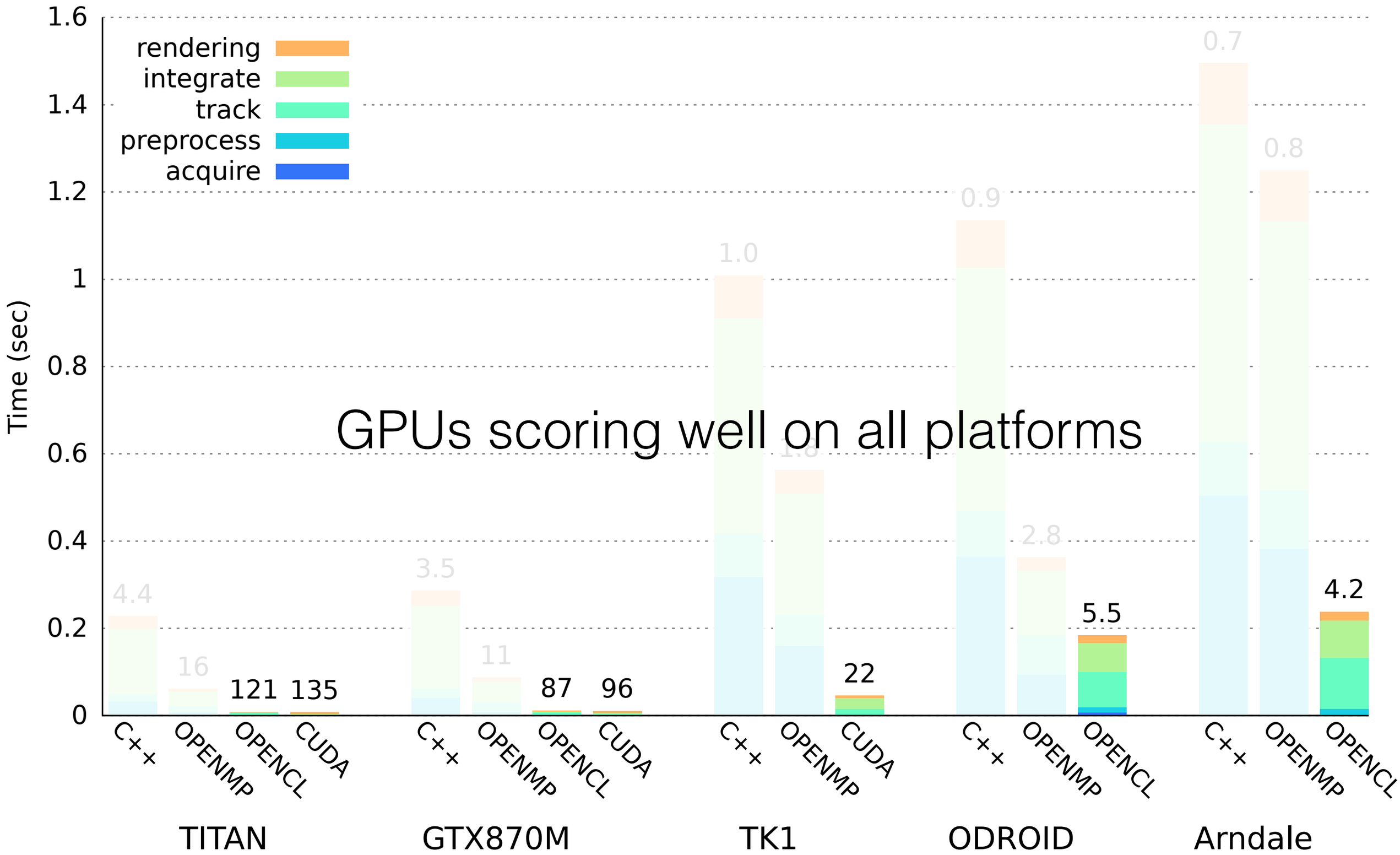

GPUs scoring well on all platforms

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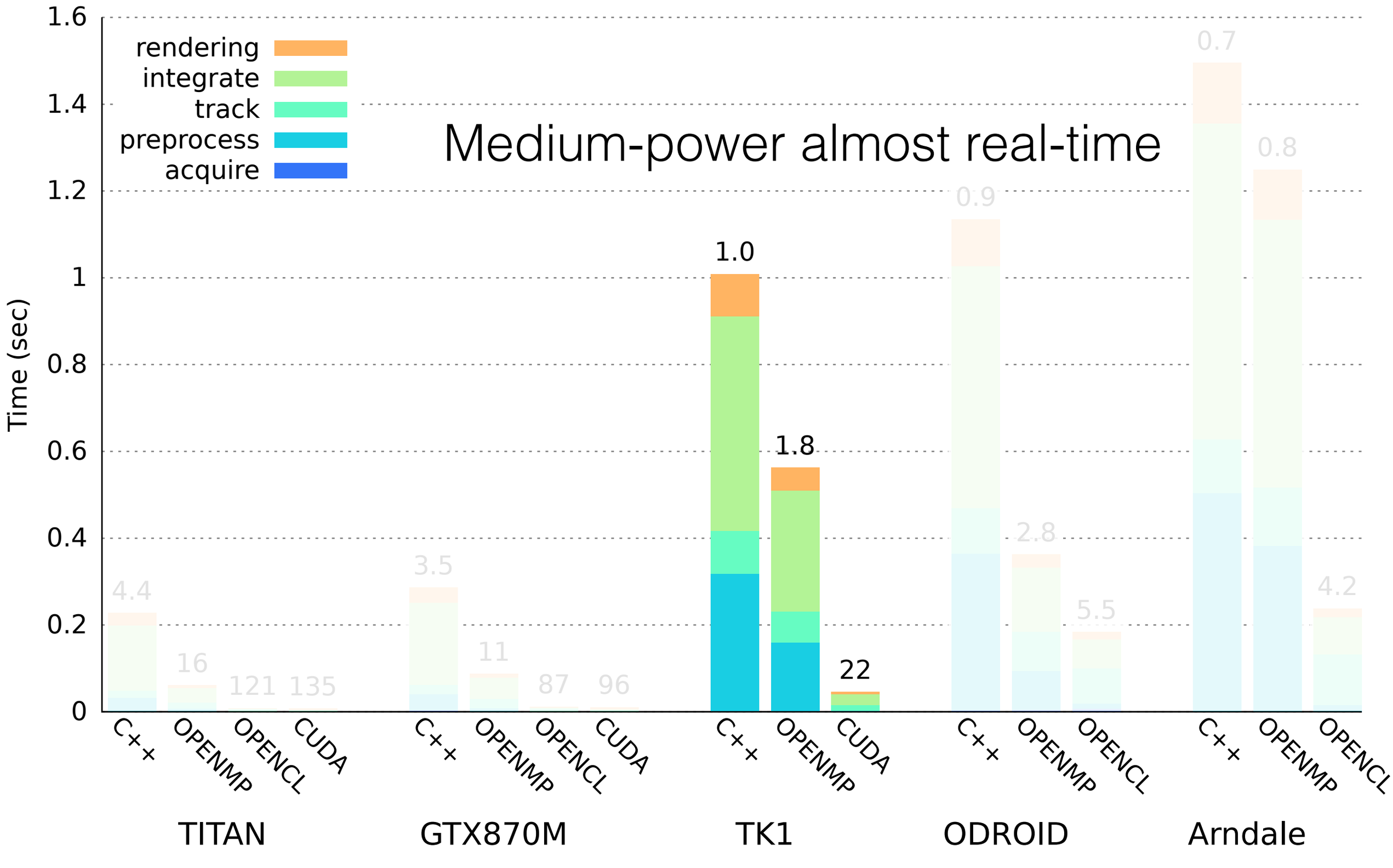

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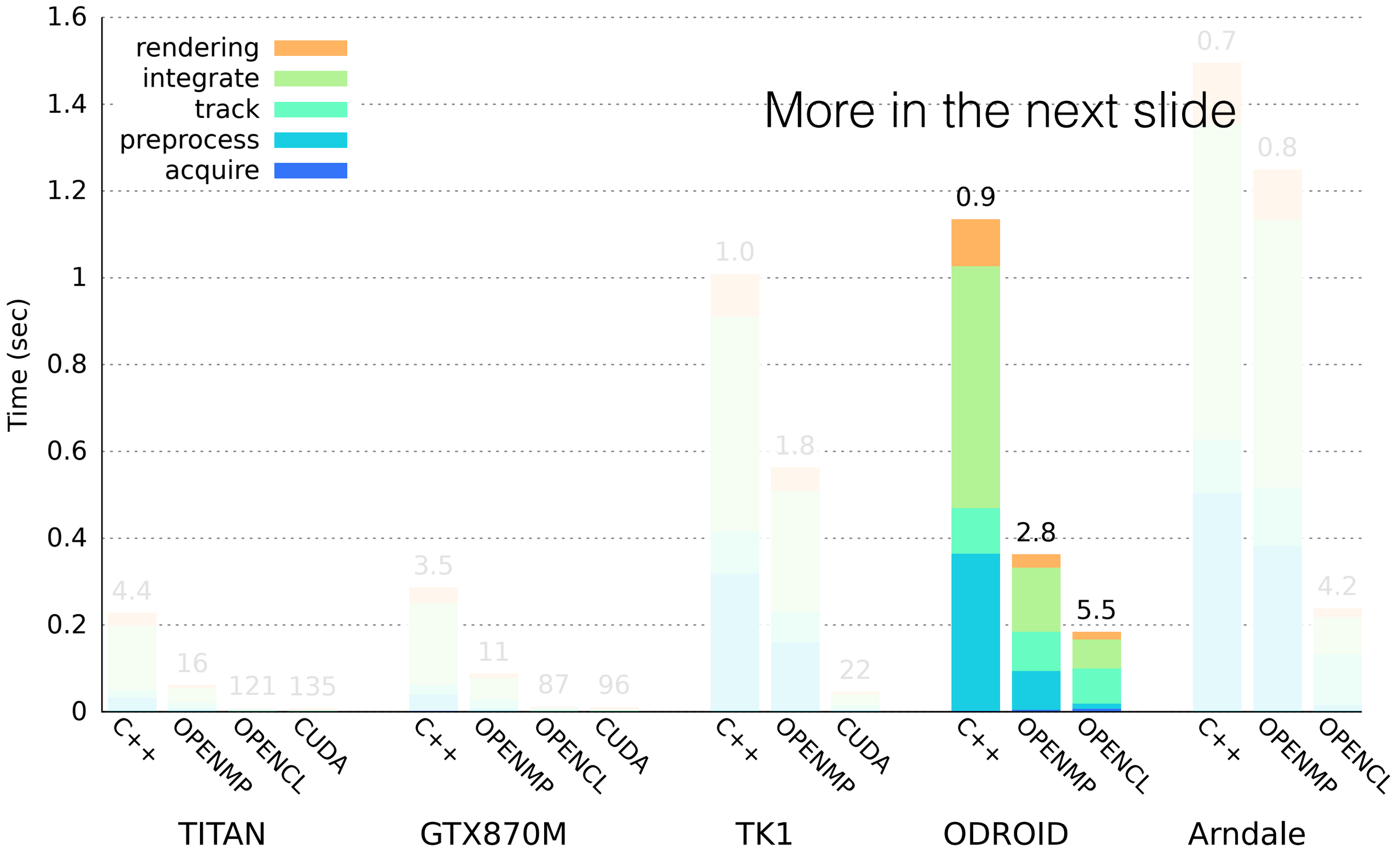
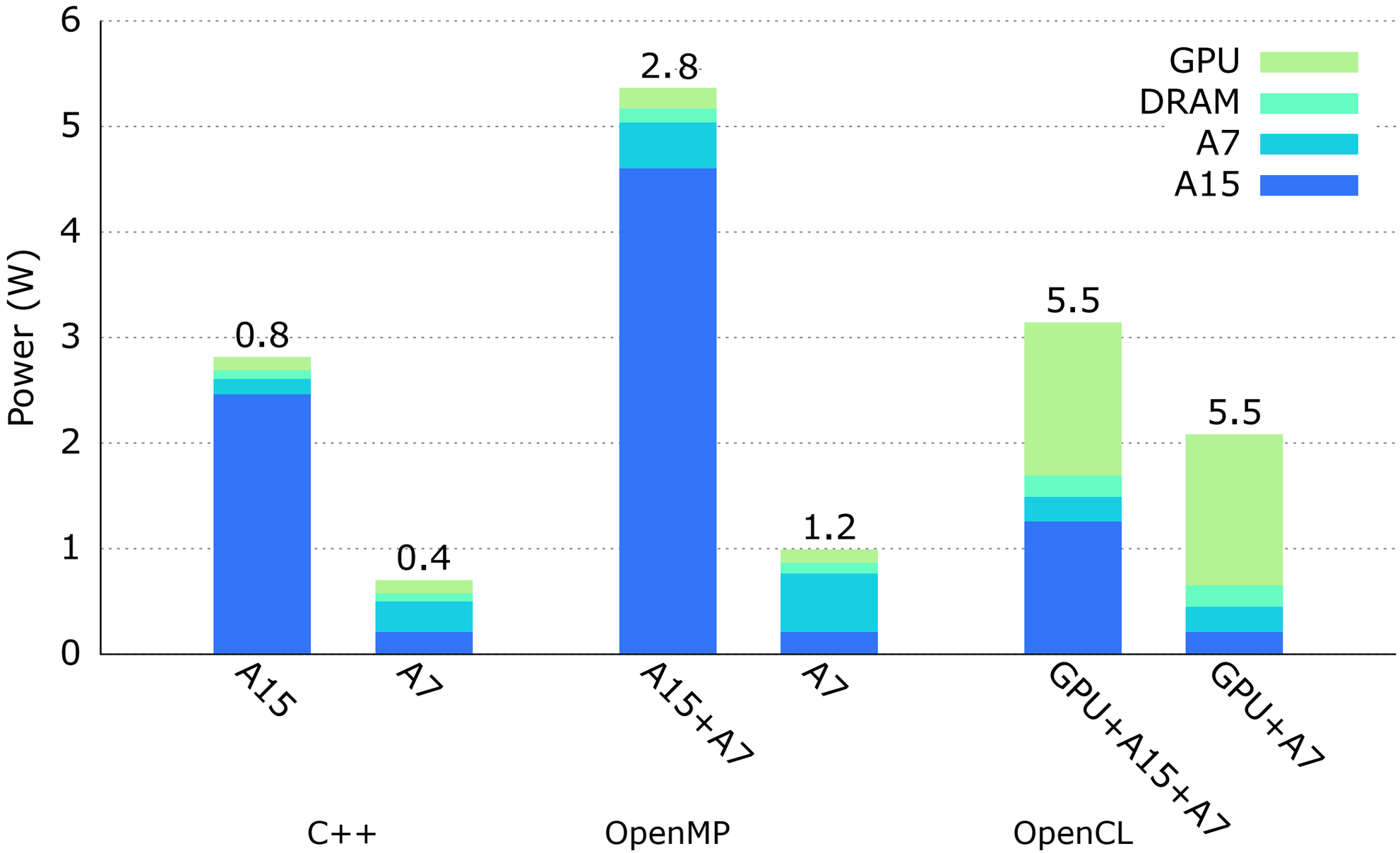


“Performance” power (ODROID-XU3)

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



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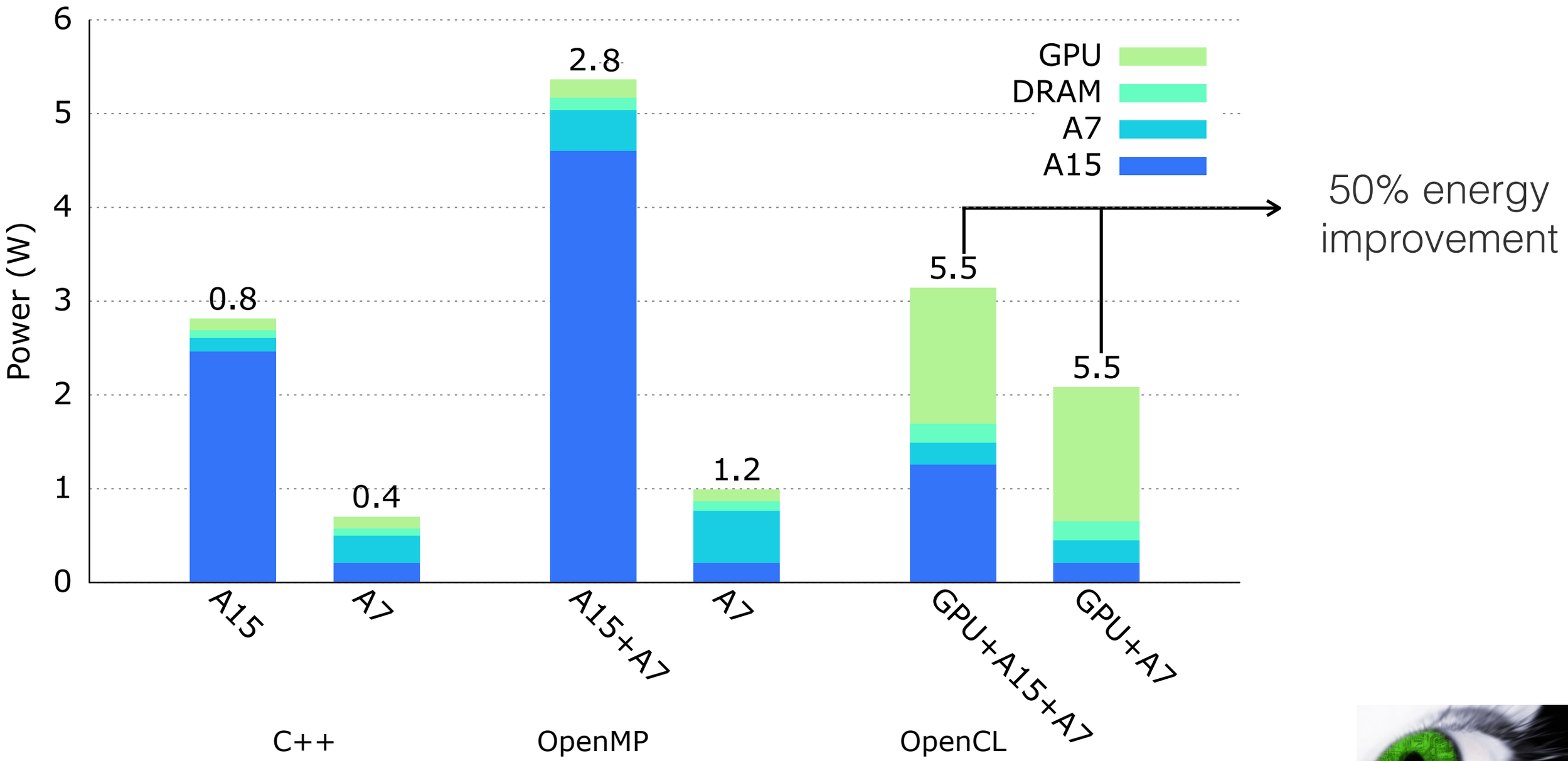

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SLAMBench today

- Publicly released 13/11/2014 (300 downloads today): http://apt.cs.manchester.ac.uk/projects/PAMELA/tools/SLAMBench/

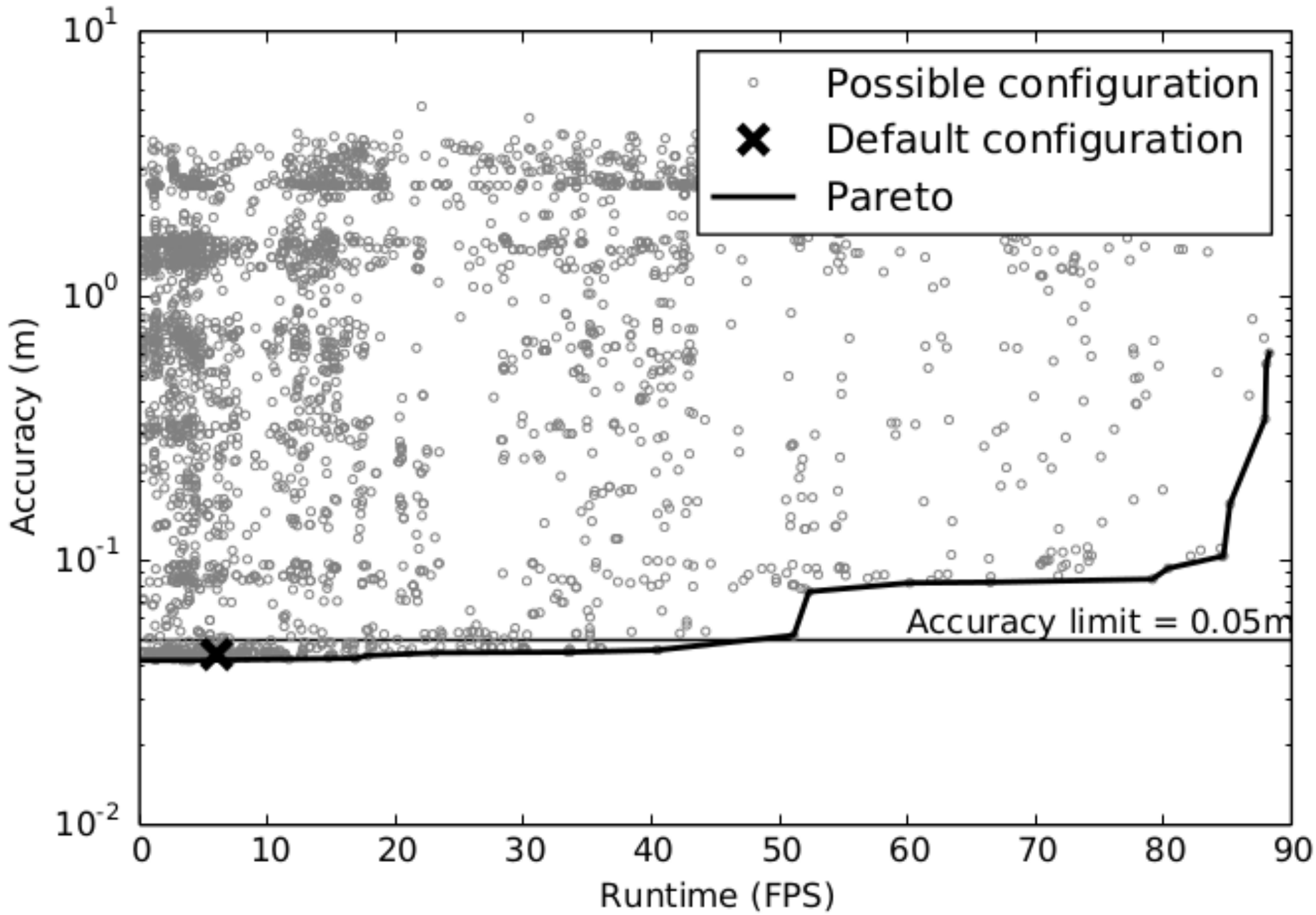
- "*Introducing SLAMBench, a performance and accuracy benchmarking methodology for SLAM"*, Nardi et al., IEEE Int. Conf. on Robotics and Automation (ICRA), May 2015. Available: arxiv.org/abs/1410.2167

- Early adopters (vanity metric):
  - **CV**: Amazon, Microsoft, Toyota, Ocado, Magic Leap, FutureBots, Cnaptic
  - **Compiler/runtime**: ARM, Codeplay and many universities
  - **Architecture**: NVIDIA, Intel, IBM, TI, Movidius, Samsung

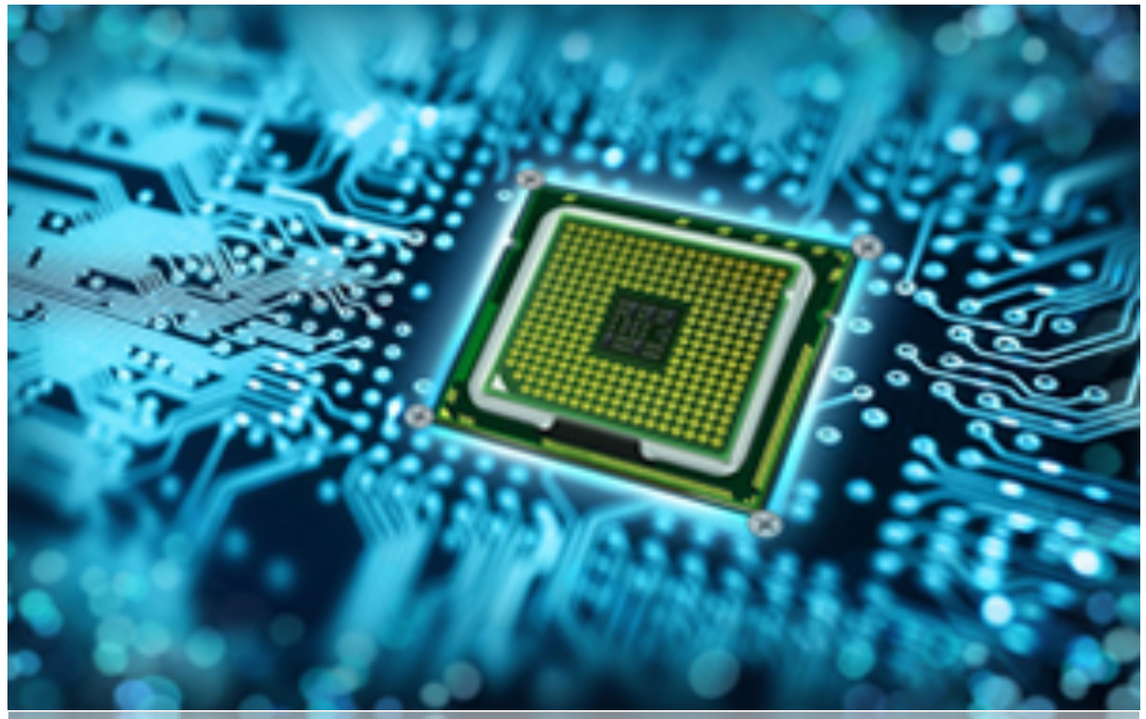
ATE enables aggressive design-space exploration (DSE):

- Algorithmic, compiler and hardware parameters
- Huge space, use machine learning, i.e. active learning

An example: algorithmic DSE

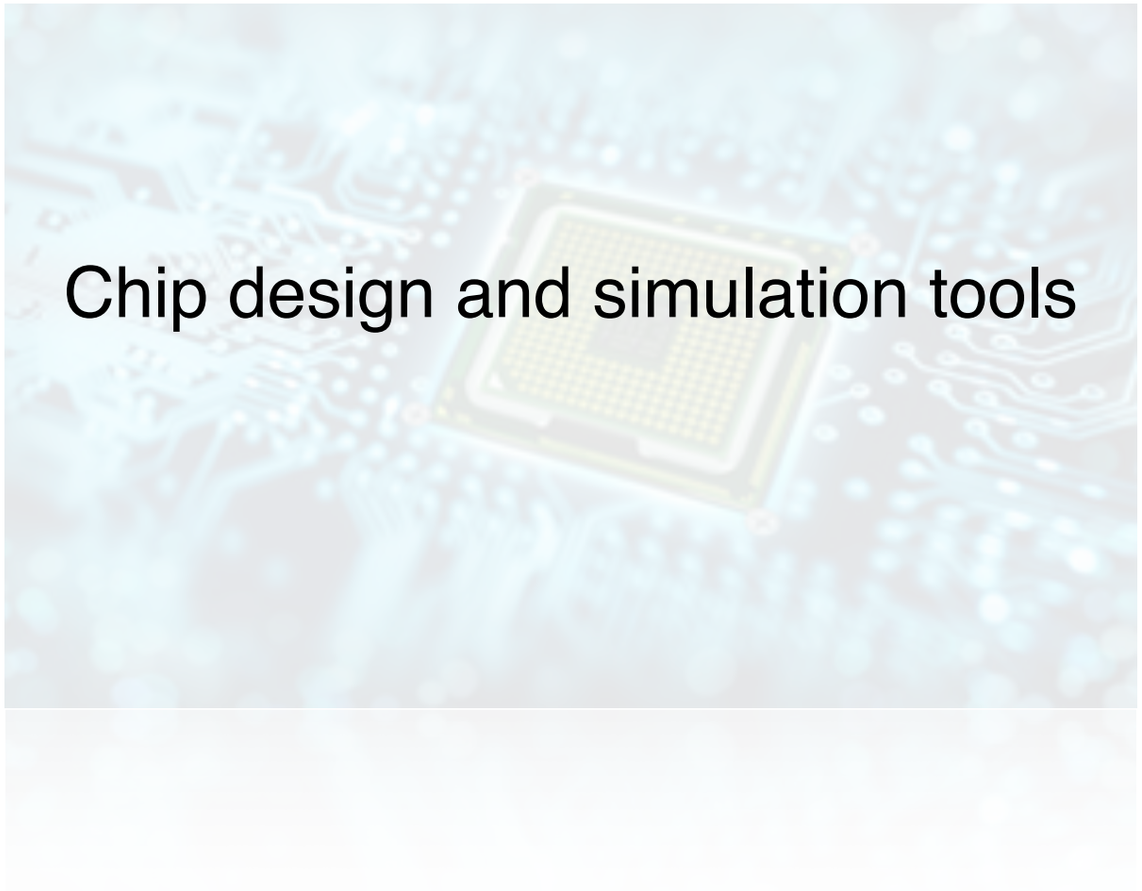


SLAMBench opportunities



Chip design and simulation tools

SLAMBench opportunities



SLAMBench opportunities

Chip design and simulation tools

SLAMBench evolution:

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

Kernels can be improved individually

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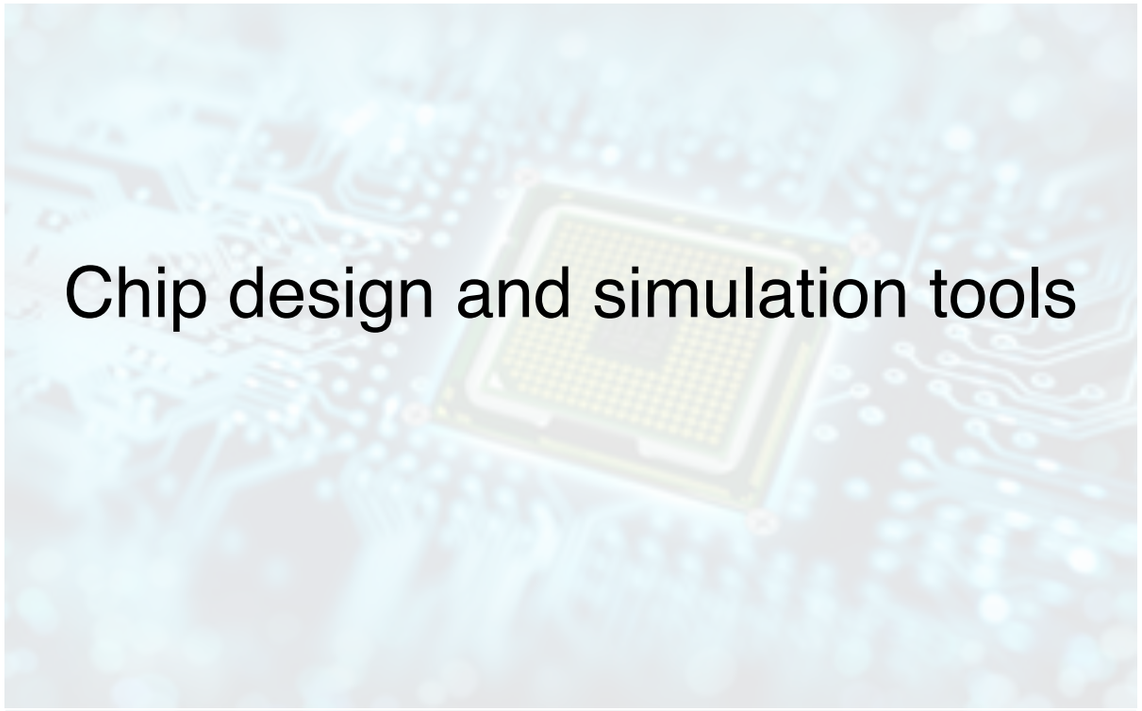

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- Feature-based SLAM

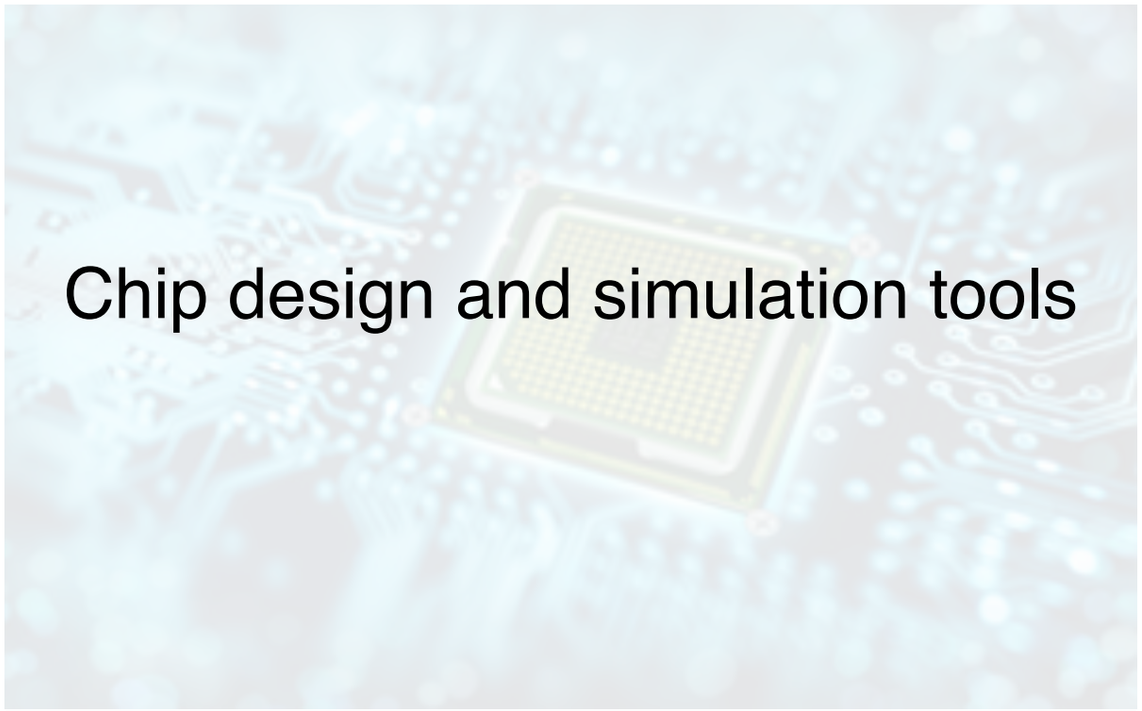
Kernels can be improved individually

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



SLAMBench evolution:

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

Kernels can be improved individually

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

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SLAMBench opportunities

Chip design and simulation tools

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

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

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- Point fusion
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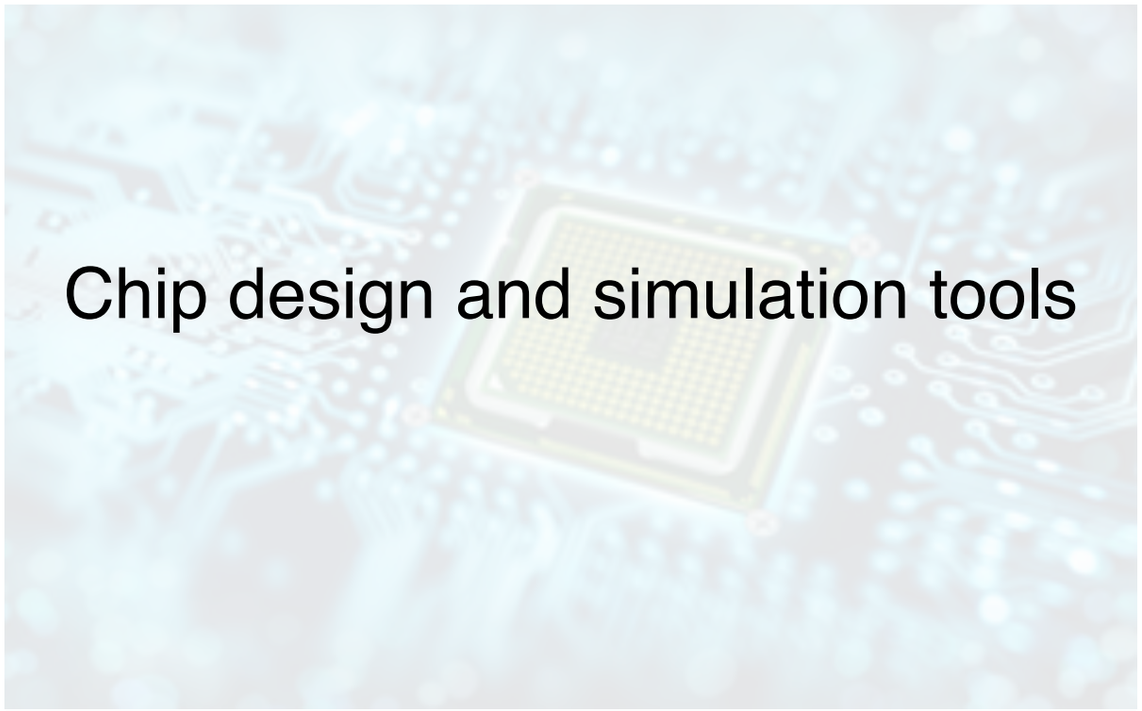
SLAMBench opportunities



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SLAMBench evolution:

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

Kernels can be improved individually

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

References

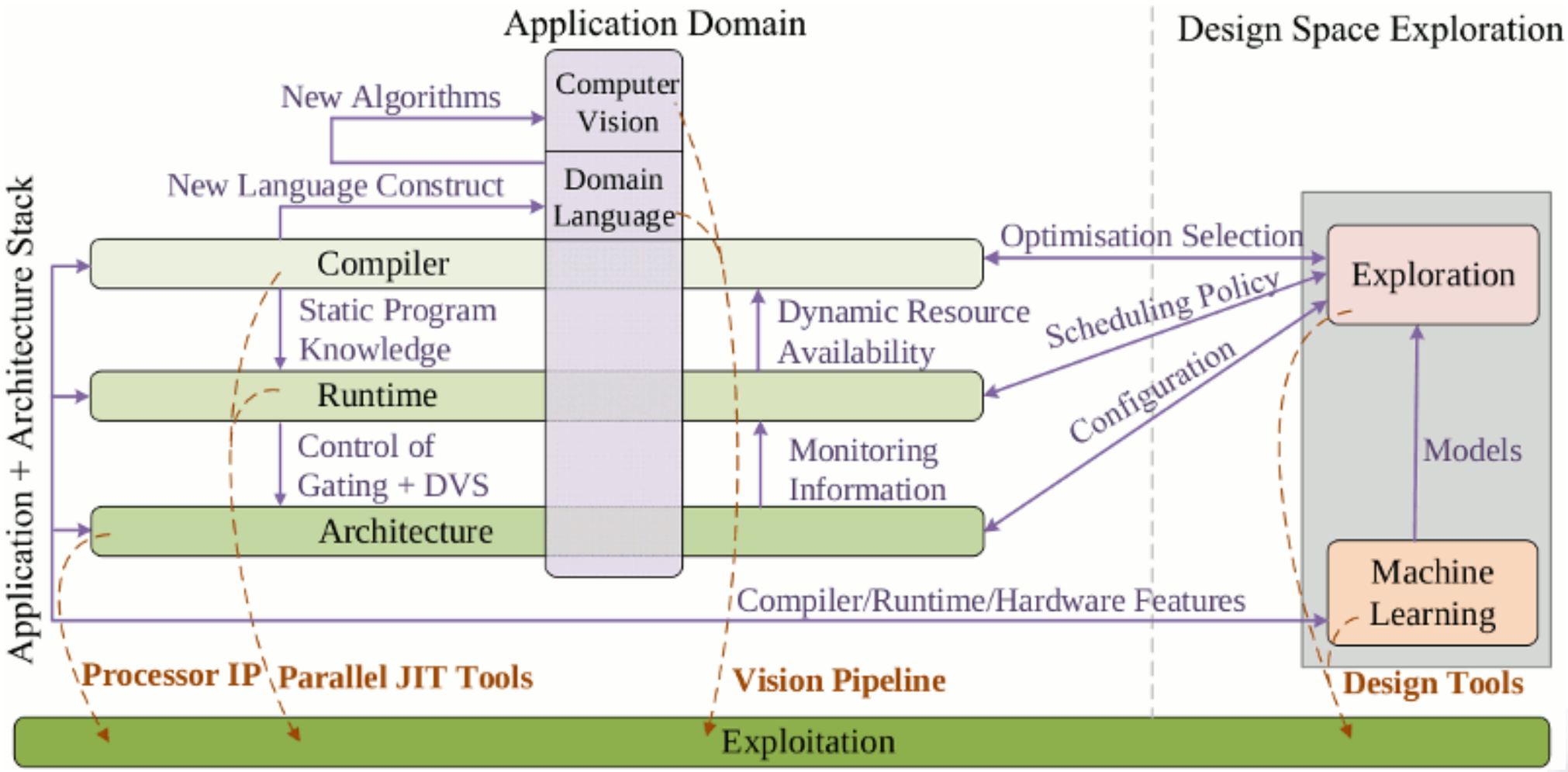
1. [Nardi et al. 2015] L. Nardi, B. Bodin, M. Z. Zia, J. Mawer, A. Nisbet, P. H. J. Kelly, A. J. Davison, M. Luján, M. F. P. O'Boyle, G. Riley, N. Topham, and S. Furber. "Introducing SLAMBench, a performance and accuracy benchmarking methodology for SLAM." Submitted, arXiv:1410.2167, 2015.
2. [Newcombe 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

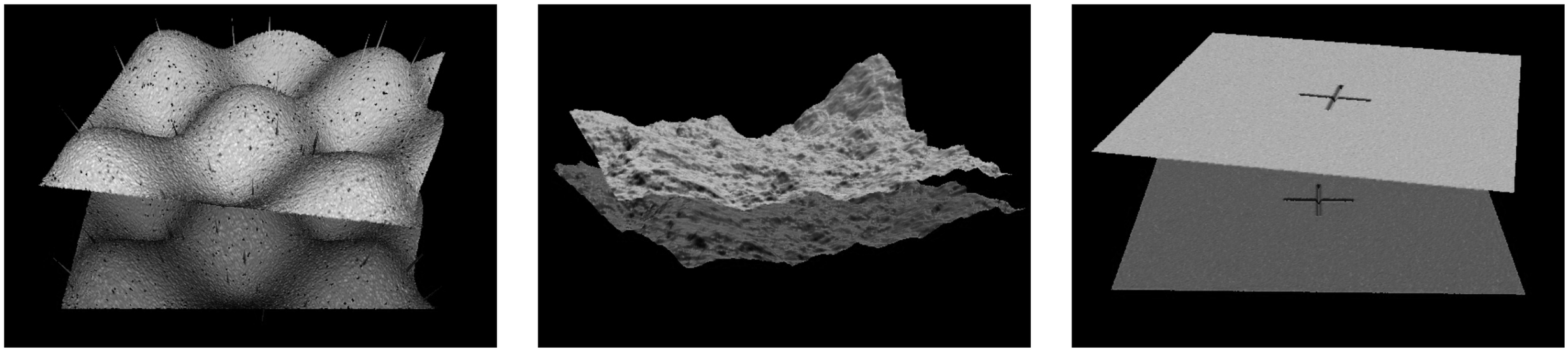
PAMELA project

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

5-year EPSRC grant: Imperial, Manchester and Edinburgh

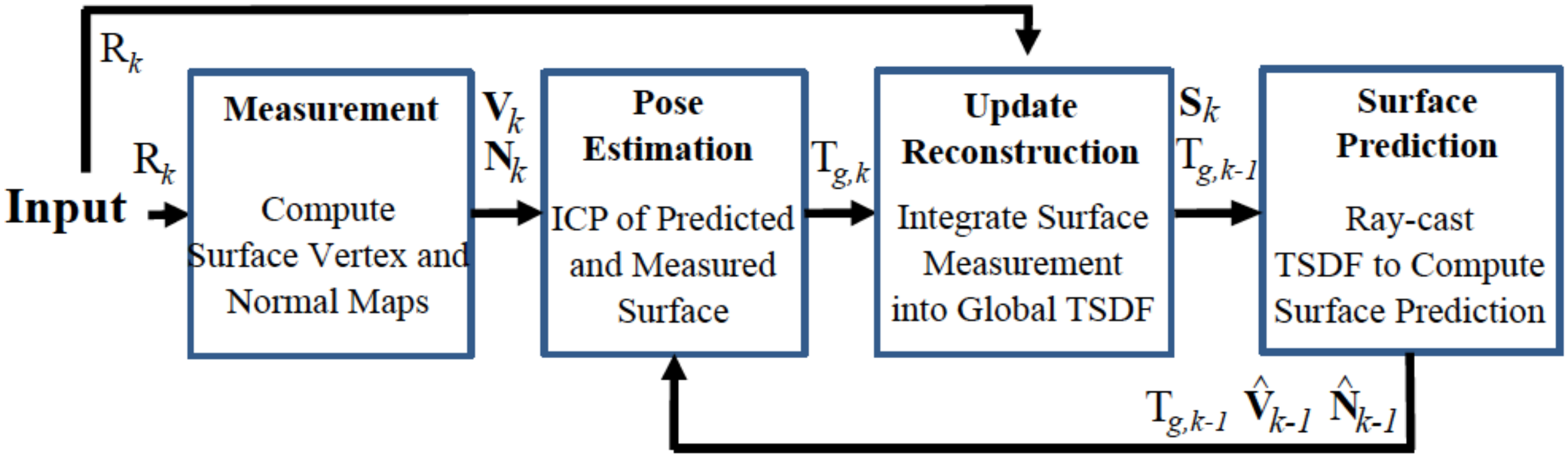


ICP registration



[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

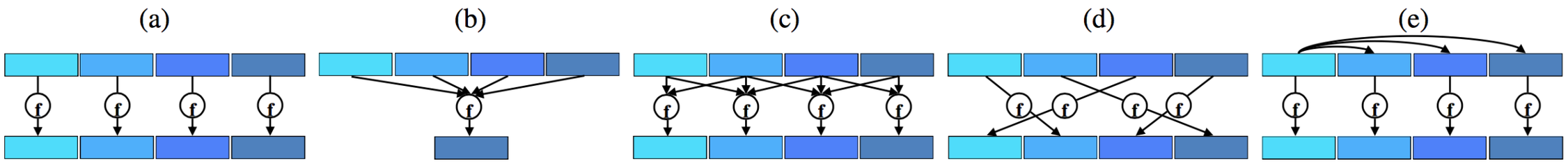


KinectFusion pipeline

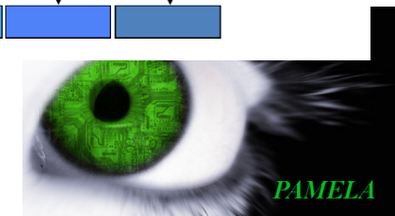
- First dense monocular SLAM algorithm [Newcombe et al. ISMAR 2011]
- Adopted as a major building block in more recent SLAM systems
- Implementation based on [Reitmayr 2011] CUDA implementation

SLAMBench kernels

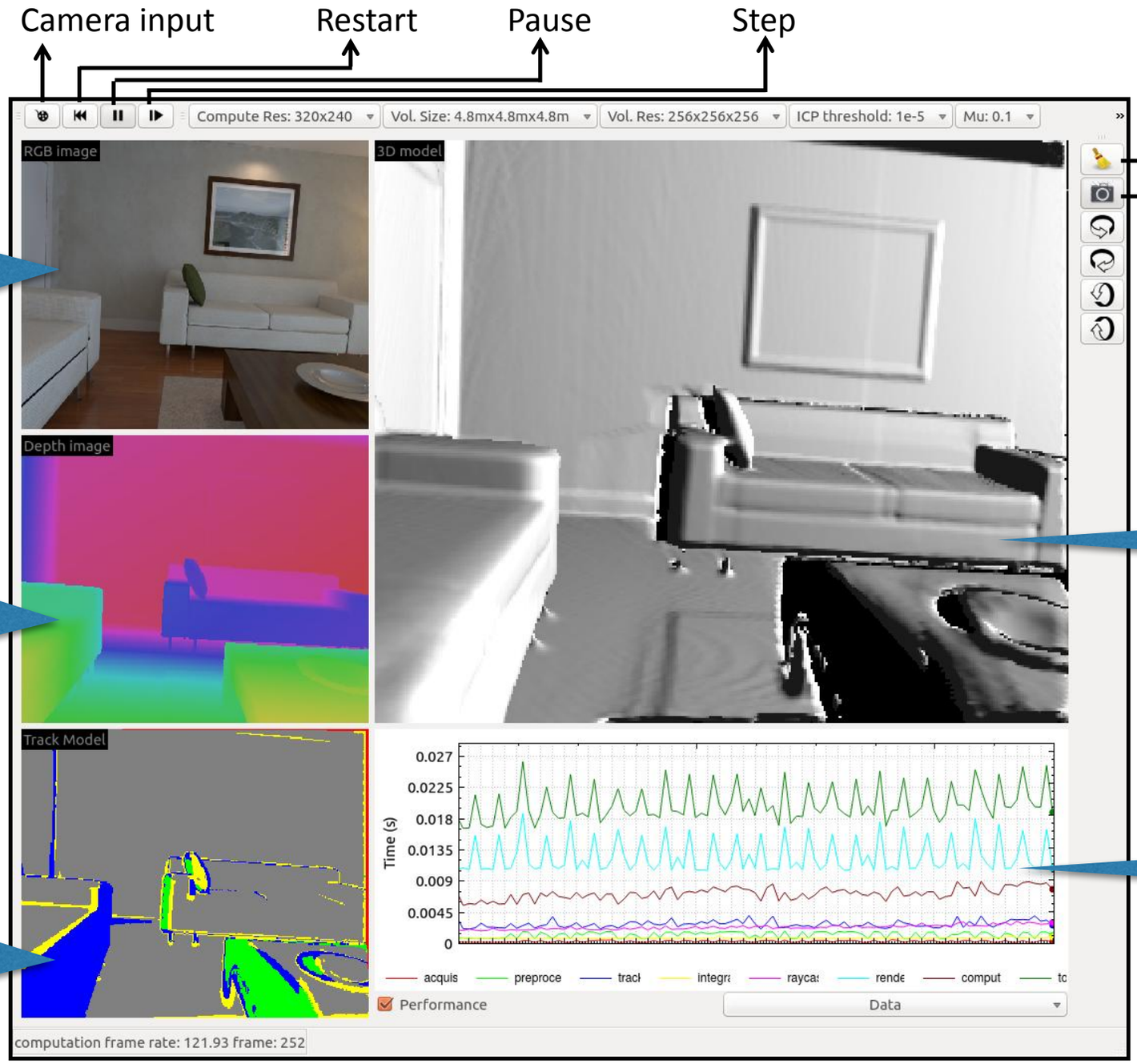
Kernels	Pipeline	Pattern	In	Out	%
acquire	Acquire	n/a	pointer	2D	0.03
mm2meters	Preprocess	Gather	2D	2D	0.06
bilateralFilter	Preprocess	Stencil	2D	2D	33.68
halfSample	Track	Stencil	2D	2D	0.05
depth2vertex	Track	Map	2D	2D	0.11
vertex2normal	Track	Stencil	2D	2D	0.27
track	Track	Map/Gather	2D	2D	4.72
reduce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



RGB camera (not used)

Depth camera

Tracked points

3D model

Performance

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)	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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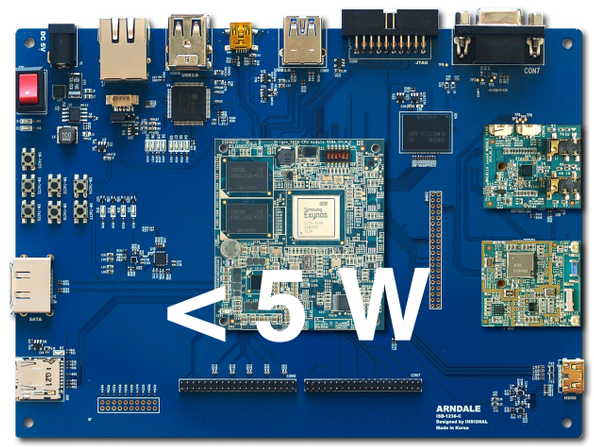

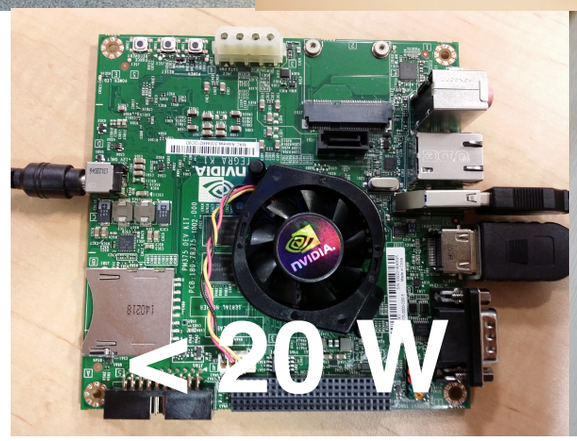

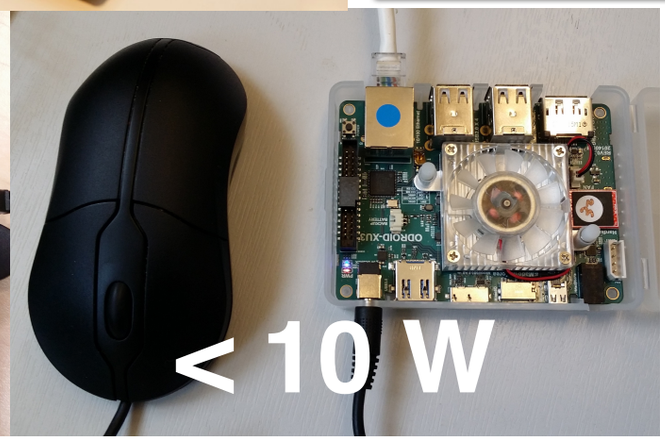

Textual User Interface

```
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%
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For benchmarking purposes, SSH and post-processing tools friendly

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hickory%
```

Easy run

frame	acquisition	preprocessing	tracking	integration	raycasting	rendering	computation	total	X	Y	Z	tracked	integrated
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

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Textual User Interface

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grated													
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3	0.002663	0.000335	0.000905	0.000467	0.000604	0.000219	0.002311	0.005193			0.000000	0	1

Raw data

Sum up

```
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
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```

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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
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High-level blocks statistics

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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

Sum up

```
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
```

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

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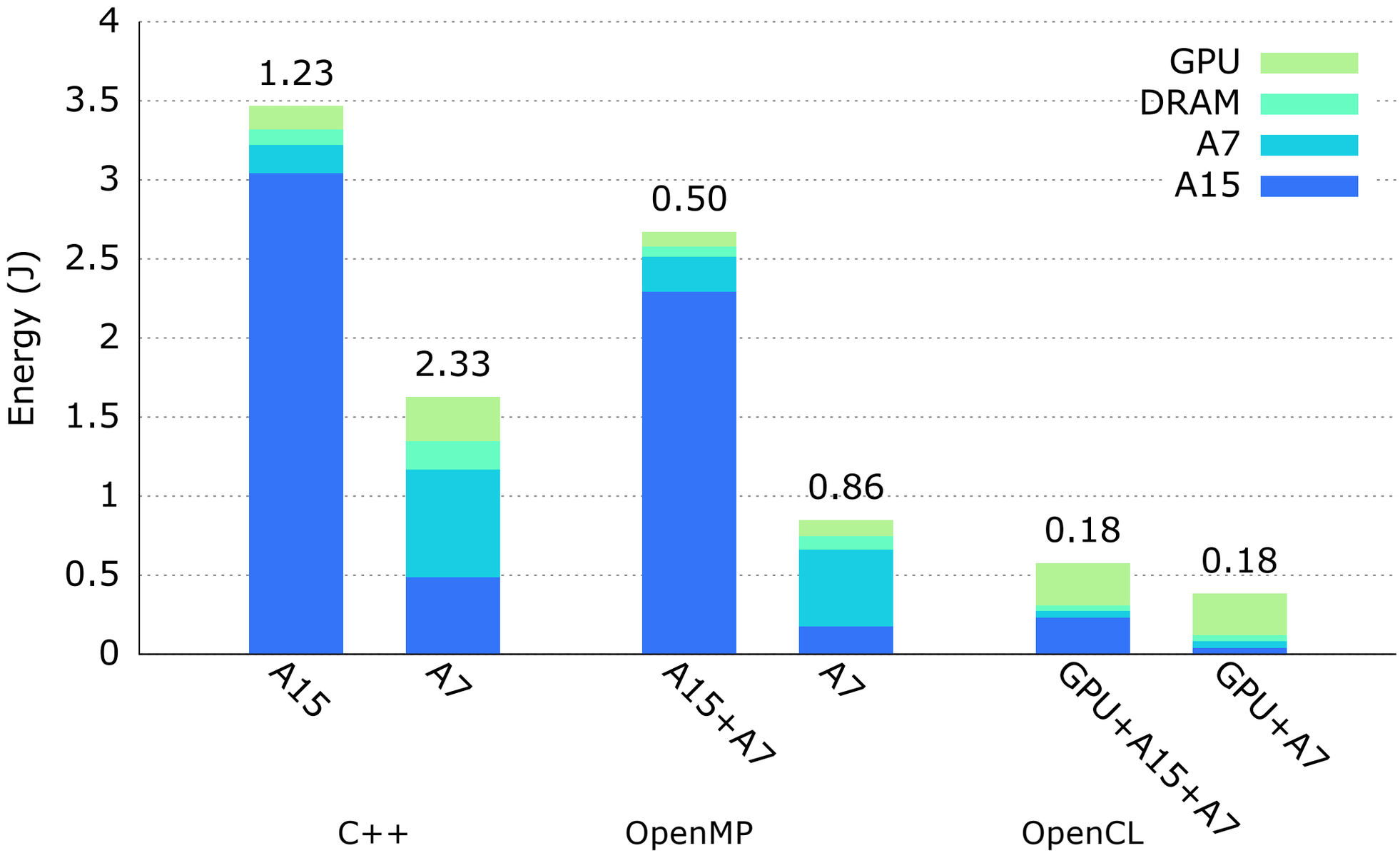

Energy usage per frame, mean time as marked

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- This research paves the way for **systematic holistic evaluation**

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- Author: unknown. Microsoft Kinect camera. [Image]. Retrieved from http://channel9.msdn.com/Series/KinectSDKQuickstarts/Understanding-Kinect-Hardware
- Author: Dyson Ltd. Dyson 360 Eye. [Video]. Retrieved from https://www.youtube.com/watch?v=OadhuICDAjk
- Author: Google Inc. Google Tango project. [Image]. Retrieved from http://blogthinkbig.com/en/project-tango-googles-mobile-kinect/
- Author: unknown. Audi autonomous car. [Photograph]. Retrieved from http://www.wired.com/2010/06/audis-robotic-car-looks-hot-in-old-school-livery/
- Author: ExtremeTech. Google Shaft robot. [Photograph]. Retrieved from http://www.extremetech.com/extreme/173318-google-wins-darpas-robotics-challenge-wonders-if-it-was-a-good-idea-to-turn-down-future-military-contracts
- Author: HardKernel. ODROID-XU3 board. [Photograph]. Retrieved from http://www.hardkernel.com/main/products/prdt_info.php?g_code=G135235611947
- Author: PC Specialist Ltd. Vortex series laptop. [Photograph]. Retrieved from https://www.pcspecialist.co.uk/forums/showthread.php?23366-My-new-beast-15-6-quot-Vortex-III
- Author: Arndale.org. Arndale board. [Photograph]. Retrieved from http://www.arndaleboard.org/wiki/index.php/Main_Page
- Author: Unknown. Chip. [Image]. Retrieved from https://cajalesygalileos.wordpress.com/2013/06/23/un-chip-ultrasensible-identifica-15-cepas-de-gripe/
- Author: Unknown. Eye. [Image]. Retrieved from http://gallery.digitalculture.asu.edu/?/interactive-environments/computer-vision/
- Author: Unknown. Compiler. [Image]. Retrieved from http://d3q6qq2zt8nhwv.cloudfront.net/107/large-icon.png