

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

- SLAMBench -

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Imperial College London  
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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



The University of Manchester



Imperial College  
London

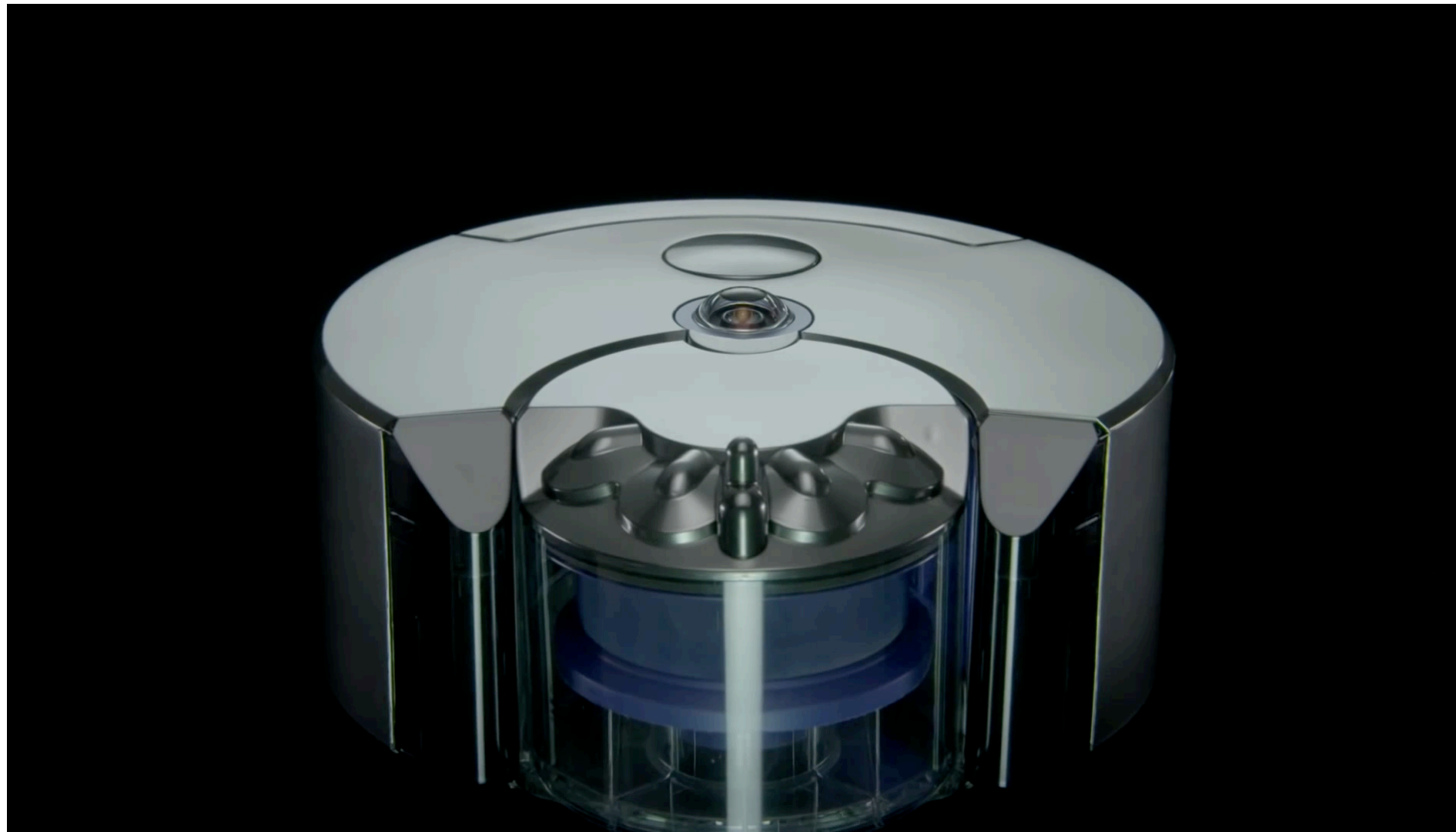
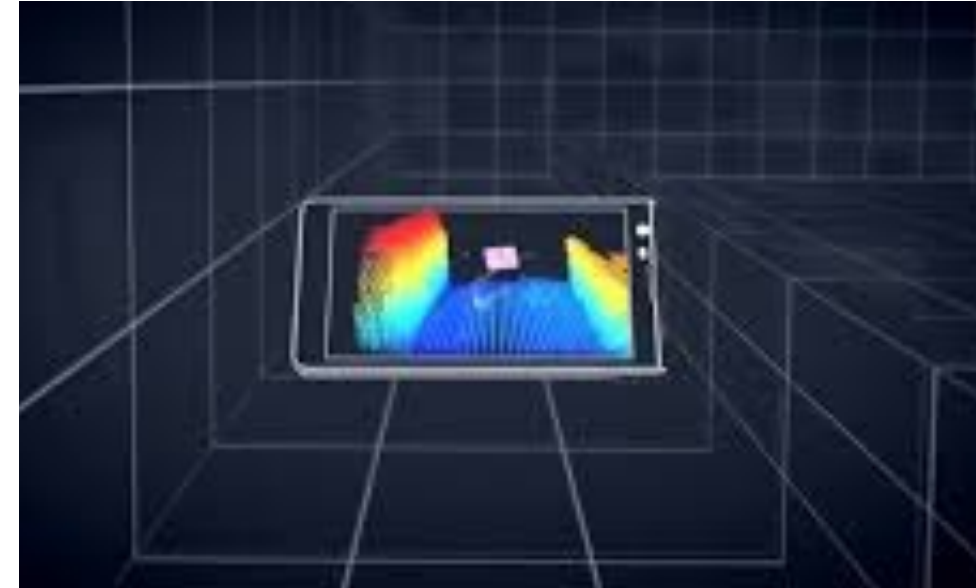


# Simultaneous localisation and mapping (SLAM)

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

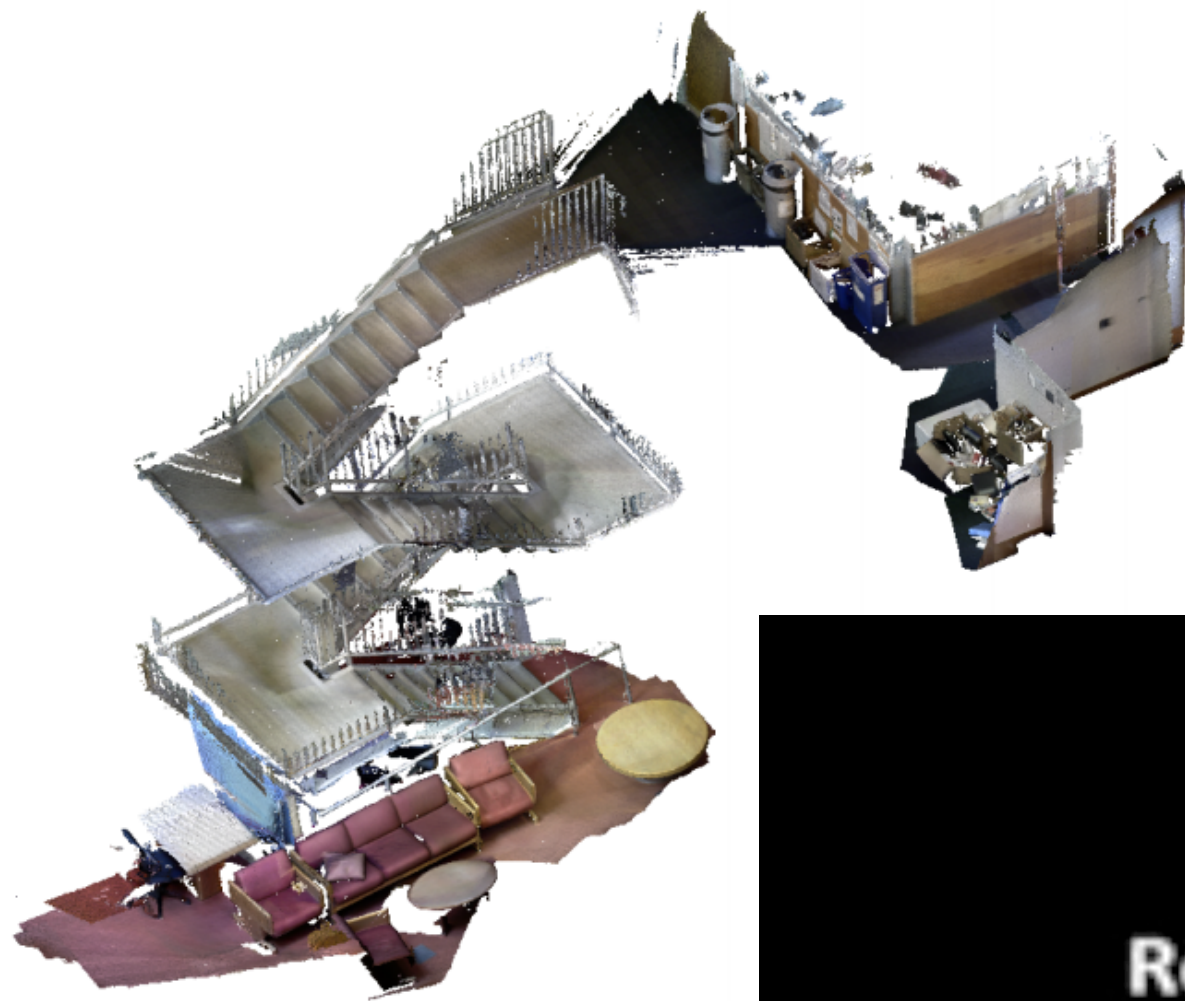


Video:  
[Dyson 360 Eye](#)

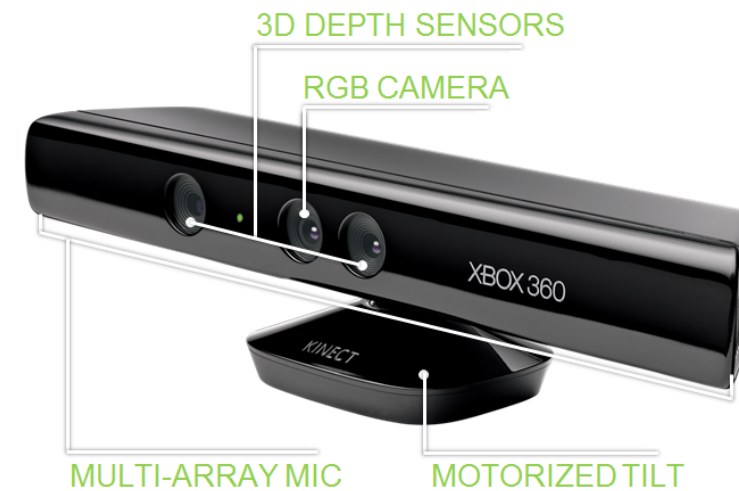




# Simultaneous localisation and mapping (SLAM)



[Whelan et al. 2012]



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

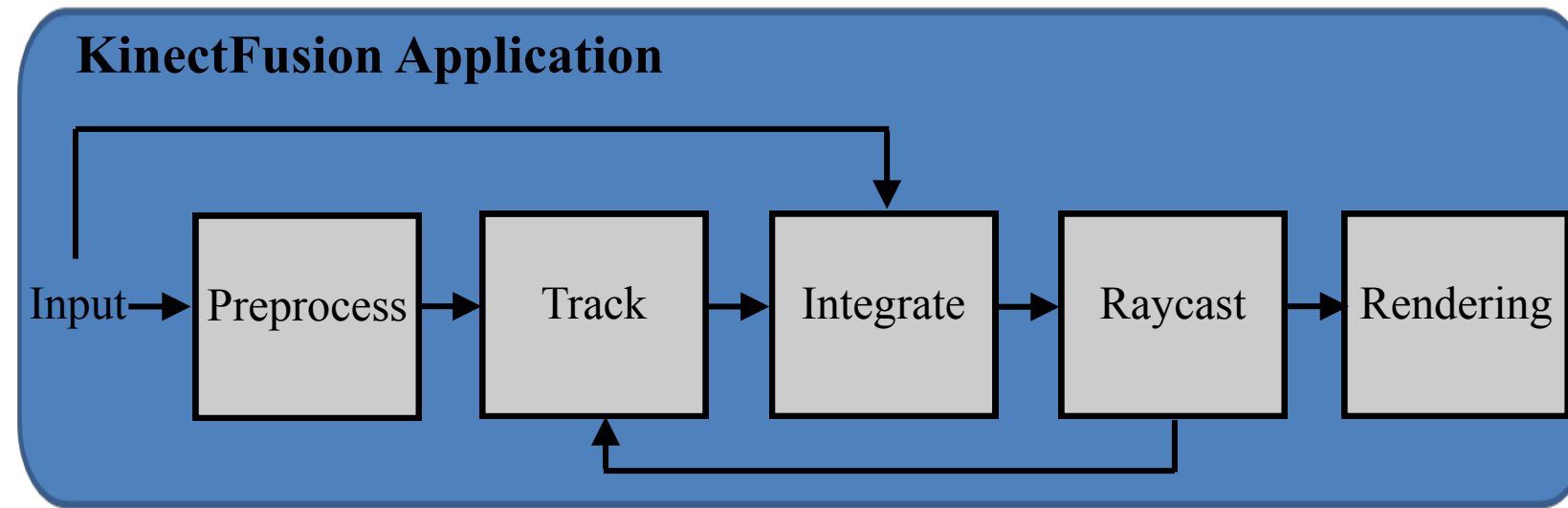
Shahram Izadi 1, Richard Newcombe 2, David Kim 1,3, Otmar Hilliges 1,  
David Molyneaux 1,4, Pushmeet Kohli 1, Jamie Shotton 1,  
Steve Hodges 1, Dustin Freeman 5, Andrew Davison 2, Andrew Fitzgibbon 1

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

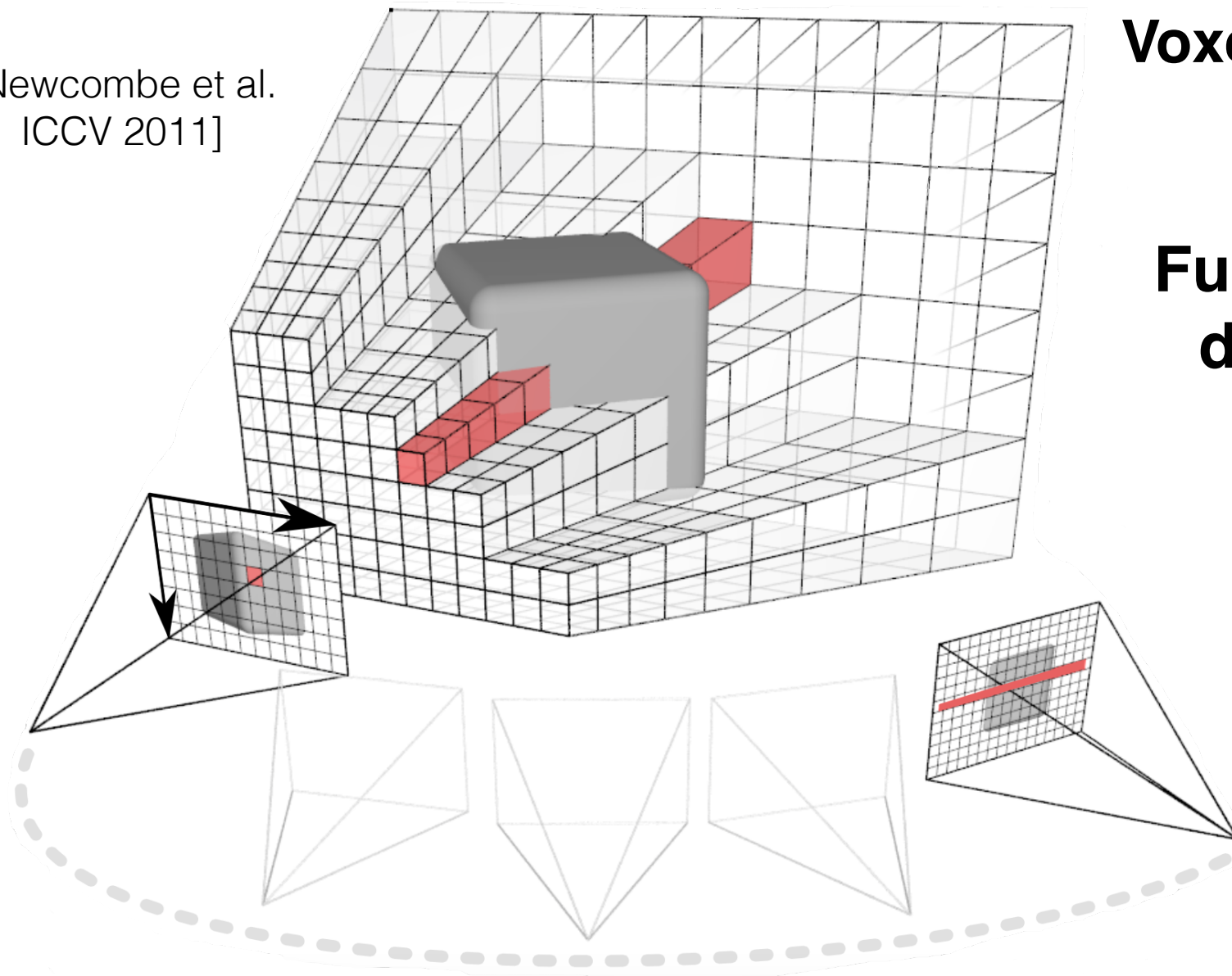
Video:

[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





# Outline

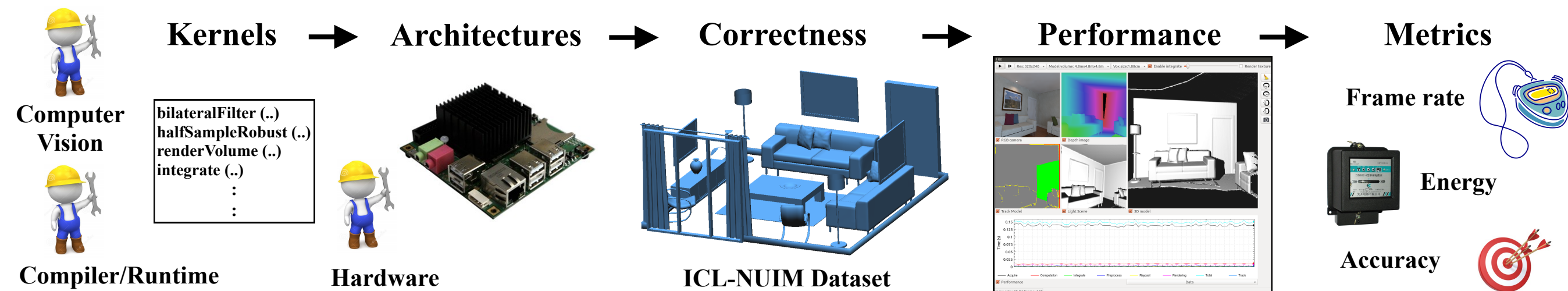
- Simultaneous localisation and mapping (SLAM) application
- **Performance metrics in SLAM**
- From desktop to embedded
- SLAMBench



# 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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SLAM computation depends on:

- Images acquired
- Way the camera is moved
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**Need for reproducibility  
and accuracy check**

*Pre-recorded scenes*

Process-every-frame mode

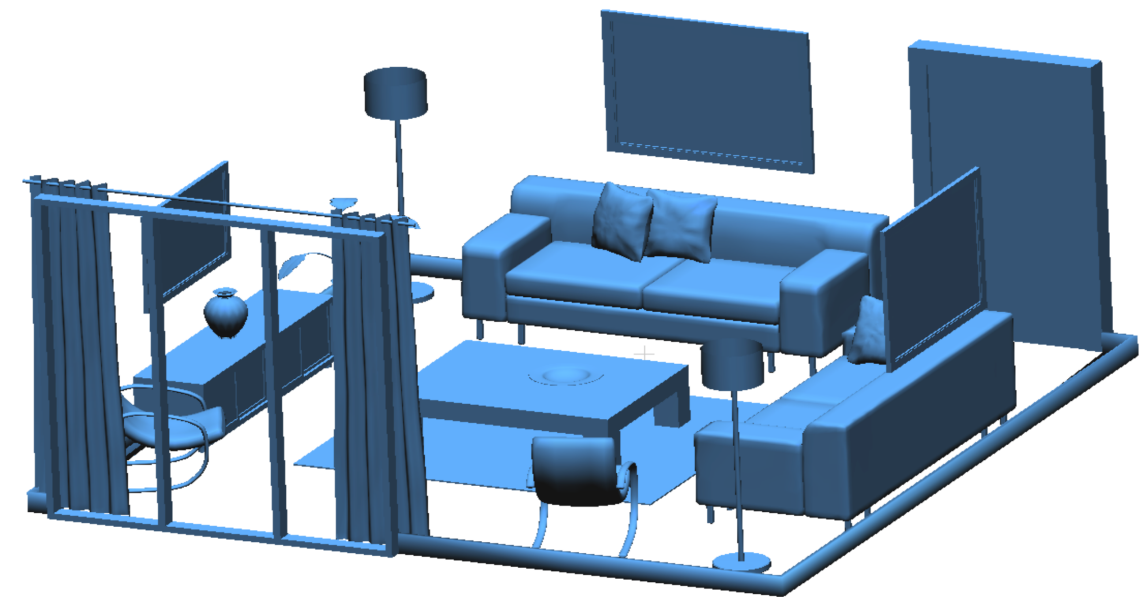
*ICL-NUIM dataset  
(frames and ground truth)*



# ICL-NUIM dataset

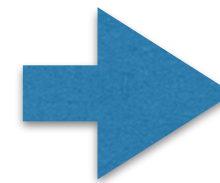
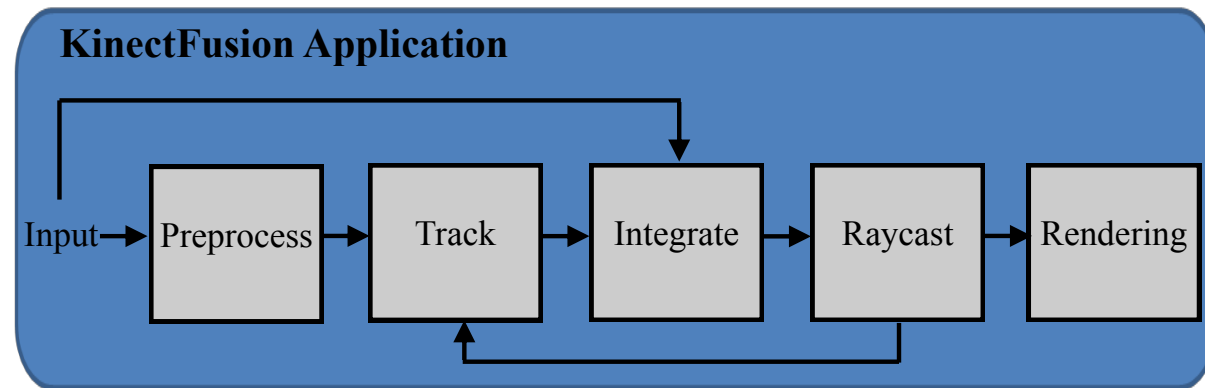


- ICL-NUIM synthetic dataset [Handa et al. 2014]
- 880 RGB-D frames at 30 FPS



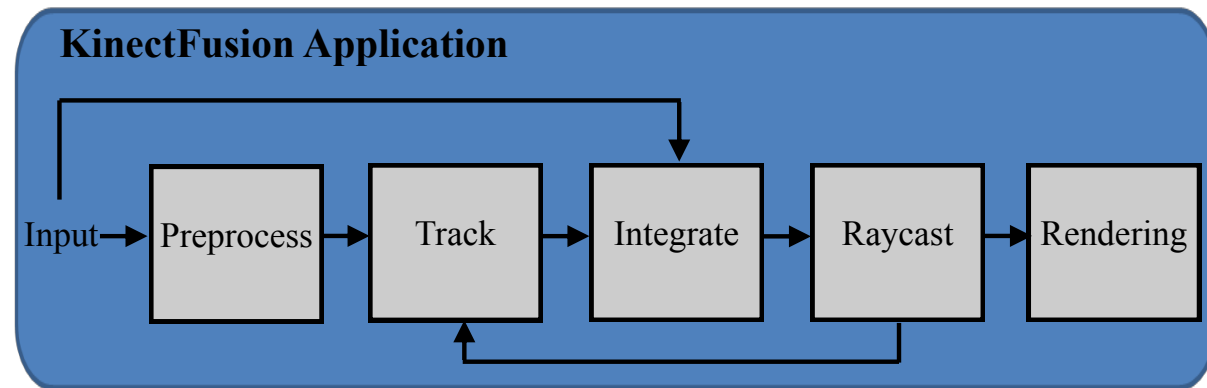
- Absolute trajectory error (ATE) based on ground truth

# SLAMBench framework

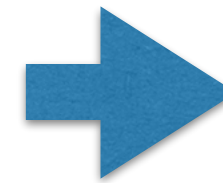
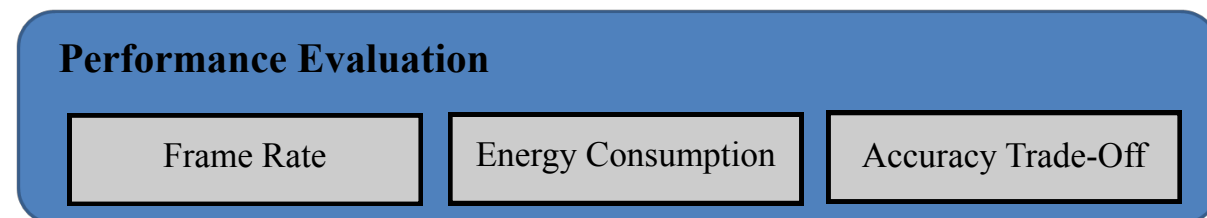


high-level blocks composed  
by 14 lower level kernels  
based on [Reitmayr 2011]

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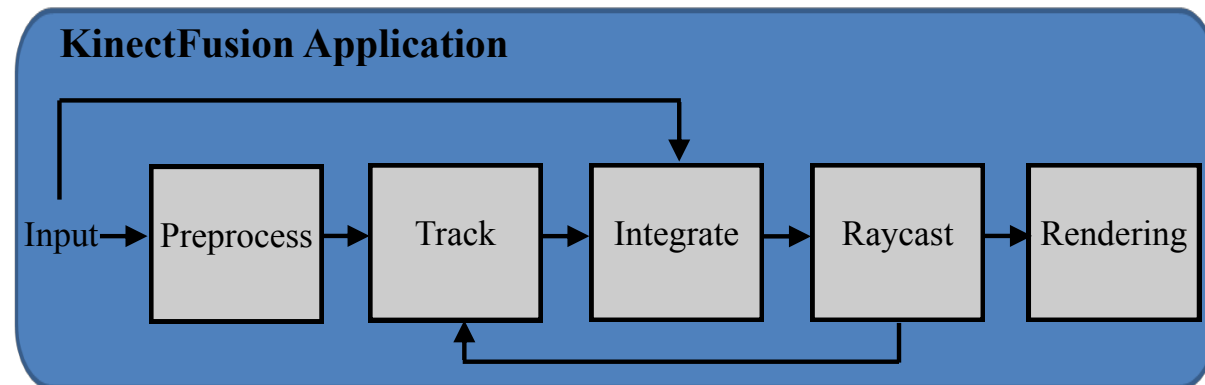
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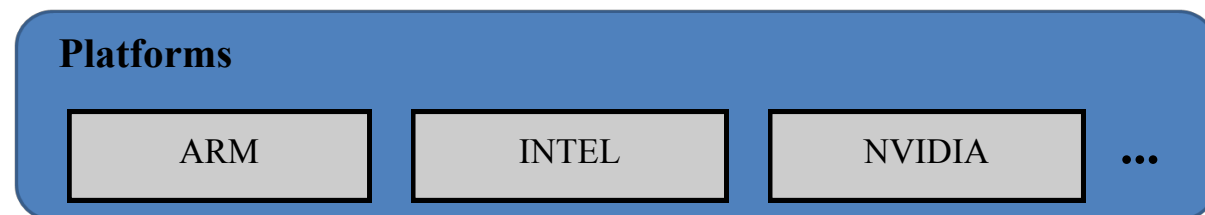
3 metrics:  
execution time/energy/accuracy



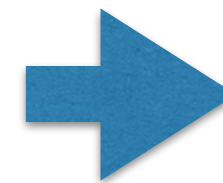
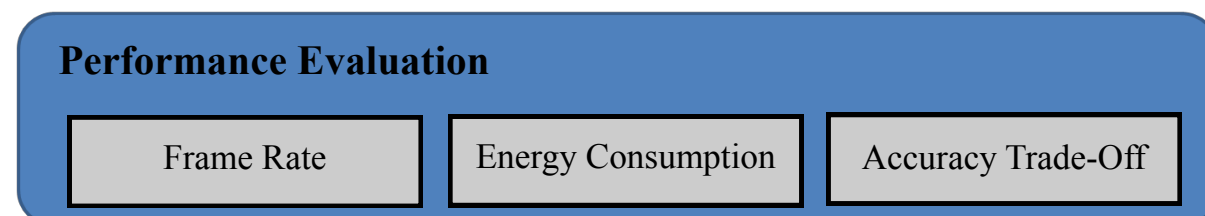
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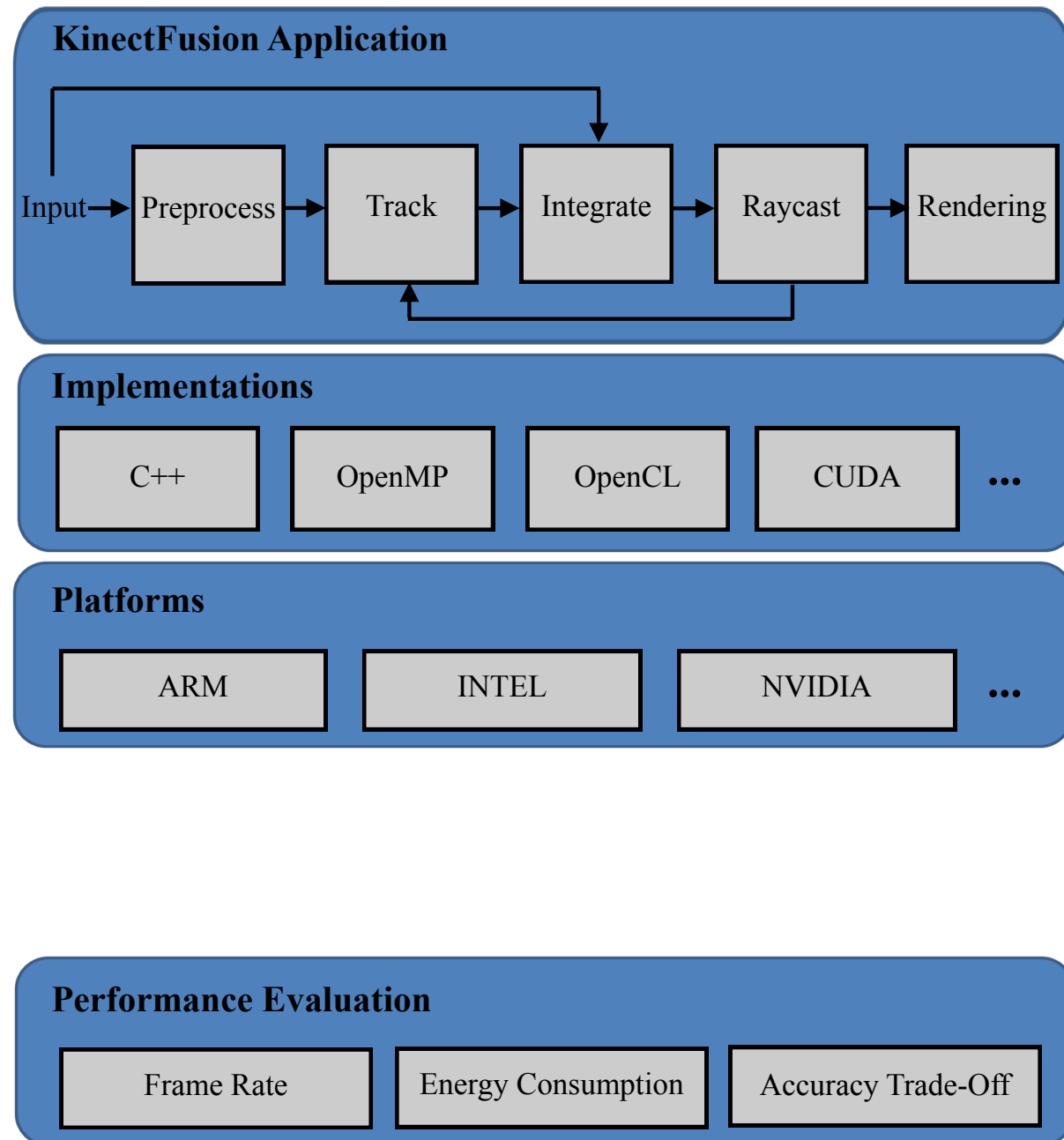


desktop, mobile, embedded:  
multi-core and many-core

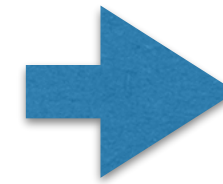


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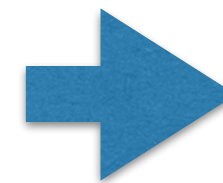
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wide range of languages

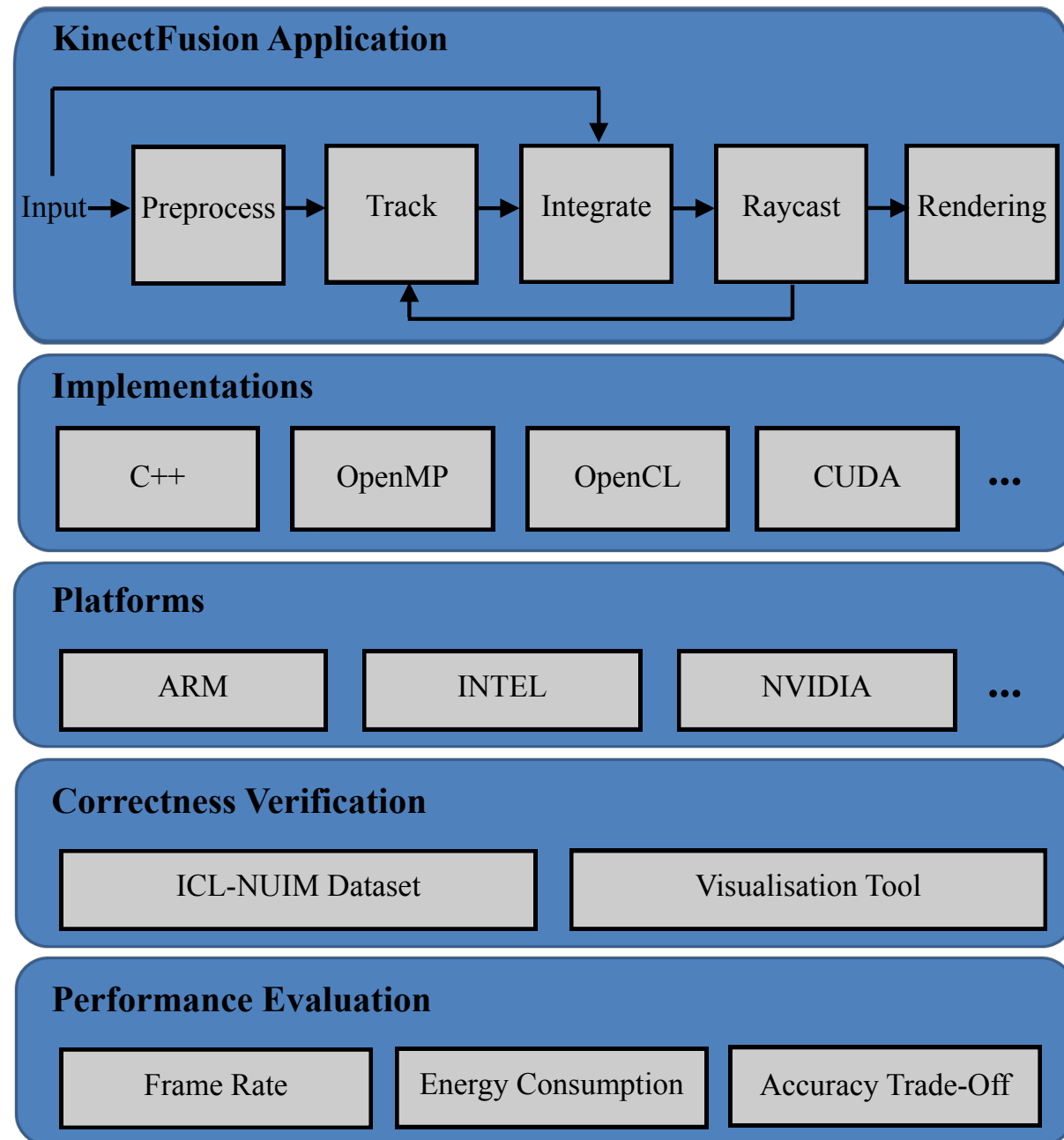


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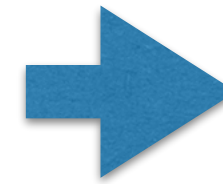


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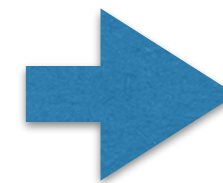
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desktop, mobile, embedded:  
multi-core and many-core



integrated  
verification/visualisation



3 metrics:  
execution time/energy/accuracy

# Outline

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





| 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           |
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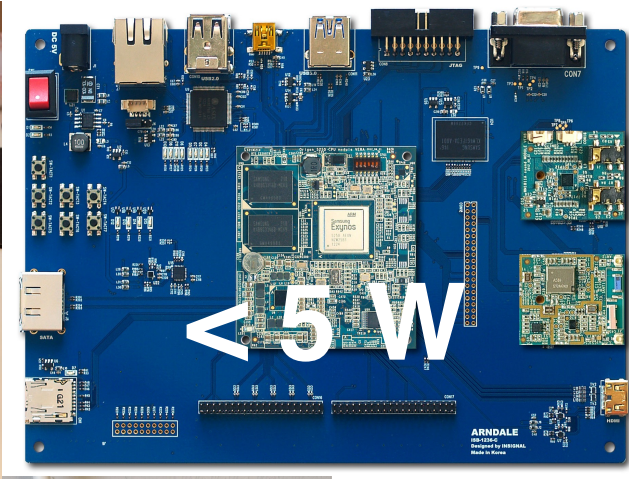


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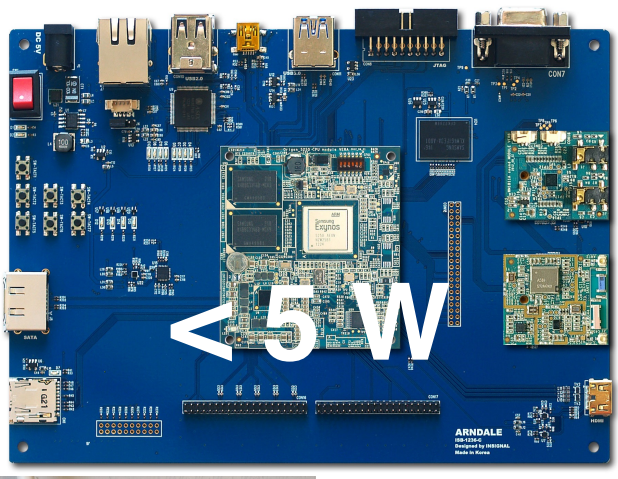


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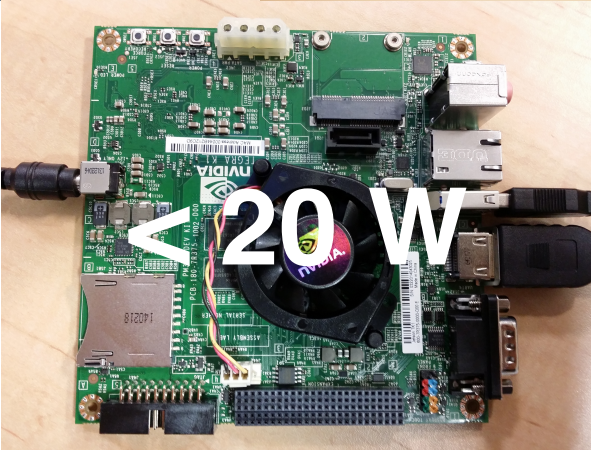




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# Platforms



# “Performance”: accuracy

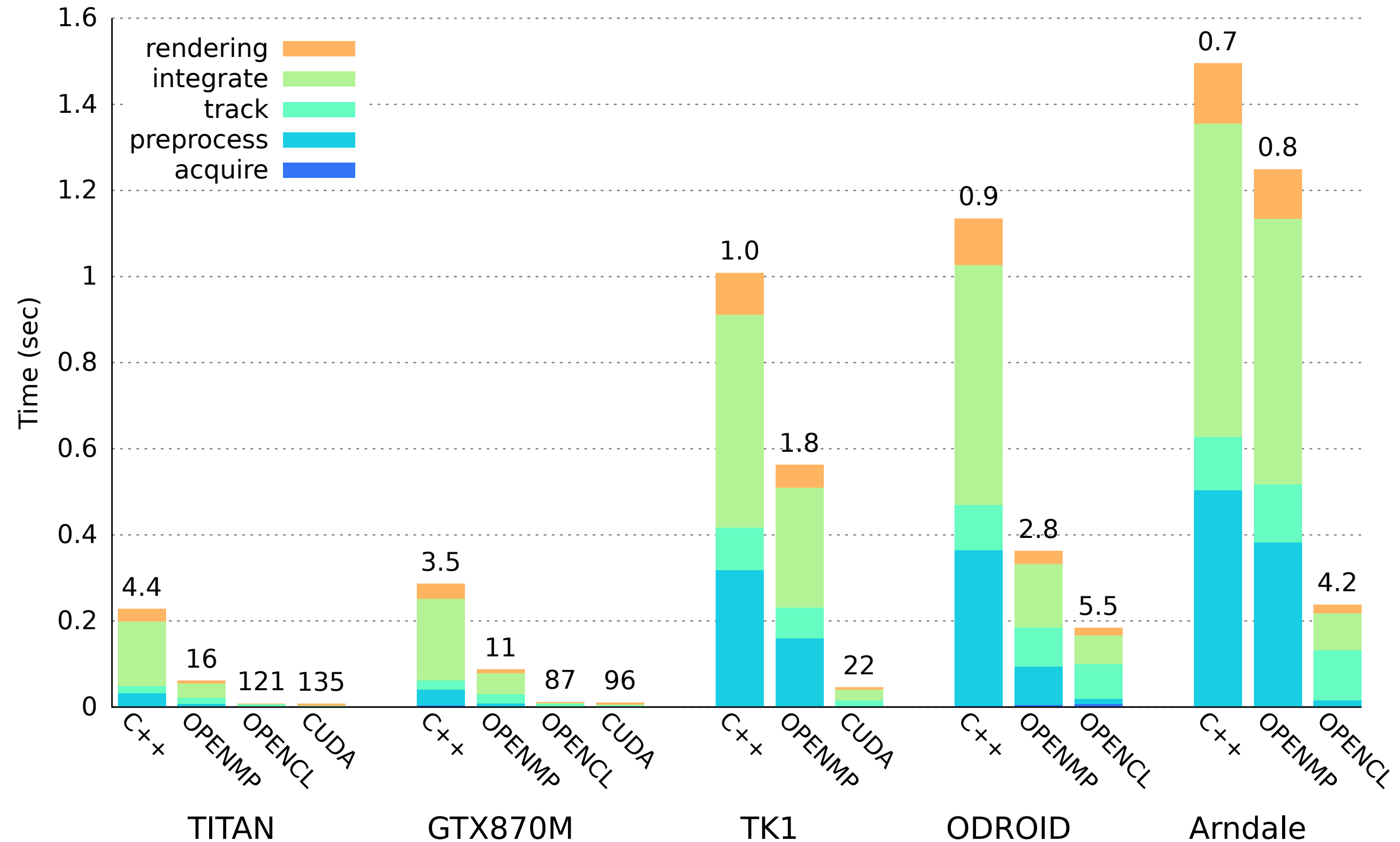
Absolute trajectory error (ATE) - default algorithmic configuration

| ATE in cm     | TITAN | GTX870M | TK1  | ODROID | Arndale |
|---------------|-------|---------|------|--------|---------|
| <b>C++</b>    | 2.07  | 2.07    | 2.06 | 2.06   | 2.06    |
| <b>OpenMP</b> | 2.07  | 2.07    | 2.06 | 2.06   | 2.06    |
| <b>OpenCL</b> | 2.07  | 2.07    | n/a  | 2.01   | 2.07    |
| <b>CUDA</b>   | 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

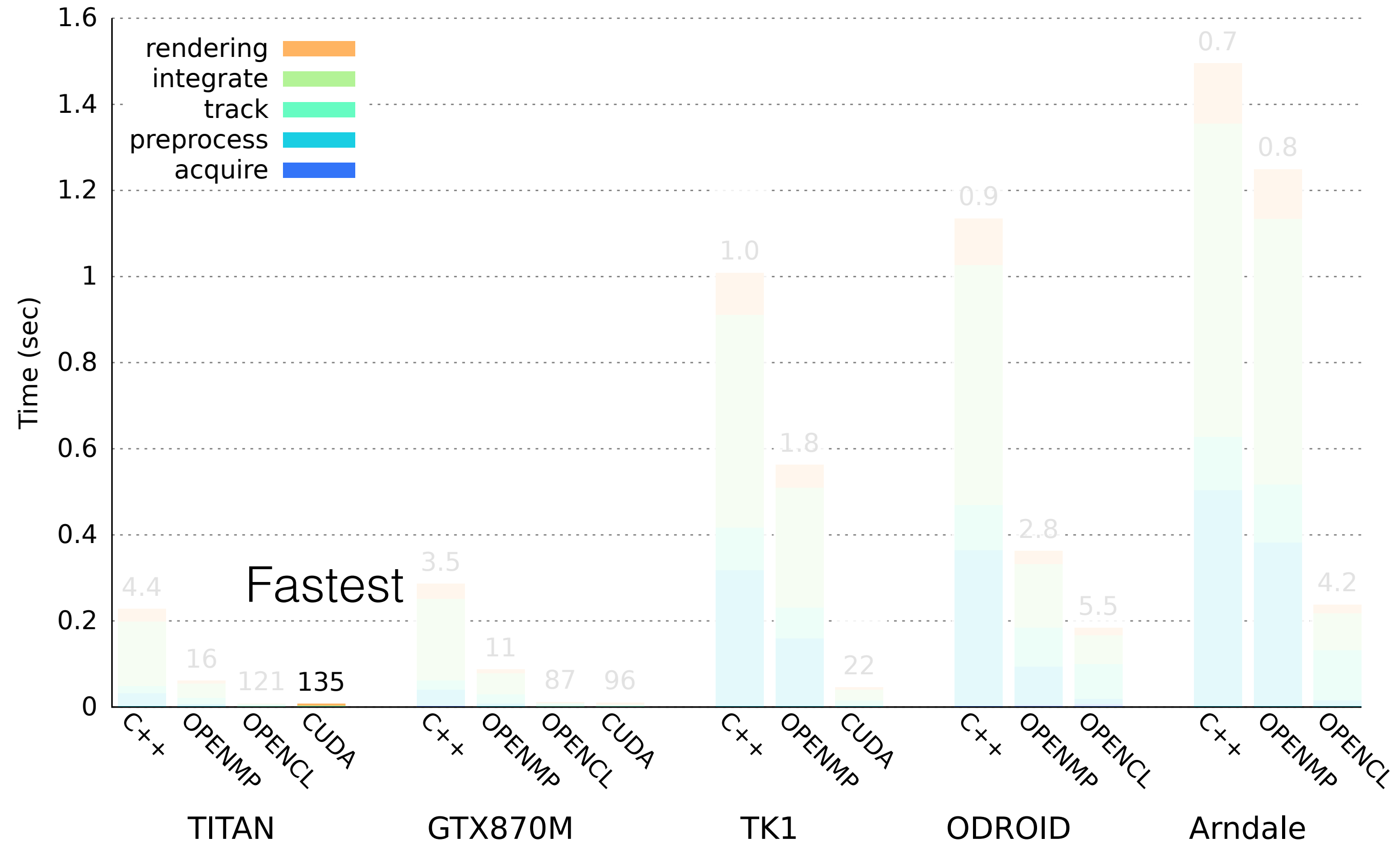
Mean time per frame (lower is better)





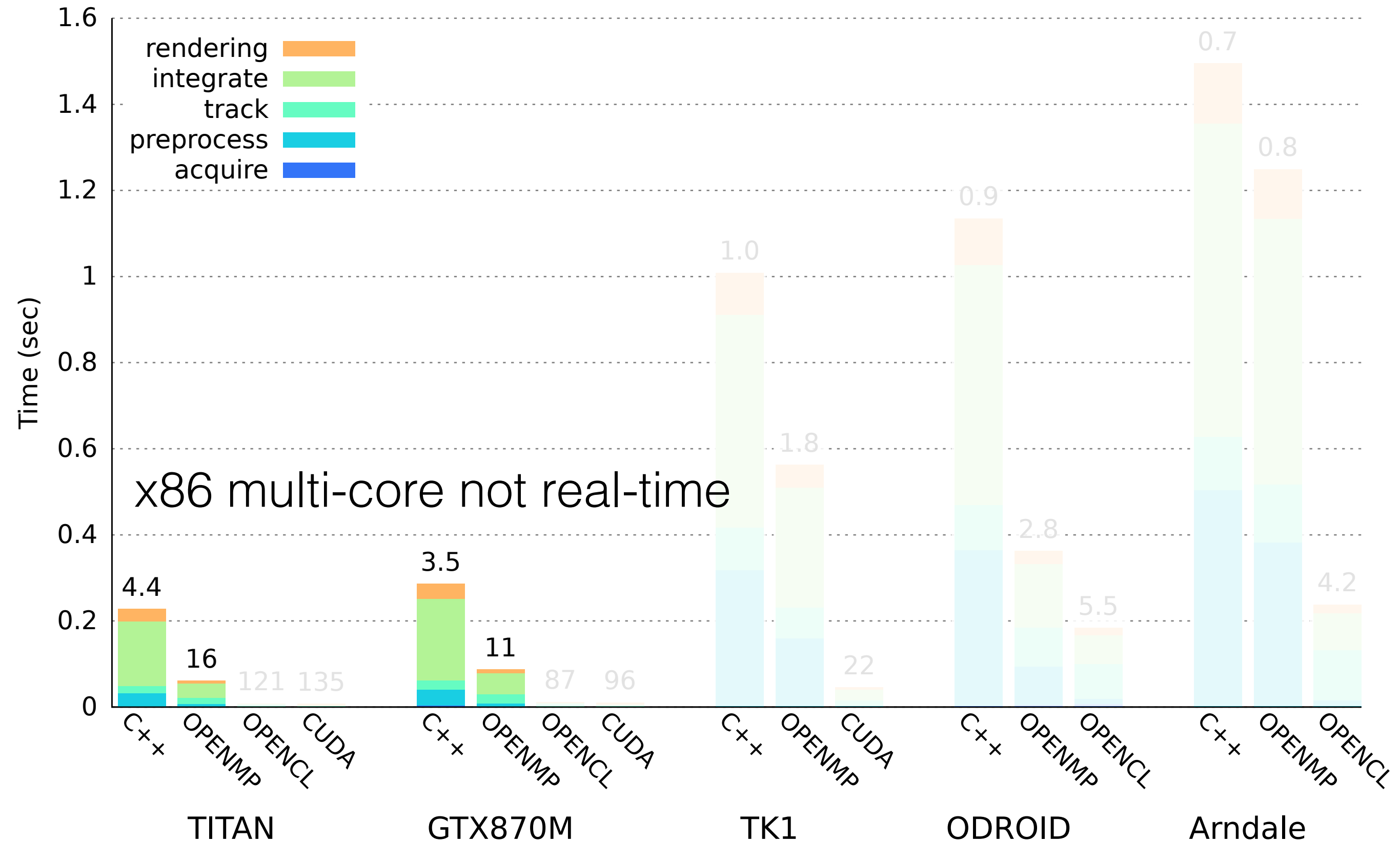
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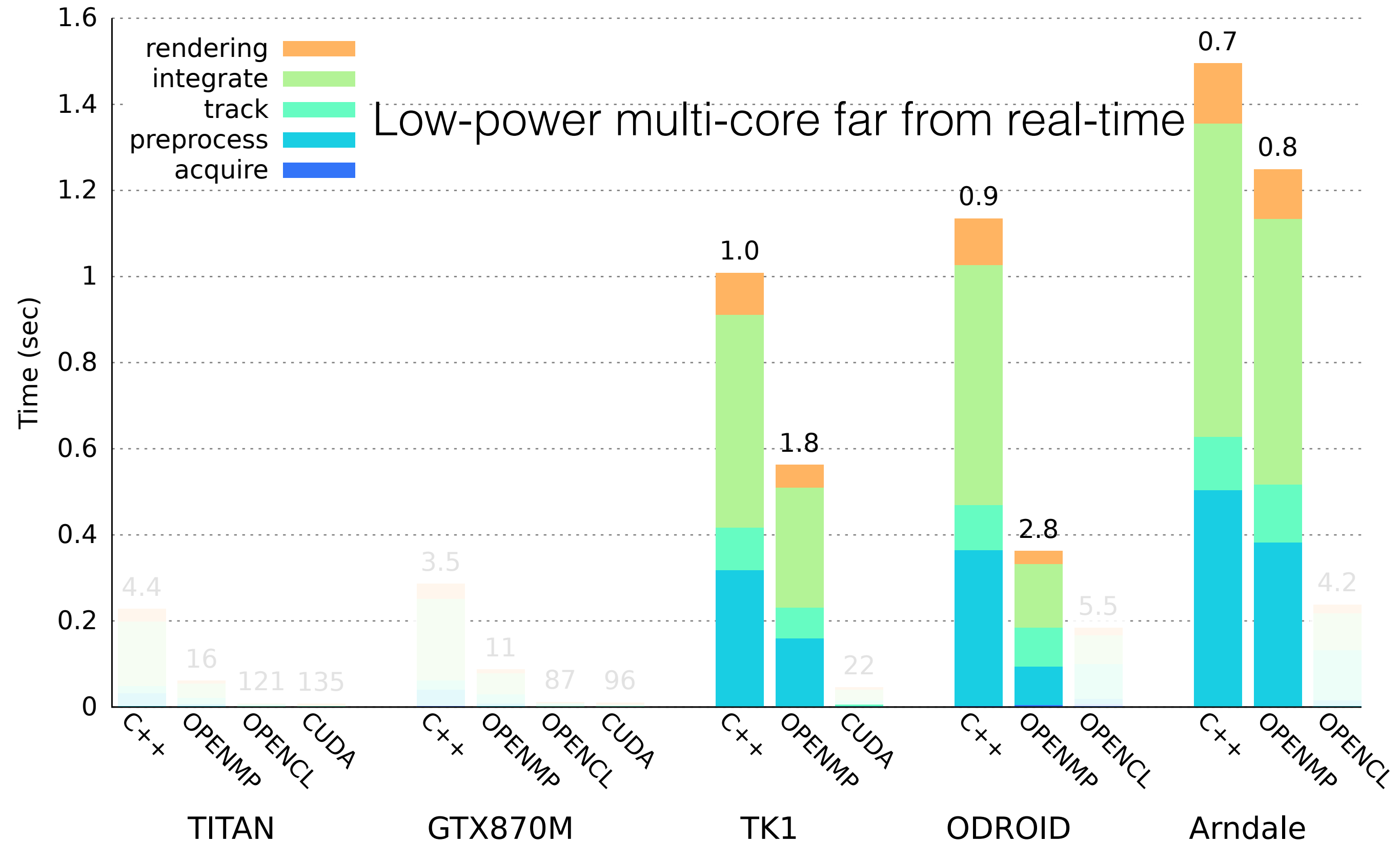
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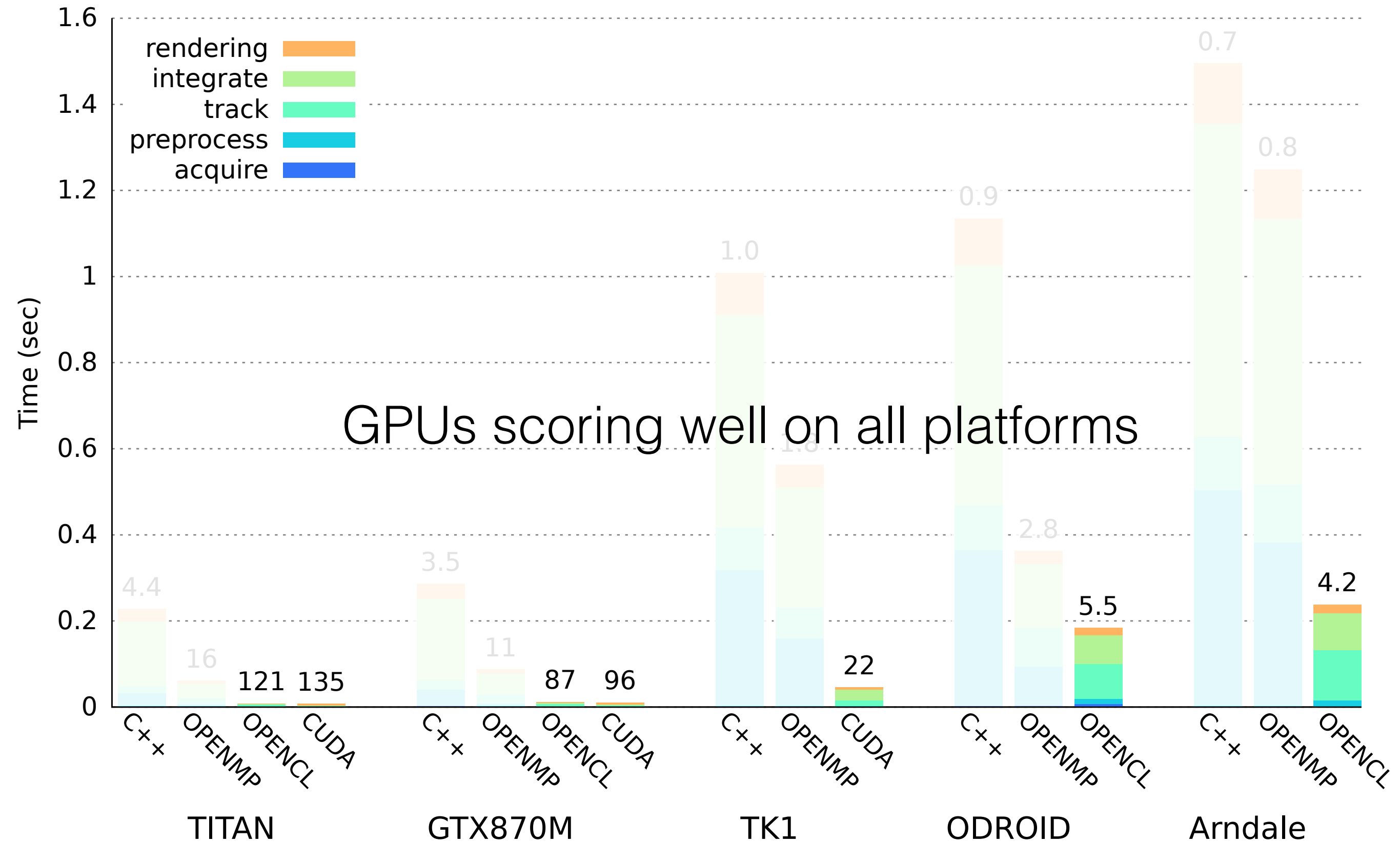
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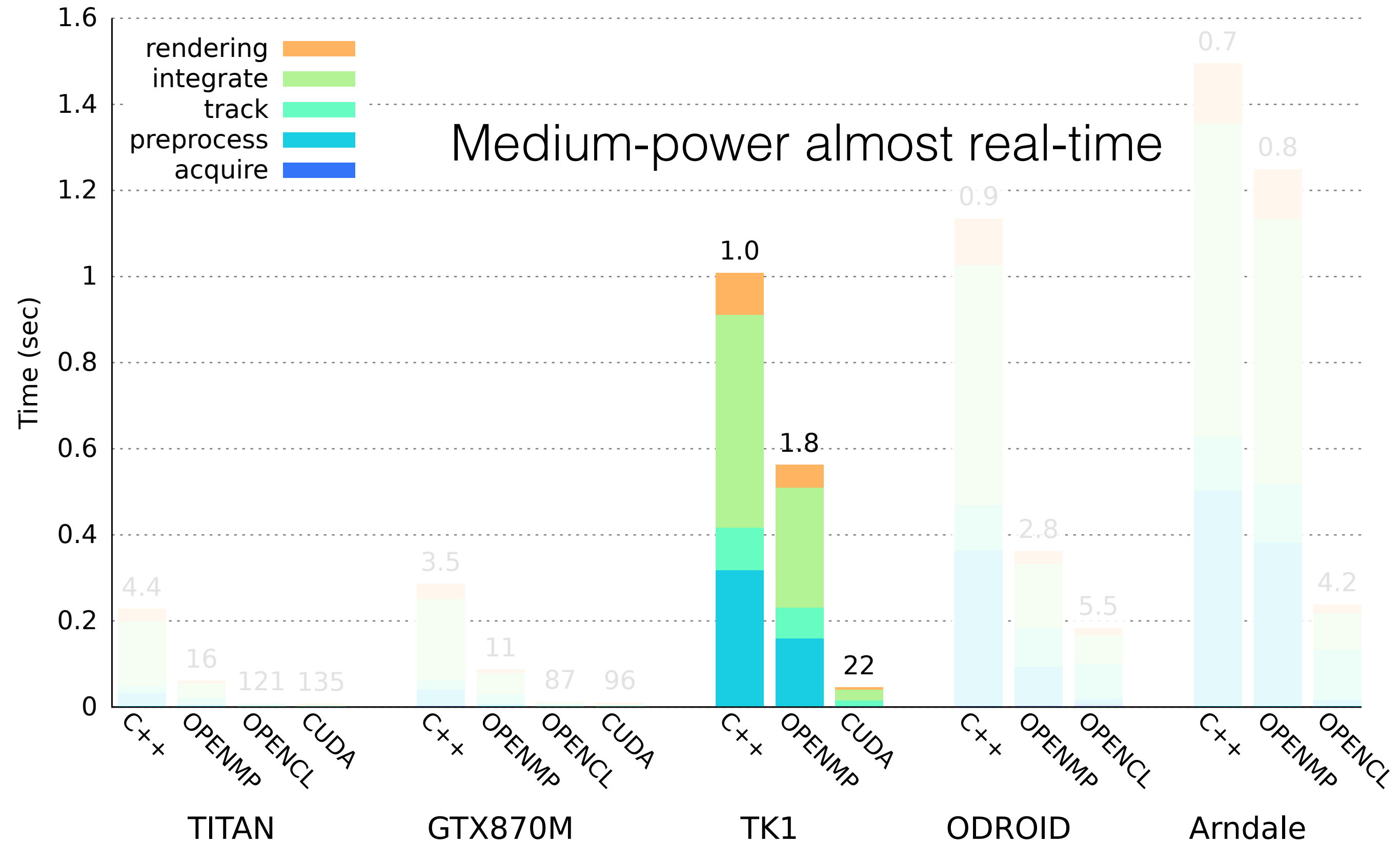
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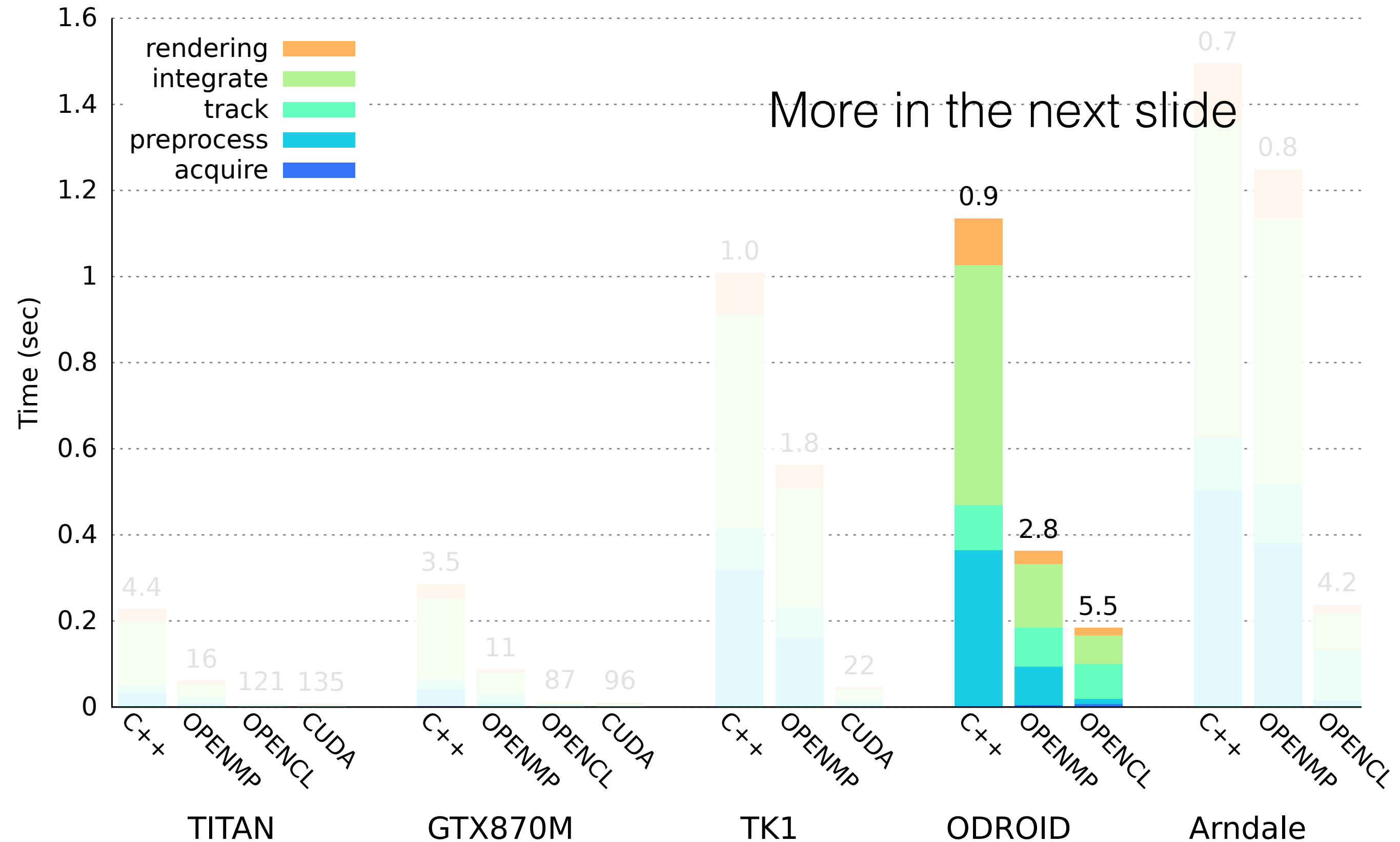
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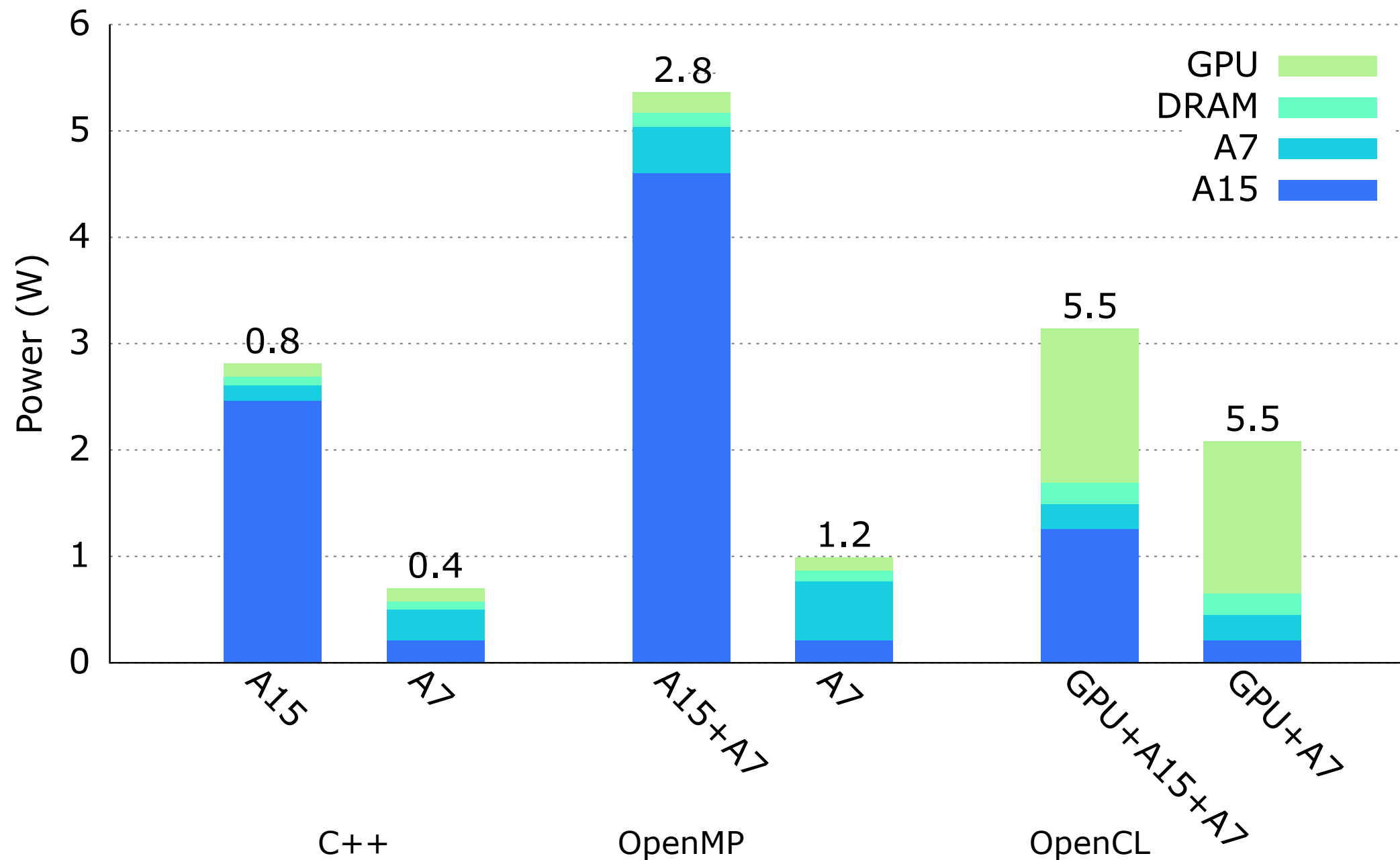
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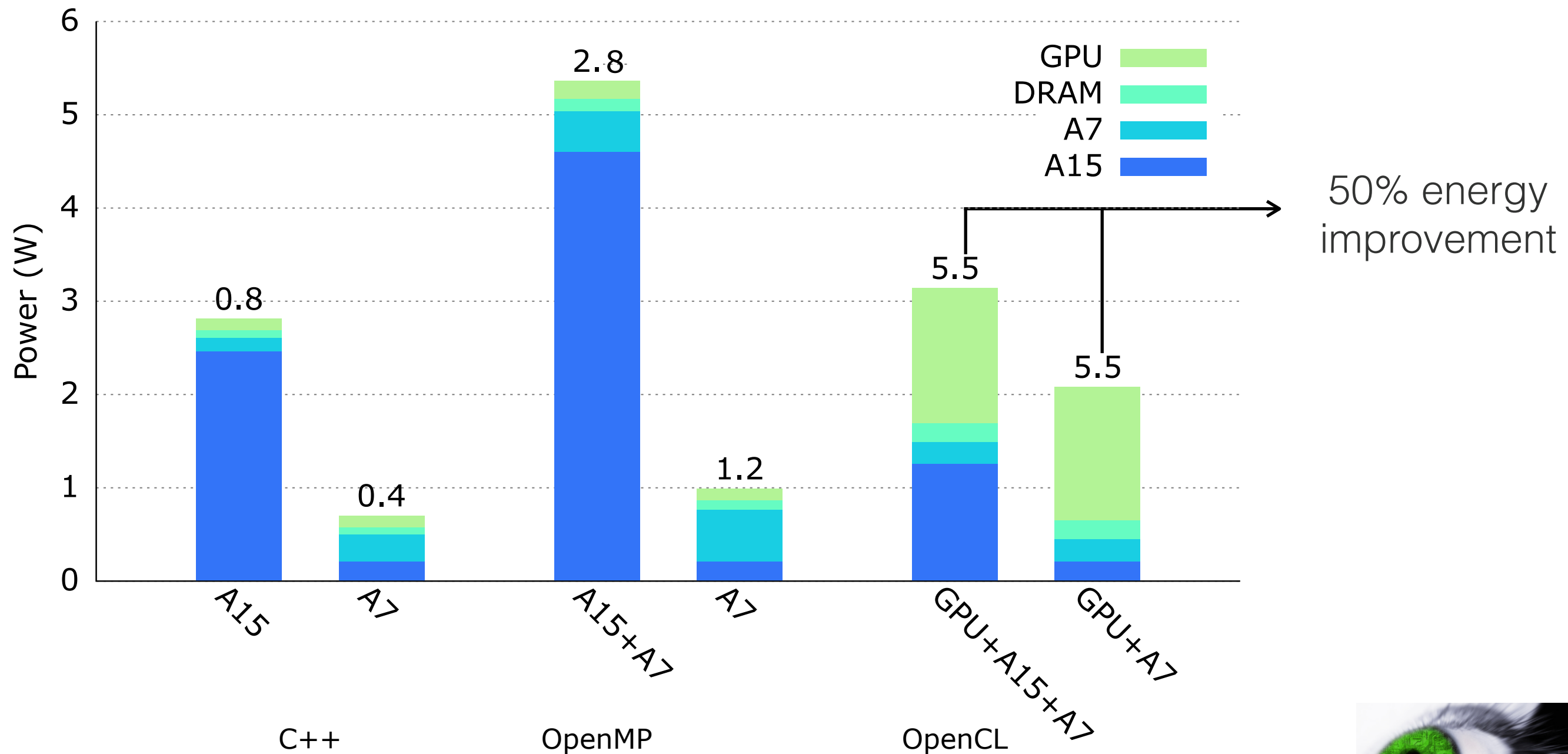
# “Performance” power (ODROID-XU3)

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



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On-board voltage/current sensors and split power rails:  
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- From desktop to embedded
- **SLAMBench**



# SLAMBench today

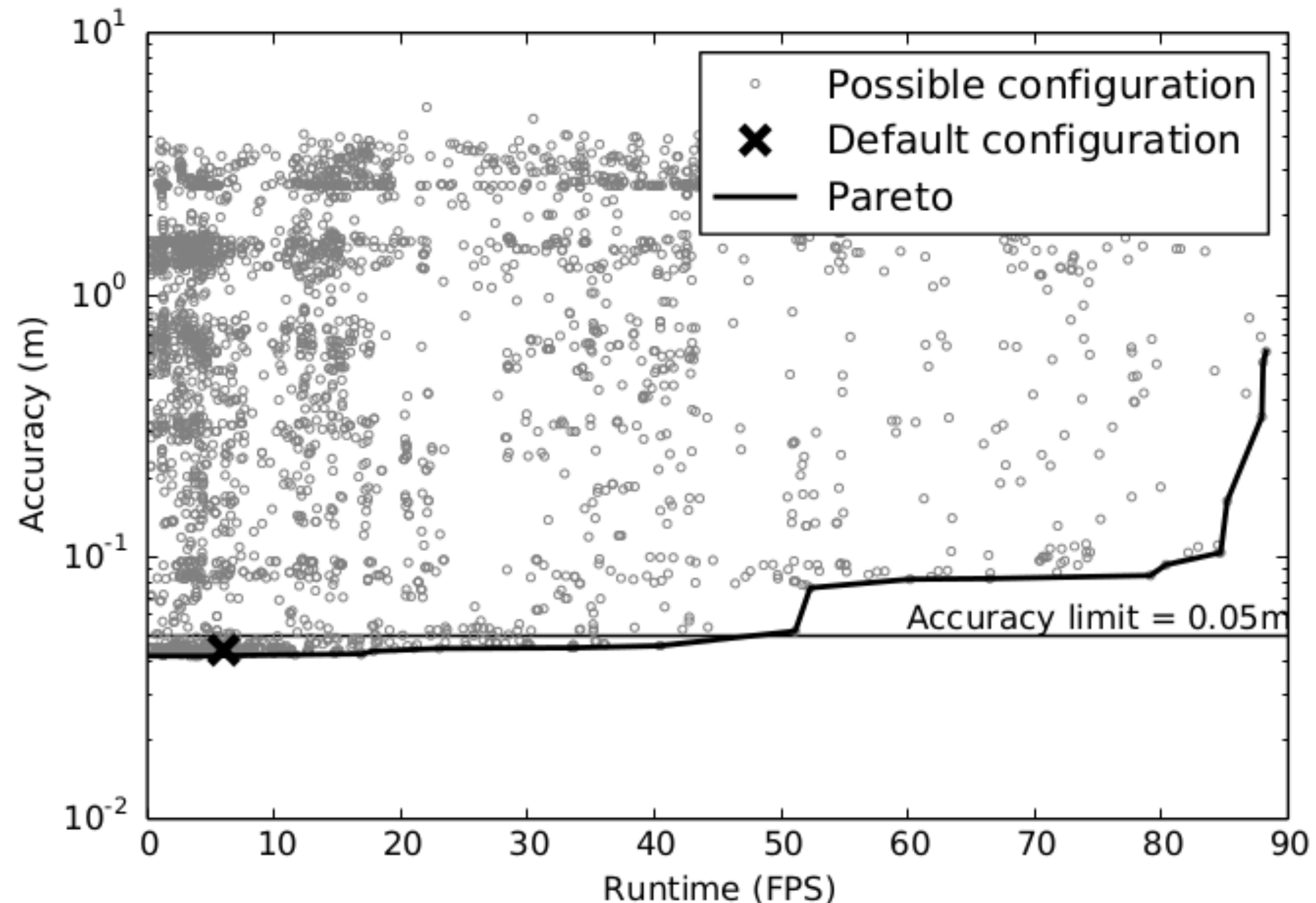
- Publicly released 13/11/2014 (300 downloads today):  
<http://apt.cs.manchester.ac.uk/projects/PAMELA/tools/SLAMBench/>
- "*Introducing SLAMBench, a performance and accuracy benchmarking methodology for SLAM*", Nardi et al., IEEE Int. Conf. on Robotics and Automation (ICRA), May 2015. Available: [arxiv.org/abs/1410.2167](http://arxiv.org/abs/1410.2167)
- 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



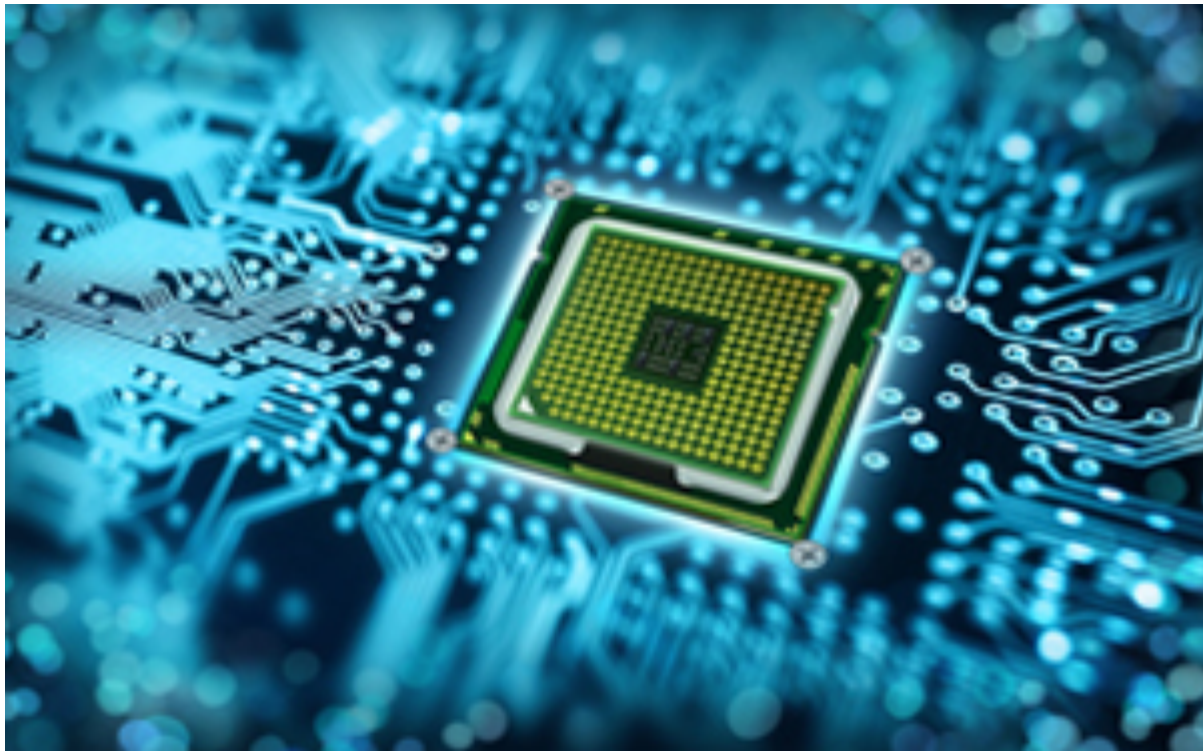
ATE enables aggressive design-space exploration (DSE):

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

An example:  
algorithmic DSE



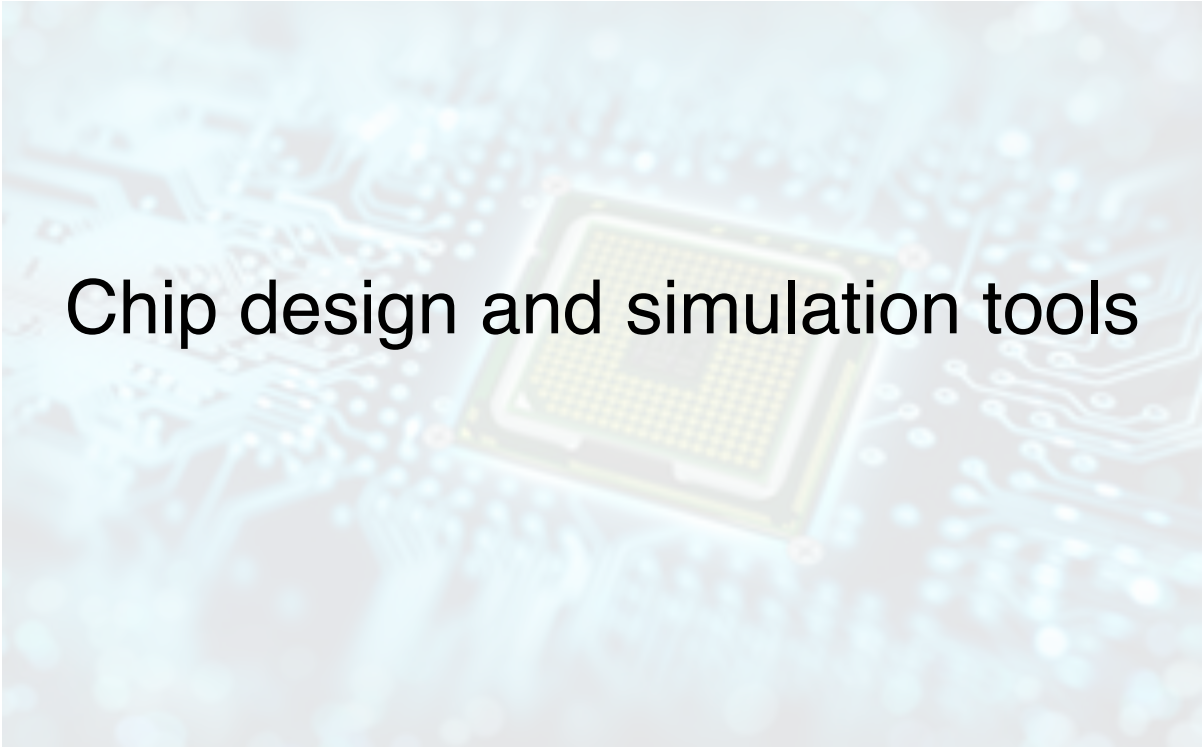
# SLAMBench opportunities



Chip design and simulation tools



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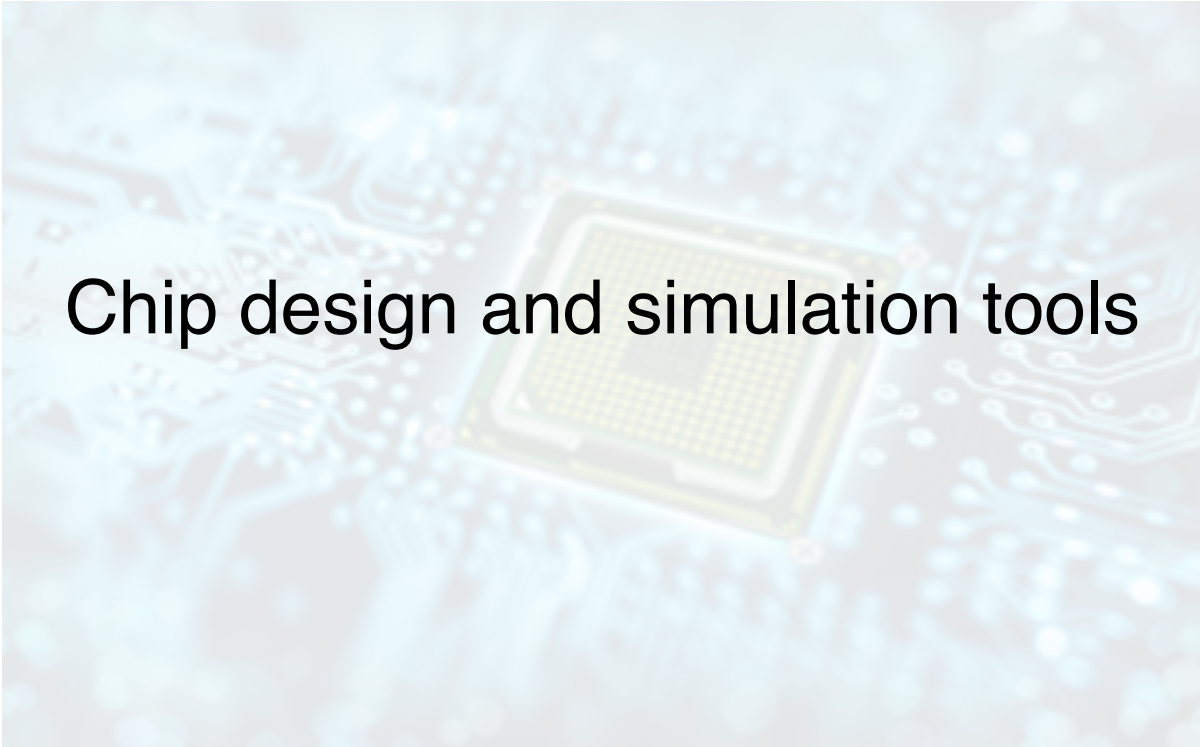


Chip design and simulation tools





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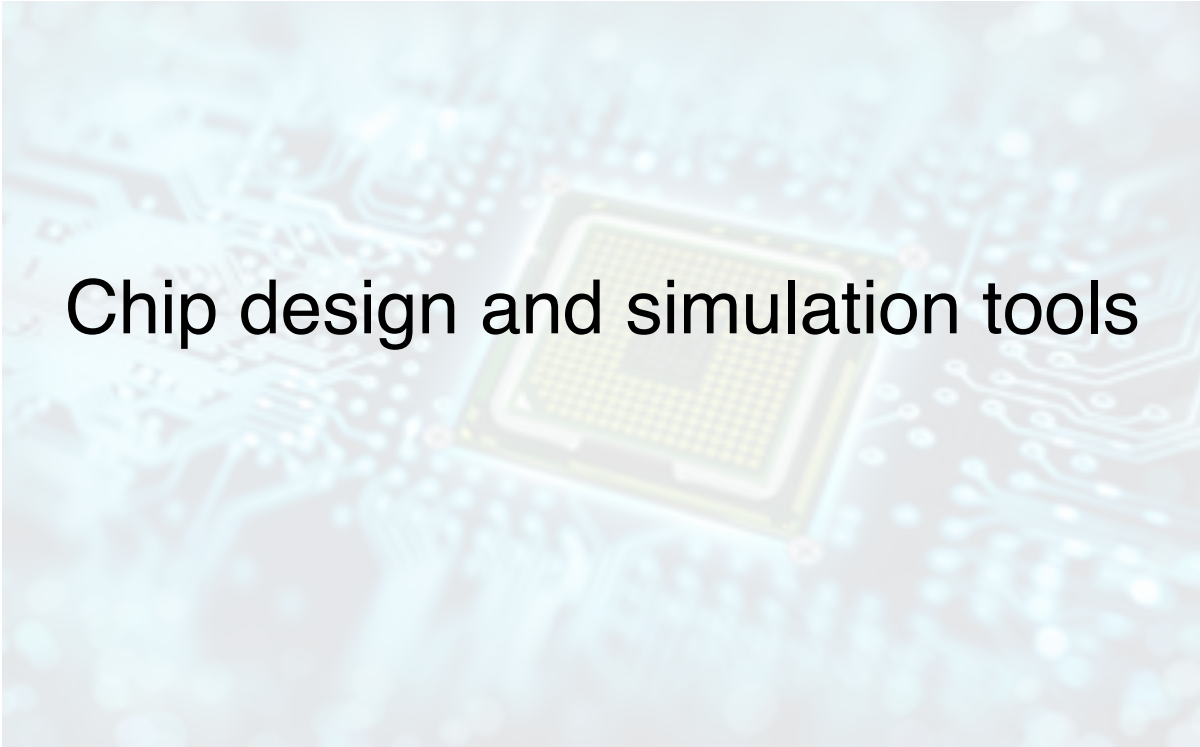
SLAMBench evolution:

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

Kernels can be improved individually



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Kernels can be improved individually

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

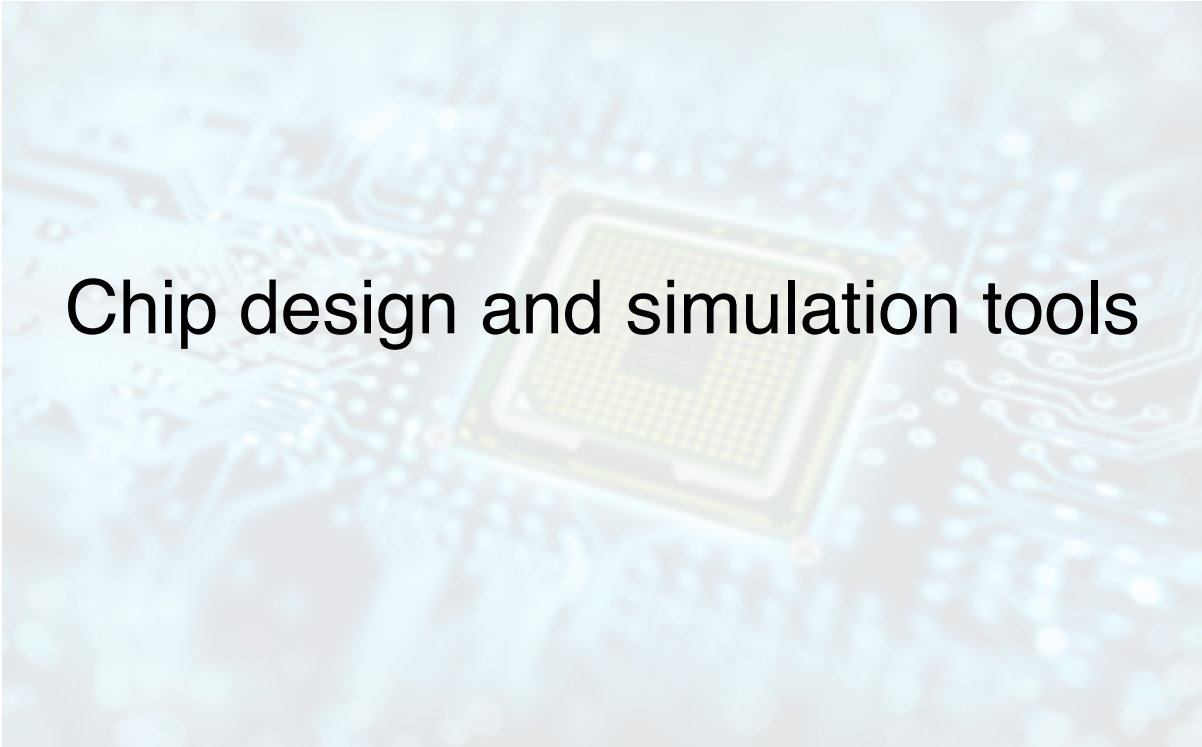
Design-space exploration, e.g. algorithmic, compiler and hardware parameters

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





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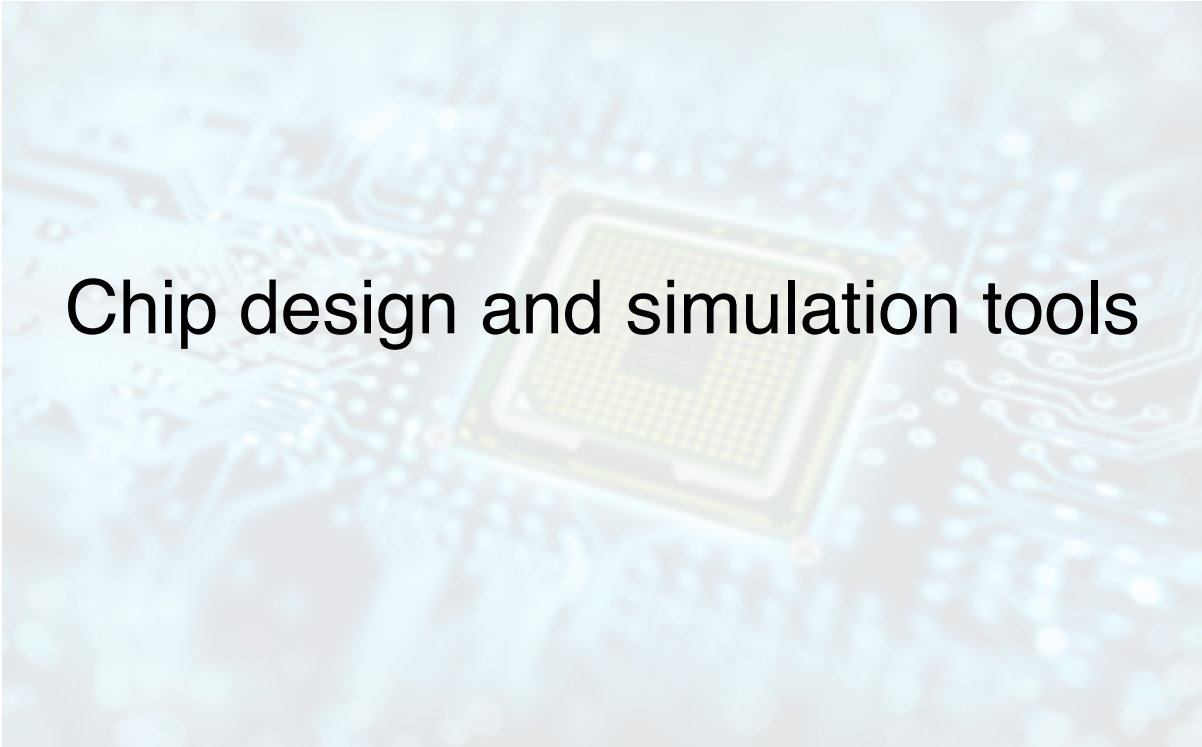
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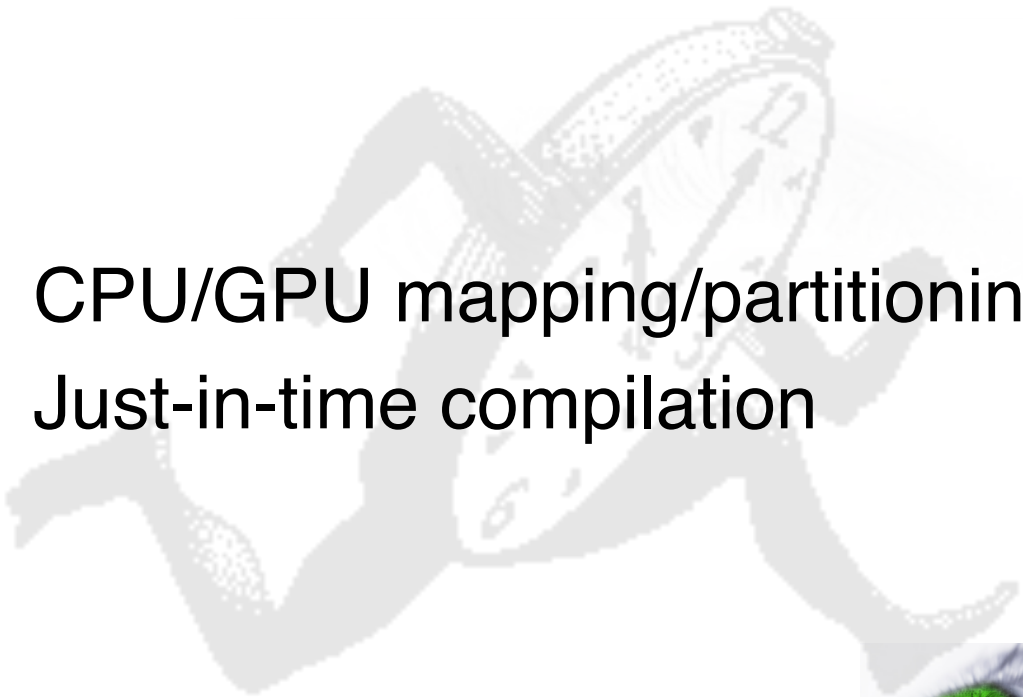
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Kernels can be improved individually

- 
- 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.
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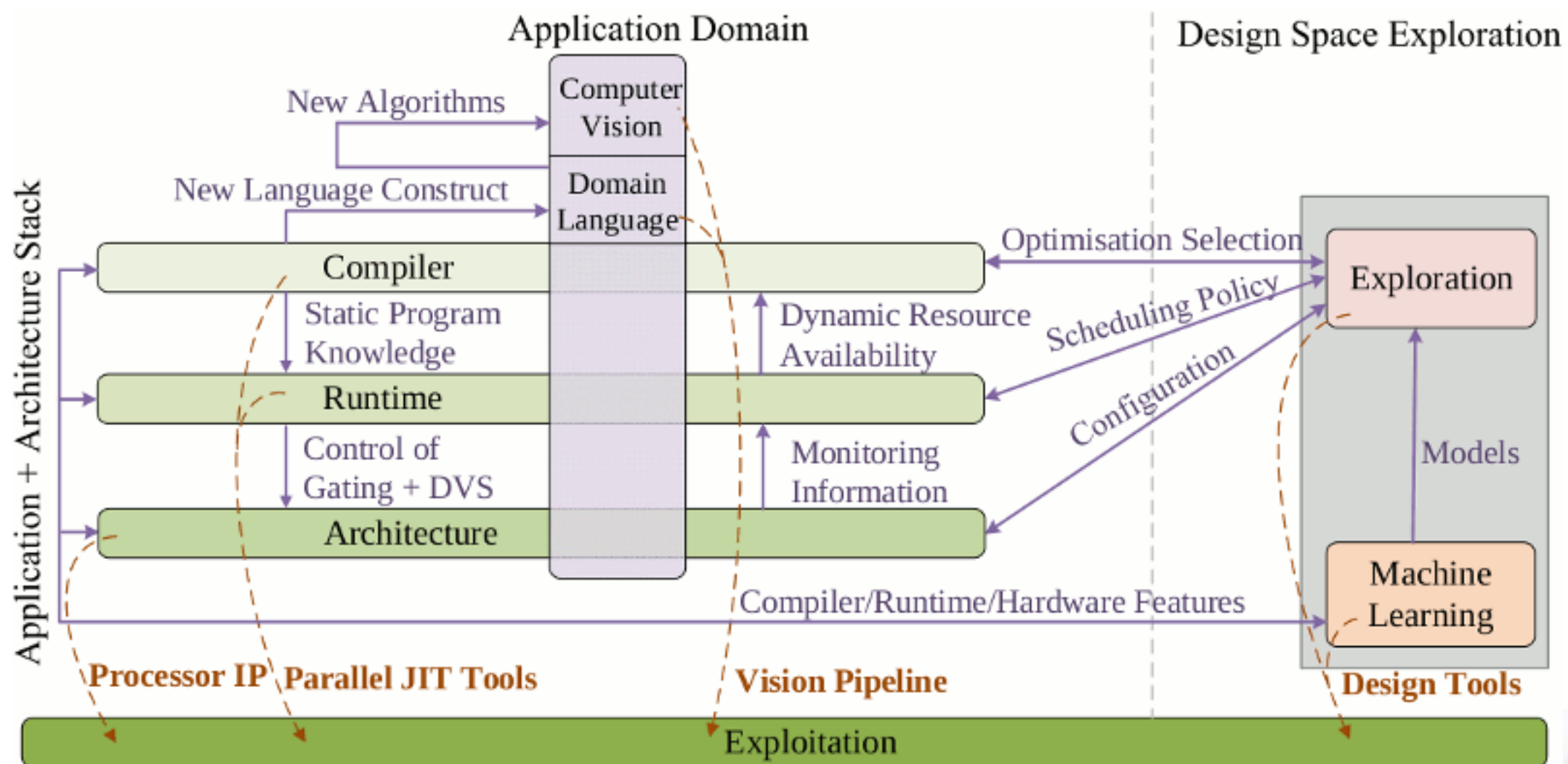
# Backup slides



# PAMELA project

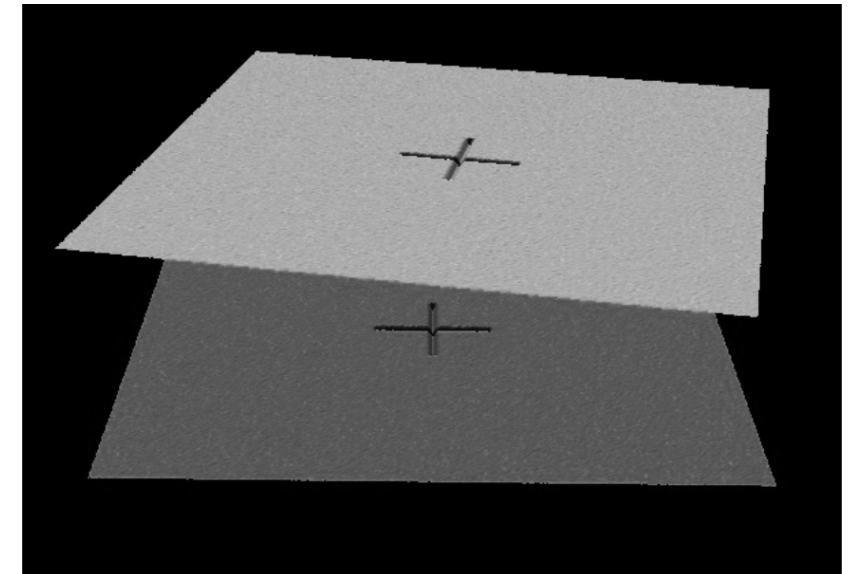
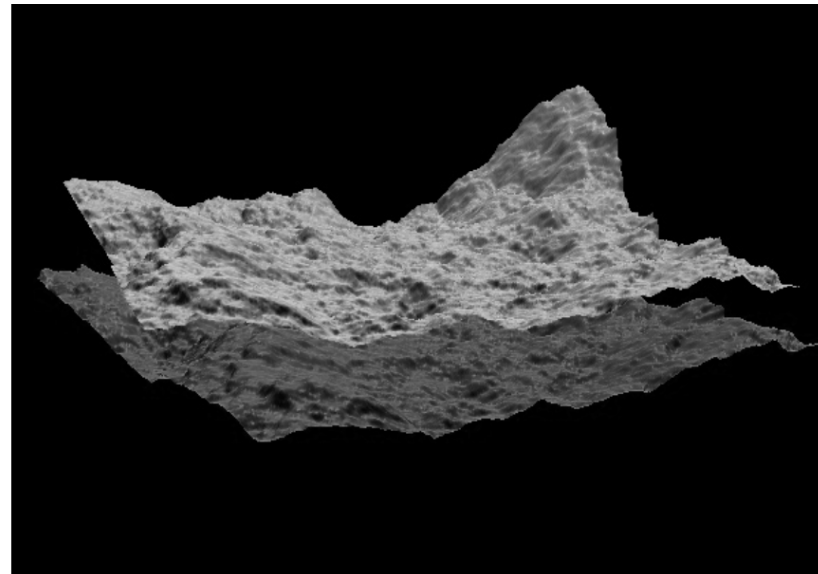
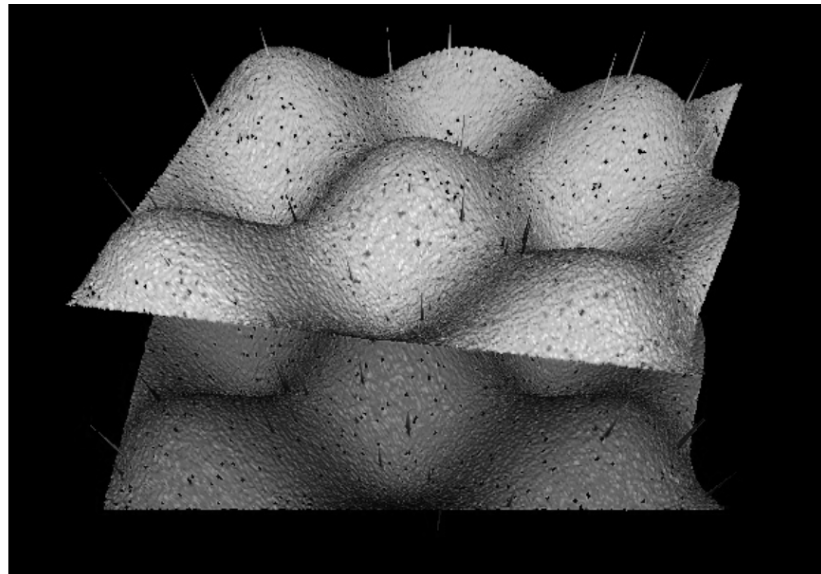
Panoramic Approach to the Many-core LAndscape -  
from application to end-device: a holistic approach

5-year EPSRC grant: Imperial, Manchester and Edinburgh





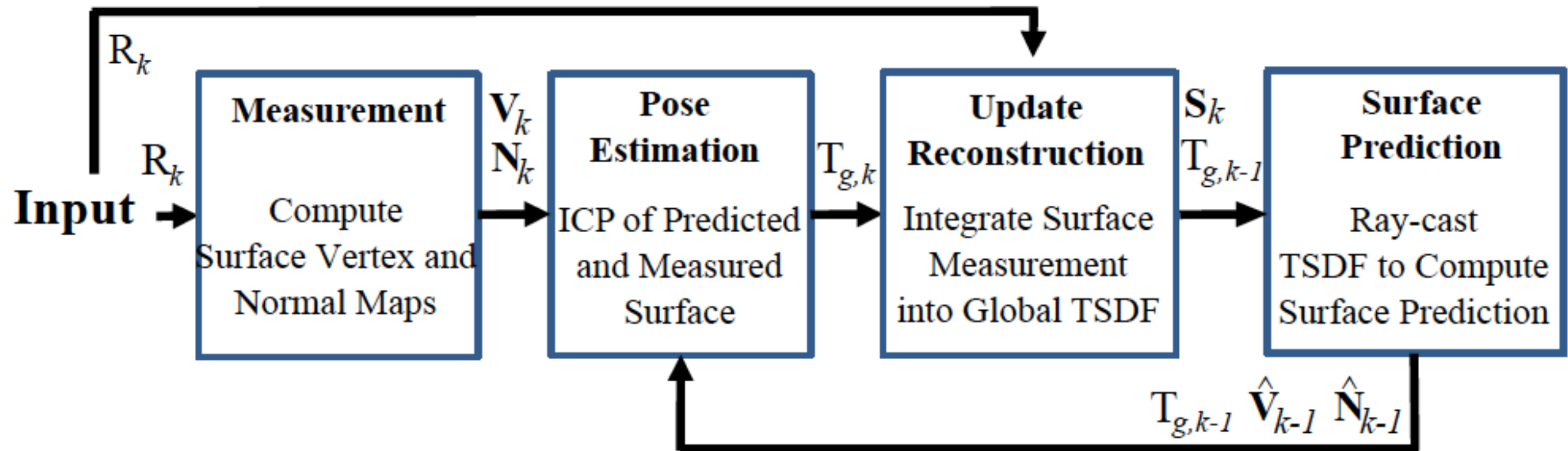
# ICP registration



[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





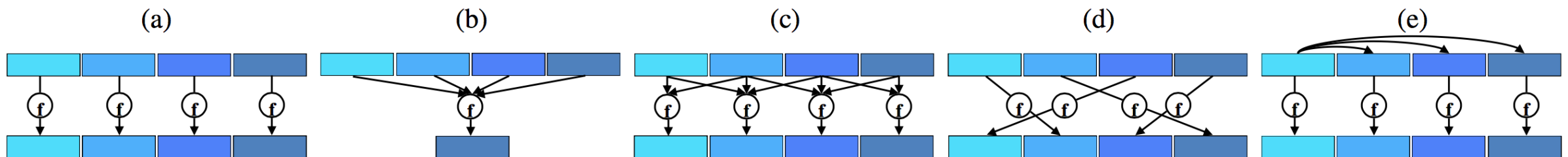
# KinectFusion pipeline

- 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  |

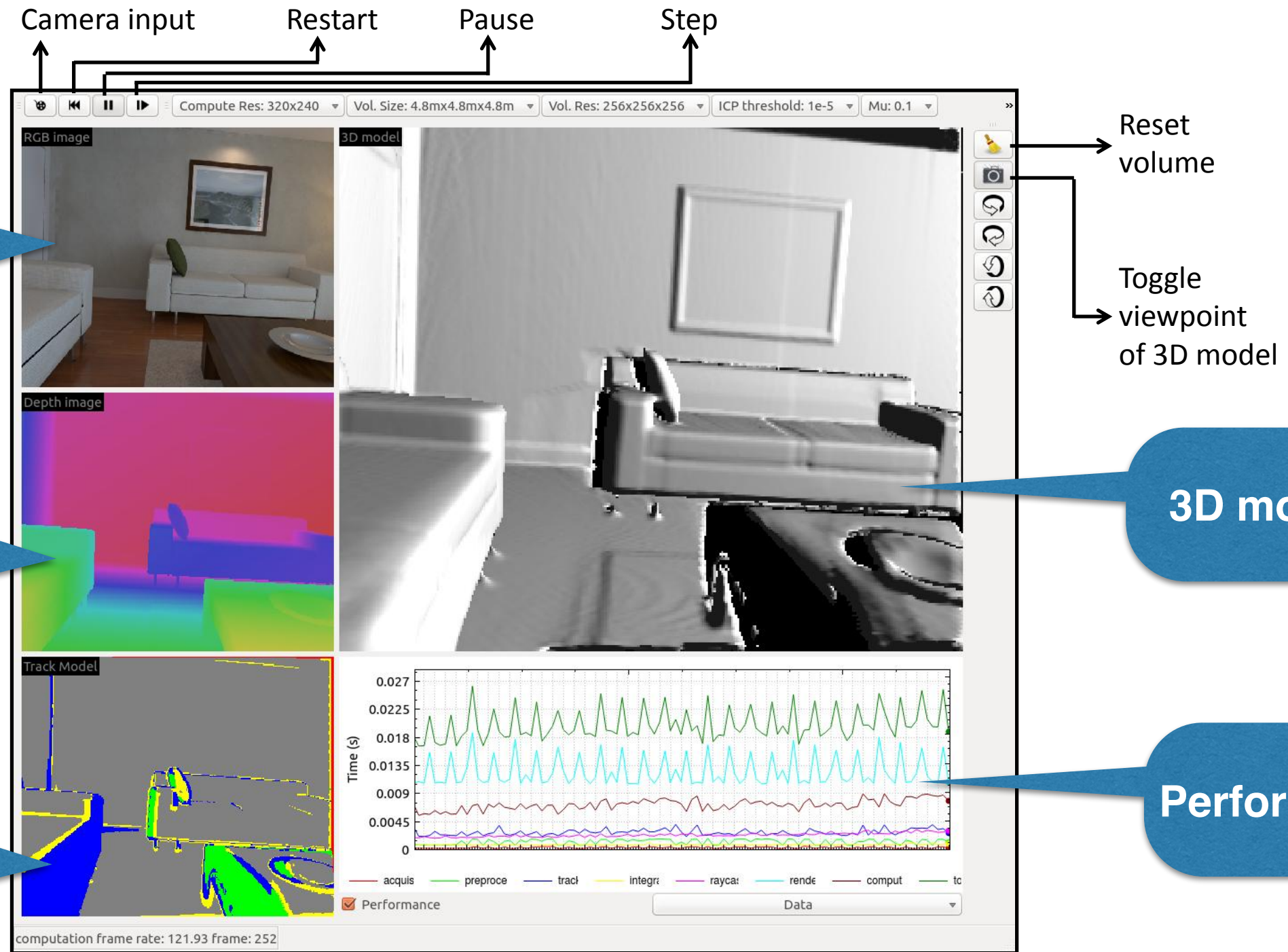


Parallel patterns: (a) Map, (b) Reduction, (c) Stencil, (d) Gather and (e) Search.





# SLAMBench GUI



RGB camera  
(not used)

Depth camera

Tracked  
points





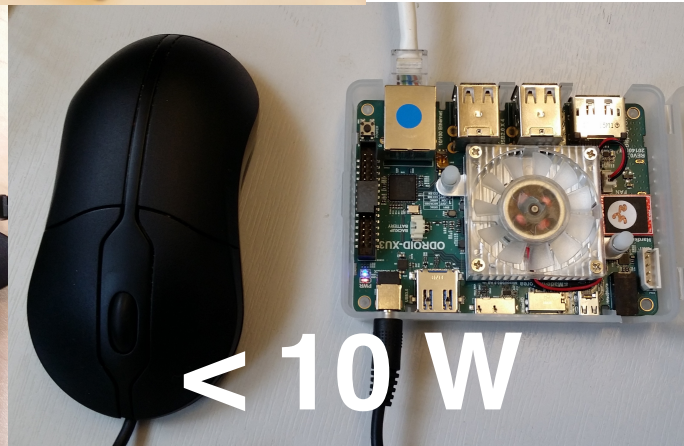
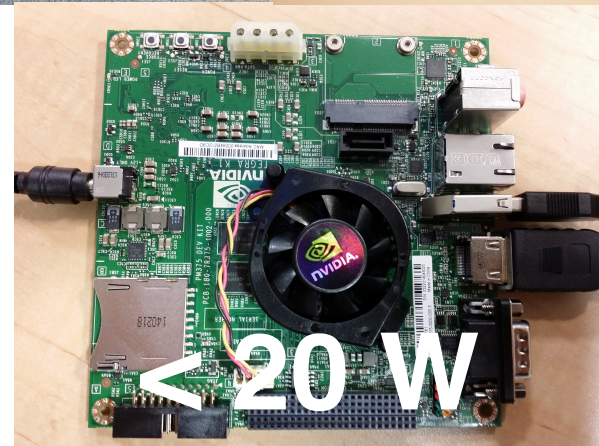
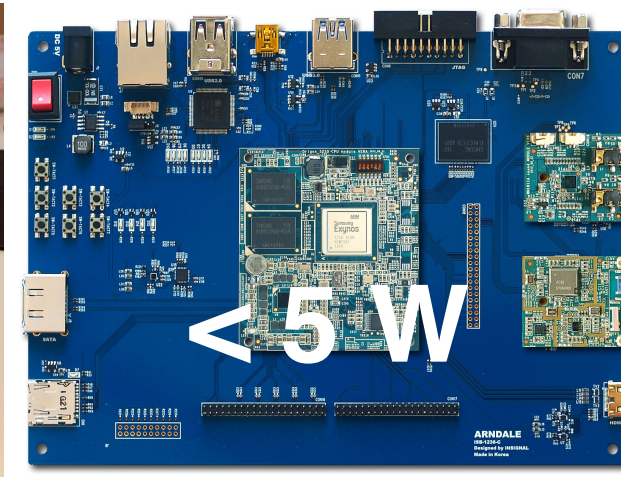
# Platforms

| Machine names             | TITAN           | GTX870M         | TK1                | ODROID (XU3)                   | Arndale           |
|---------------------------|-----------------|-----------------|--------------------|--------------------------------|-------------------|
| <b>Machine type</b>       | Desktop         | Laptop          | Embedded           | Embedded                       | Embedded          |
| <b>CPU</b>                | i7 Haswell      | i7 Haswell      | NVIDIA 4-Plus-1    | Exynos 5422                    | Exynos 5250       |
| <b>CPU cores</b>          | 4               | 4               | 4 (Cortex-A15) + 1 | 4 (Cortex-A15) + 4 (Cortex-A7) | 2 (Cortex-A15)    |
| <b>CPU GHz</b>            | 3.5             | 2.4             | 2.3                | 1.8                            | 1.7               |
| <b>GPU</b>                | NVIDIA TITAN    | NVIDIA GTX 870M | NVIDIA Tegra K1    | ARM Mali-T628-MP6              | ARM Mali-T604-MP4 |
| <b>GPU architecture</b>   | Kepler          | Kepler          | Kepler             | Midgard 2nd gen.               | Midgard 1st gen.  |
| <b>GPU FPU32s</b>         | 2688            | 1344            | 192                | 60                             | 40                |
| <b>GPU MHz</b>            | 837             | 941             | 852                | 600                            | 533               |
| <b>GPU GFLOPS (SP)</b>    | 4500            | 2520            | 330                | 60+30 (72+36)                  | 60 (71)           |
| <b>Language</b>           | CUDA/OpenCL/C++ | CUDA/OpenCL/C++ | CUDA/C++           | OpenCL/C++                     | OpenCL/C++        |
| <b>OpenCL version</b>     | 1.1             | 1.1             | n/a                | 1.1                            | 1.1               |
| <b>Toolkit version</b>    | CUDA 5.5        | CUDA 5.5        | CUDA 6.0           | Mali SDK1.1.                   | Mali SDK1.1       |
| <b>Ubuntu OS (kernel)</b> | 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)    |



# Platforms

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| 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               |
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| 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



```
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



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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_
encl.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
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./kfusion/thirdparty/checkKernels.py kernels.2.openc1.log >> resume.2.openc1.log
hickory%
```

| 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 | 0.000000 | 0.000000 | 0.000000 | 0       | 1    |
| 1      | 0.002724    | 0.000352      | 0.000903 | 0.000467    | 0.000001   | 0.000212  | 0.001722    | 0.004658 | 0.000000 | 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 | 0.000000 | 0.000000 | 0       | 1    |
| 3      | 0.002663    | 0.000335      | 0.000905 | 0.000467    | 0.000604   | 0.000219  | 0.002311    | 0.005193 | 0.000000 | 0.000000 | 0.000000 | 0       | 1    |



# Textual User Interface

Easy  
run

Raw  
data

Sum  
up

For benchmarking purposes,  
SSH and post-processing  
tools friendly



```
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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_
encl.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%
```

| 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 | 0.0000 | 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.
2 Skip kfusion line :
3 Skip nuim line :
4 kfusion file: Valid frames 882 dropped frames: 0
5 kfusion result      : 882 positions.
6 NUIM result        : 880 positions.
7 Working position is : 880
8 Untracked frames: 0
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
18 raycasting Min : 0.000001 Max : 0.003313 Mean : 0.001345 Total : 1.18644400
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
26 halfSampleRobust Count : 1764 Min : 6624 Max : 328480 Mean : 9546.557823 Total : 16840128
27 integrate Count : 443 Min : 270880 Max : 793664 Mean : 485648.469526 Total : 215142272
28 mm2meters Count : 882 Min : 6912 Max : 13632 Mean : 8977.306122 Total : 7917984
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
32 renderTrack Count : 882 Min : 16608 Max : 33088 Mean : 18716.081633 Total : 16507584
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



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hickory%
```

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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 | 0.0000 | 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    |

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# Textual User Interface

Easy  
run

Raw  
data

Sum  
up

High-level blocks statistics

Kernels statistics

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hickory%
```

| frame  | acquisition | preprocessing | tracking | integration | raycasting | rendering | computation | total    | X      | Y        | Z        | tracked | inte |
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17   integration  Min : 0.000001 Max : 0.000821 Mean : 0.000258 Total : 0.22773500
18   preprocessing Min : 0.000284 Max : 0.001884 Mean : 0.000441 Total : 0.38904600
19   raycasting    Min : 0.000001 Max : 0.003313 Mean : 0.001345 Total : 1.18644400
20   rendering     Min : 0.000201 Max : 0.003452 Mean : 0.000572 Total : 0.50420900
21   total         Min : 0.003882 Max : 0.020054 Mean : 0.008510 Total : 7.50584700
22   tracking      Min : 0.000903 Max : 0.006743 Mean : 0.003850 Total : 3.39543600
23
24   ResetVolume Count : 1      Min : 401056 Max : 401056 Mean : 401056.000000 Total : 401056
25   bilateral_filter Count : 882  Min : 139520 Max : 205632 Mean : 159880.199546 Total : 141014336
26   depth2vertex Count : 2646  Min : 5440  Max : 48384  Mean : 10585.167045 Total : 28008352
27   halfSampleRobust Count : 1764  Min : 6624  Max : 328480 Mean : 9546.557823 Total : 16840128
28   integrate Count : 443  Min : 270880 Max : 793664 Mean : 485648.469526 Total : 215142272
29   mm2meters Count : 882  Min : 6912  Max : 13632  Mean : 8977.306122 Total : 7917984
30   raycast Count : 879  Min : 435584 Max : 3284768 Mean : 1323028.423208 Total : 1162941984
31   reduce Count : 12117 Min : 31488  Max : 523488 Mean : 138305.687546 Total : 1675850016
32   renderDepth Count : 882  Min : 9568  Max : 39904  Mean : 12002.975057 Total : 10586624
33   renderTrack Count : 882  Min : 16608  Max : 33088  Mean : 18716.081633 Total : 16507584
34   renderVolume Count : 221  Min : 479840 Max : 3143200 Mean : 1338055.819005 Total : 295710336
35   track Count : 12117 Min : 13472  Max : 129344 Mean : 51505.231988 Total : 624088896
36   vertex2normal Count : 2646  Min : 8544  Max : 73504  Mean : 22275.362056 Total : 58940608
```



# “Performance”: energy (ODROID)

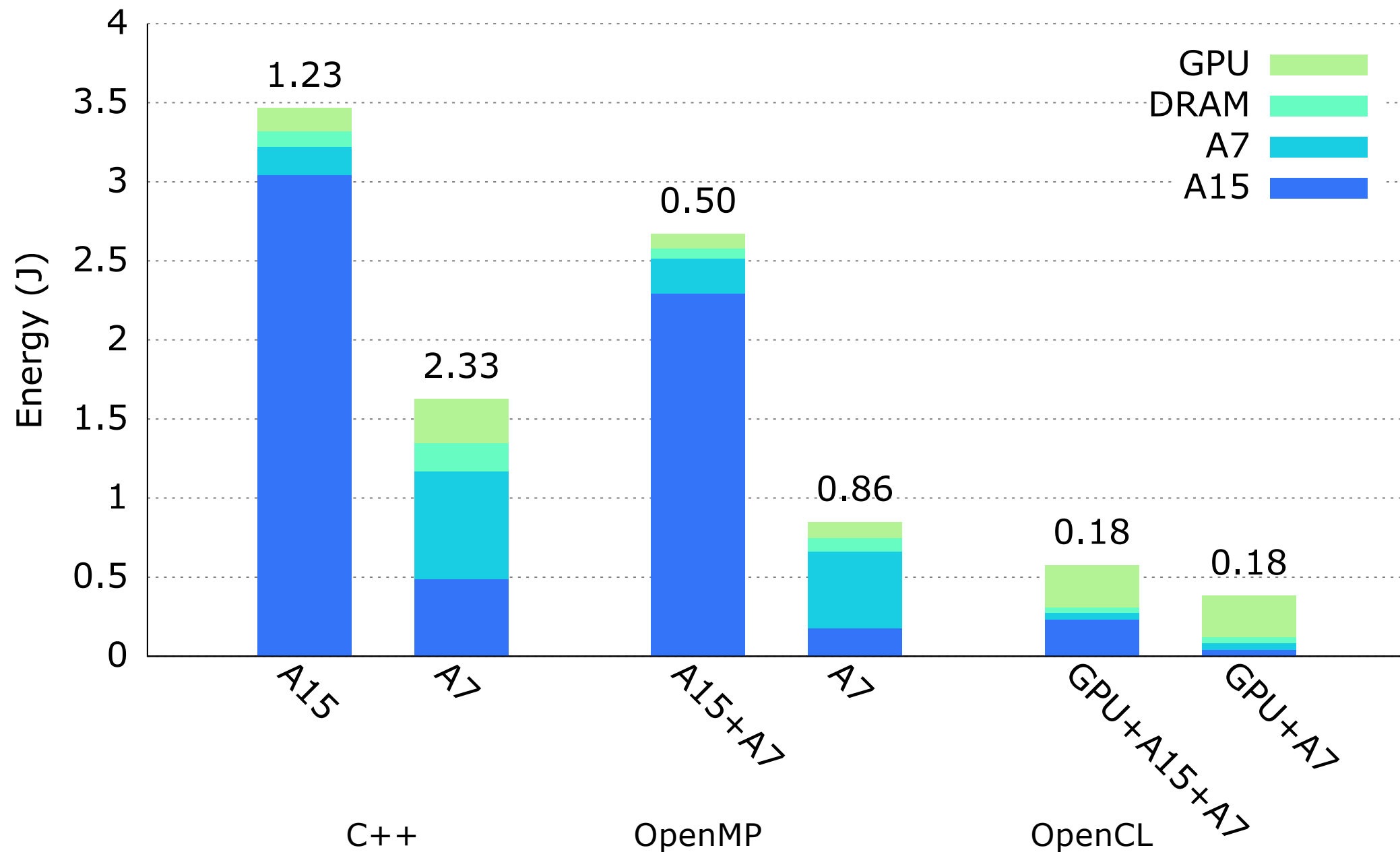
On-board voltage/current sensors and split power rails:  
power measured individually on big (A15), LITTLE (A7), GPU and DRAM





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On-board voltage/current sensors and split power rails:  
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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**



# Copyrights

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