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Accelerating Neural Network Inference in space by offloading heavy operations on systolic arrays

Constantin Papadas², Ioannis Katelouzos², Agamemnonas Kyriazis², Tilemachos

Tsiapras², Roland Brochard¹, Jérémy Lebreton¹, Lucas Marti¹, Evangelos Kioulos², Tomasz

Grzegory², Tim Helfers⁴ and Laurent Hili³,

¹Airbus Defence & Space, Toulouse Toulouse, France

²ISD S.A.Athens GREECE

³ESA-ESTEC Microelectronics Section (TEC-EDM), THE NETHERLANDS

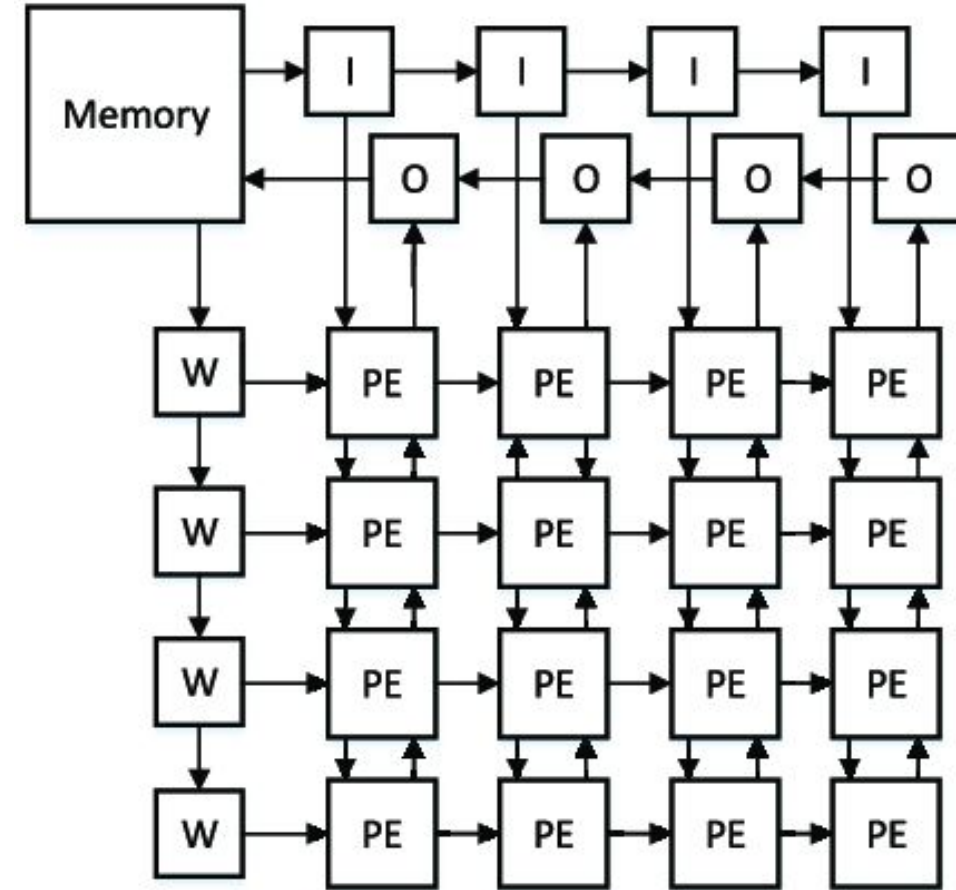
⁴AIRBUS DEFENCE & SPACE GmbH, Taufkirchen, GERMANY

Outline

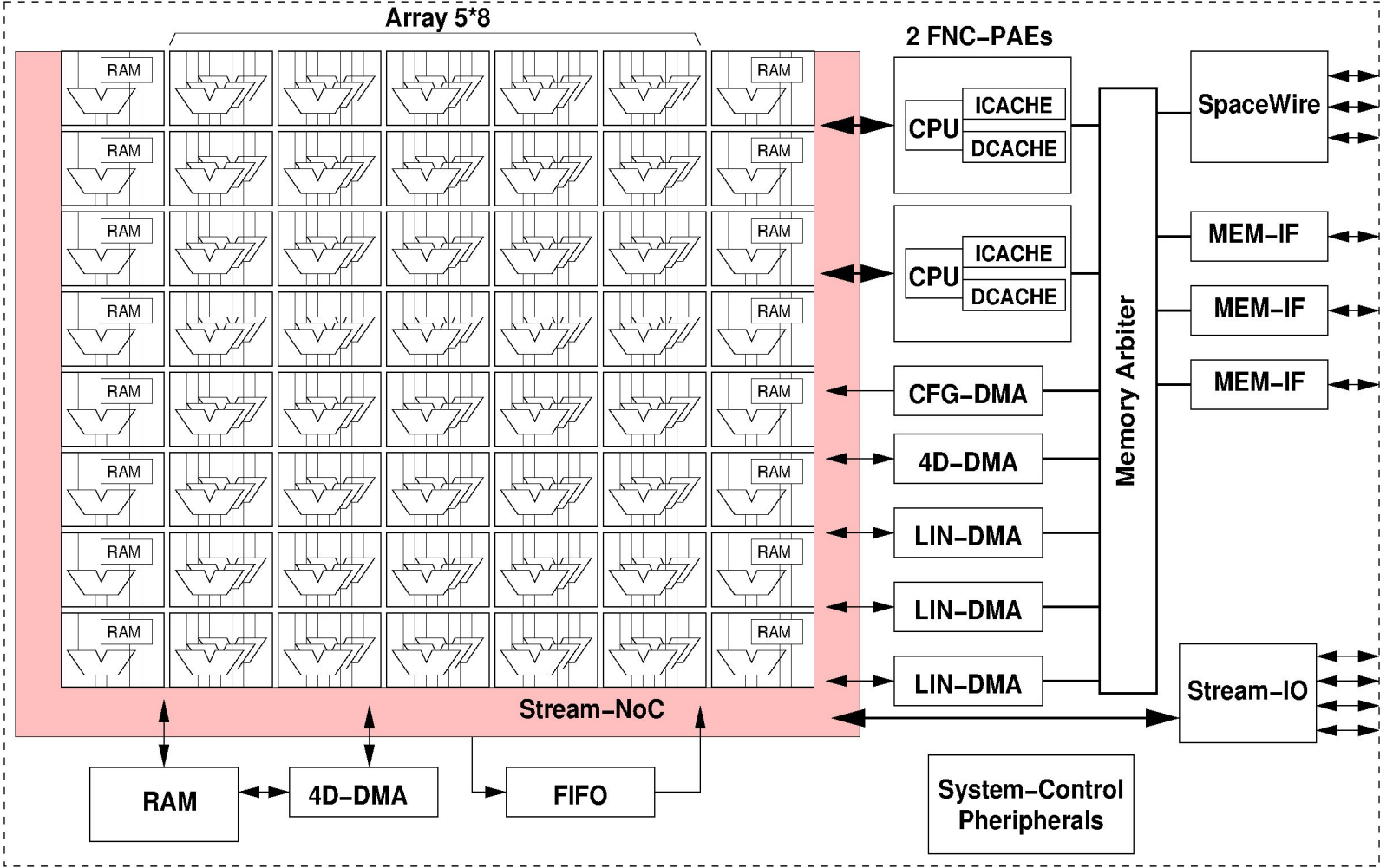
- Systolic Arrays and HPDP40
- Use cases
- Methodology
- Results
- Conclusion

Systolic Arrays

- Parallel processing Architecture
 - A grid of processing elements (PEs) that compute and pass data between them.
- Continuous Data flows
 - Inputs pass through the array in a synchronized pattern, allowing continuous computation without waiting for global memory
- Optimized for Matrix operations.
- Direct local communication
 - Each PE only talks to its neighbors, reducing the need for complex interconnects or global buses
- Deterministic Data Flow
 - Predictable timing and control make them suitable for real-time systems and fault-tolerant designs
- Energy Efficient
 - Optimized for multiply-accumulate operations, which dominate many space AI workloads



HPDP40 is a systolic array SoC



European very low power hardened device

HPDP40 - features

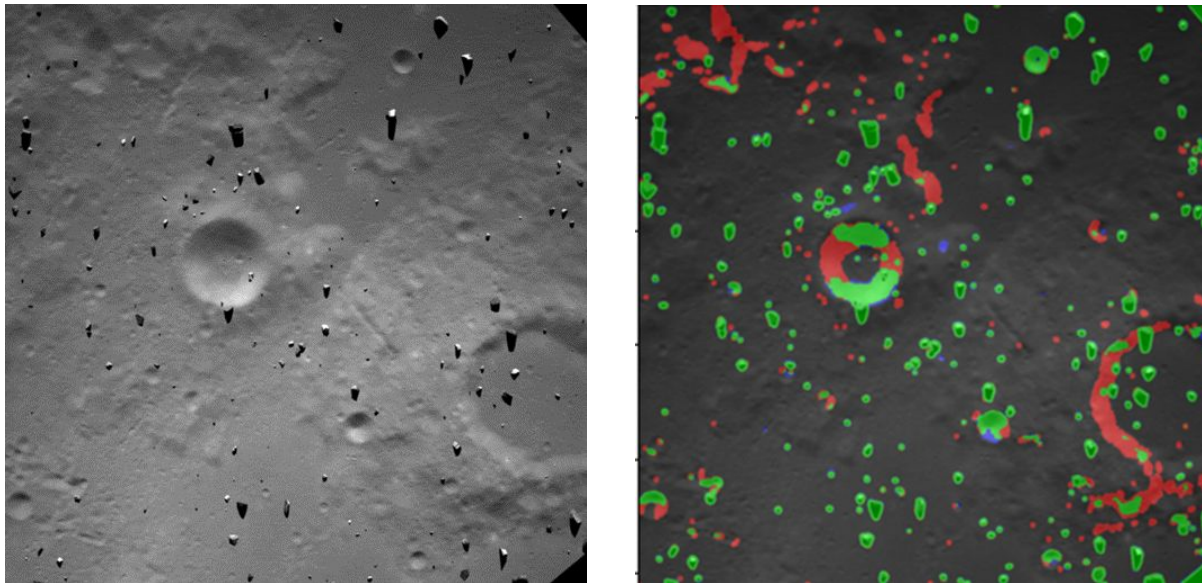
- 40Gops of arithmetic operations (floating point operations can be emulated)
- 1.65W power consumption
- **Re-configuration on the fly (1us)**
- fast boot time (few ms)
- 4x 1.4Gbps Streaming Ports
- >4 MB on-chip SRAM
- 256MB SDRAM
- Very low BoM solution
- TID > 300Krad
- SEL free for LET up to 72.2 MeV-cm²/mg @ 90°C junction temperature and max supply voltage
- Worst case SEFI under radiations: 1.25E-4 errors/device/day

European very low power hardened device

LiDAR-Free HDA

VCN is an enabler for complex missions requiring onboard autonomy for example Lunar landers

- **Terrain relative navigation (AbsNav, RelNav)**
- **Hazard Detection and Avoidance**
 - **Camera-based** hazard detection algorithm
 - U-net Convolutional Neural Network
 - LiDAR-based solution are costly and heavy
 - So far only **very small neural networks** can be used with existing platforms (1000 parameters)
 - Works very well on rocks/roughness, less on slopes



Well-detected hazards

Undetected hazards

Vision Based Navigation

Planetary Landing

In-orbit rendezvous

Debris removal

Space Situational Awareness

Rovers

LiDAR-Free HDA

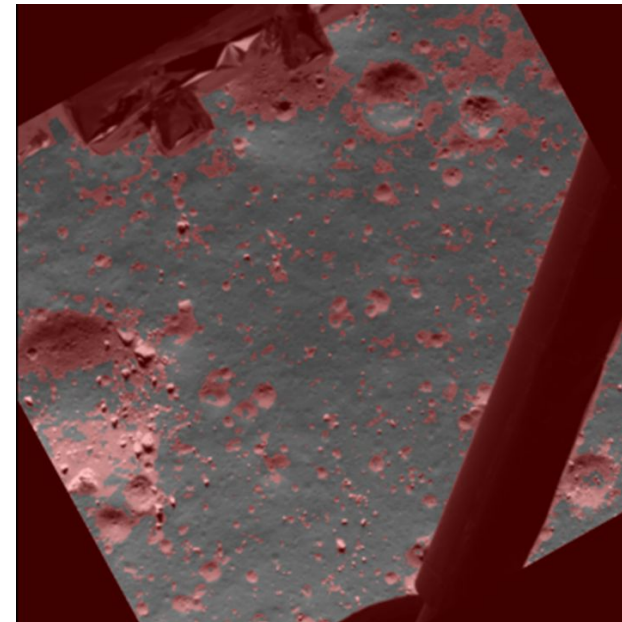
Current targeted platforms can only run small networks

- CPUs have limited processing capabilities
- Tensor convolution is heavy

New hardware acceleration could bring

- Potentially **bigger networks**
 - More robust => More challenging scenarios
- Enable online 3D estimation to help with the detection of slopes
 - No LiDAR => Less costs, less weight
- More complicated architectures with **more operations**
- **Earlier Detection to improve Avoidance strategy**
- **Running the algorithm multiple times**

Chang'E 3 Descent image from NavCam and Hazard detection



Vision Based Navigation

Planetary Landing

Software is important

Hardware is not the end of the story !

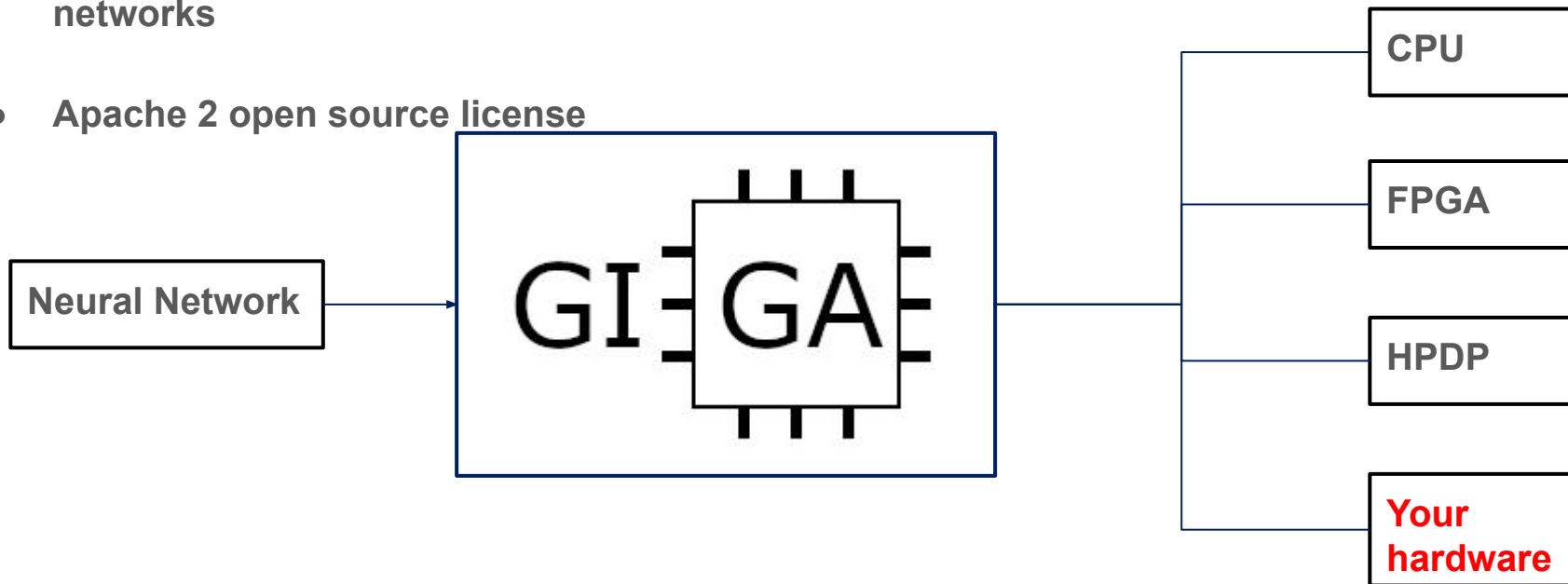
- **Acceleration is better than dedicated hardware**
 - HW accelerated common algorithmic primitives can be reused
 - Dedicated implementations are costly
- **We need good software along with the hardware !**
 - We want to target an API, not a platform
 - Focus on the added algorithmic value, not the implementation details close to the hardware
- **Already validated software blocks accelerate industrialisation of solutions**
 - Why validate a 2D convolution every time ?

GIGA

A new API for
porting Neural
Networks

Generic Interface Generic Accelerator

- **Our solution : GIGA**
 - **Platform independent API** for porting neural networks
- **Make any accelerator easy to use**
 - An accelerator implementing the API is (almost) ready to use as is
- **Already three ongoing projects (GENEVIS2, HPDP, NEURAVIS) use GIGA for porting neural networks**
- **Apache 2 open source license**



GIGA

A new API for
porting Neural
Networks

Generic Interface Generic Accelerator

- **Operations**

- 2D convolution (Backbone of many classical networks)
- Dense Layers
- ...

- **Memory**

- Memory layout and allocation is carefully considered when transcoding the network into C
- The memory usage is solved and explicit before flight

- **Validation**

- A network is a C-code with no dependencies
 - No proprietary code
 - The entire network in one C file
- C-code is generated from the very explicit and human readable NNEF format
 - Non-proprietary format
 - **Explicit and fully specified operations**



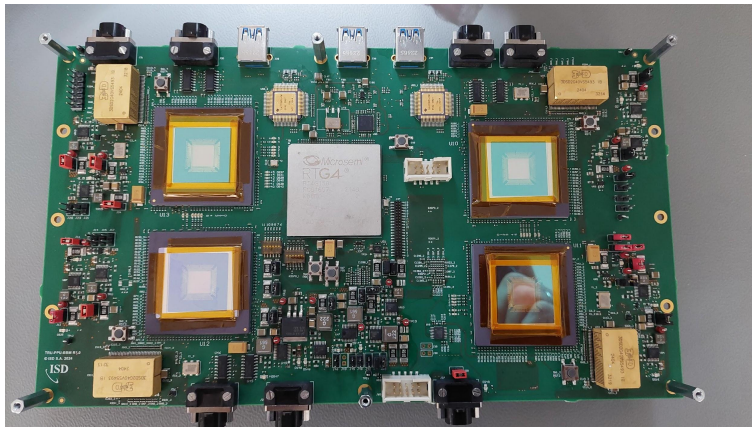
GIGA

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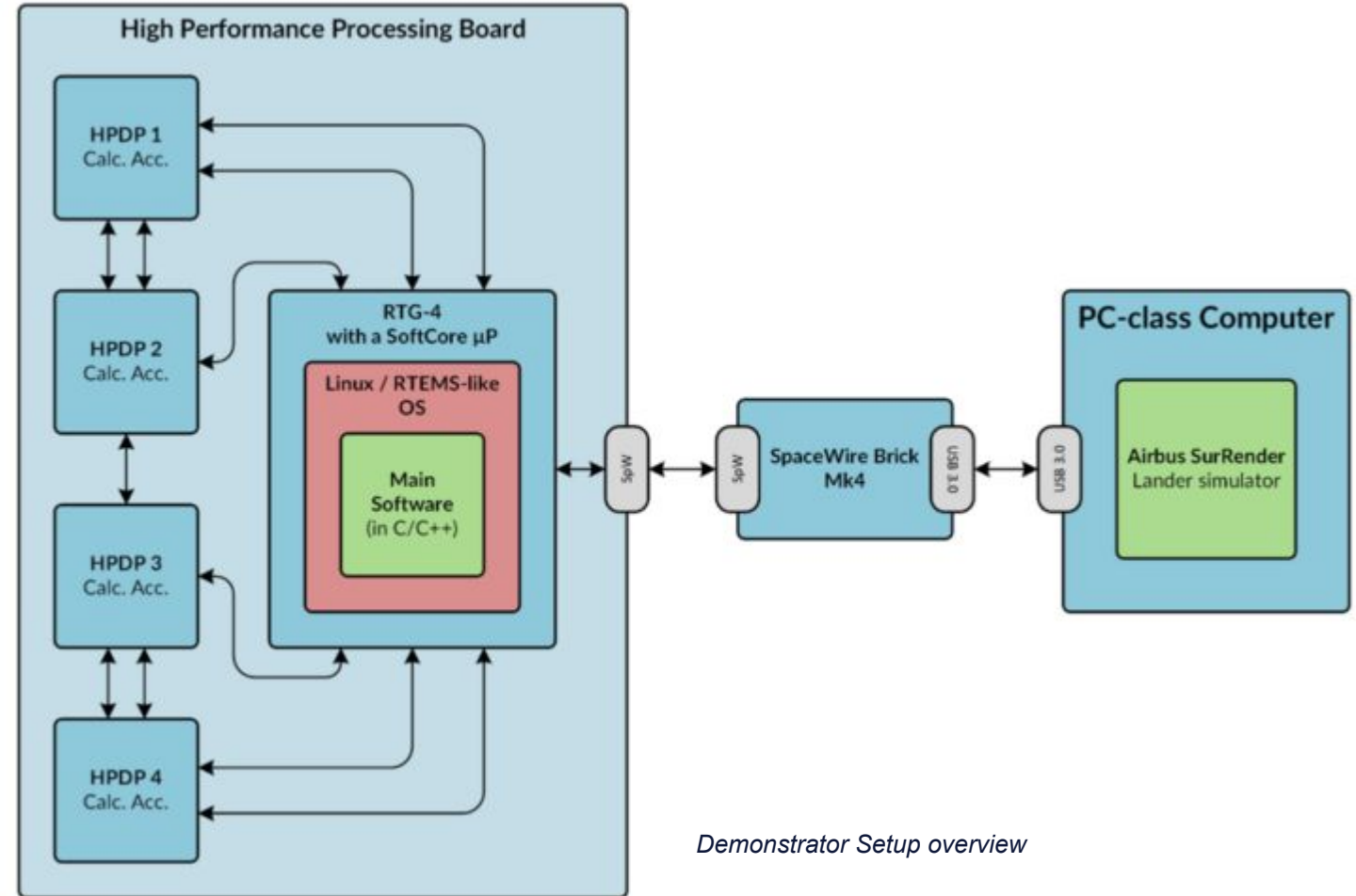
Methodology - Demonstrator

Demonstrator Components:

- The HPPB board.
 - A board comprising of 4 HPDP chips and one FPGA
- Host computer
- SurRender image simulator
- Host Demonstrator Application Software



HPPB Board



Demonstrator Setup overview

Methodology - Simulator



SURRENDER software: Airbus high performance image simulator specialized for space applications (MSR ERO, JUICE, EL3/Argonaut, in-orbit rendezvous, SSA, etc.)

- ✓ *Physical rendering in raytracing (illumination, shadows, brightness, ...)*
- ✓ *Smart raysampling, RAM mgt, double prec., giant datasets rendered continuously*
- ✓ *Flexible modelling interface: projection models, BRDF, camera models, procedural textures* ⇒ « Descent Image Generator » DIG
- ✓ *Tradeoff high quality images vs real-time*

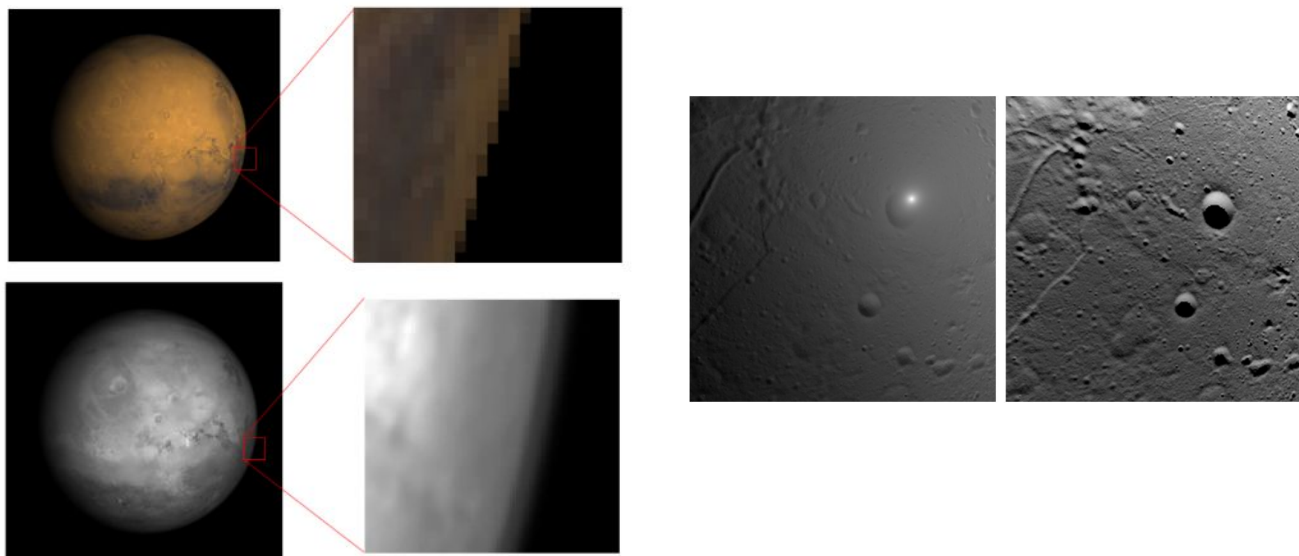


Figure 2: Rastering (OpenGL, DirectX) vs high quality raytracing (SurRender)

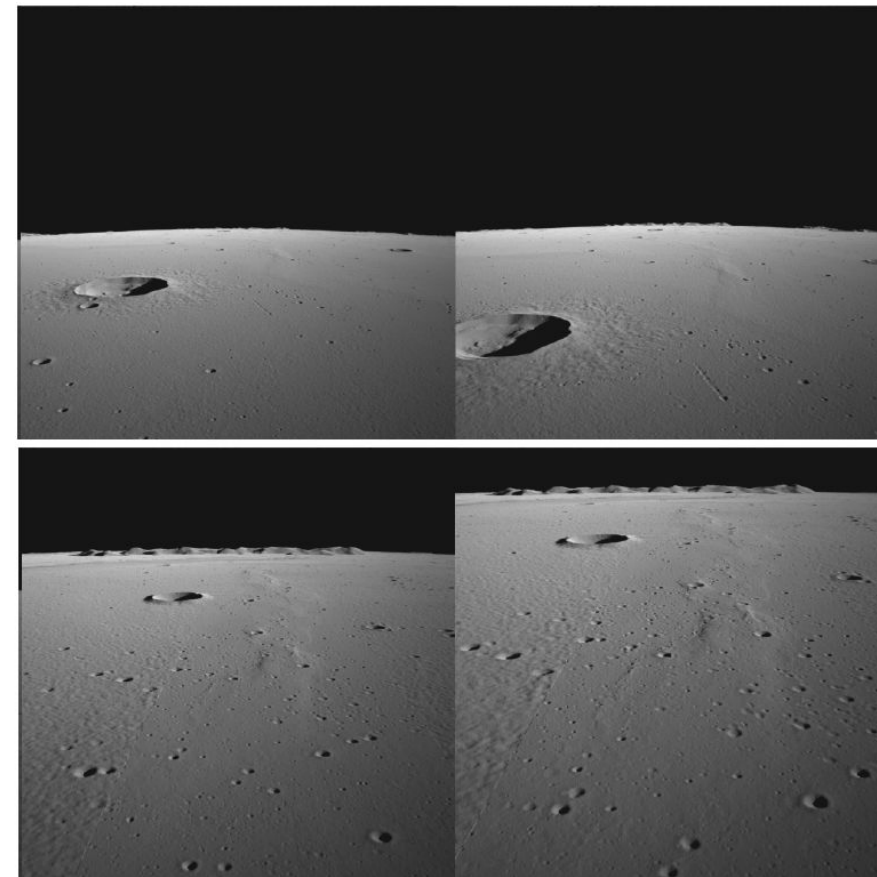
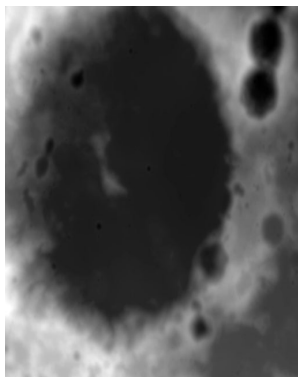


Figure 1: Examples of Moon images rendered with the SurRender software (dataset NAT-DATA-S5-slow) Here the site is the one of Chang'e-3 lander, the Lunar surface model is a fusion of a low resolution DEM and a high-resolution one in the central region, with constant albedo and a Hapke BRDF model.

Methodology - Simulator design

Lunar terrain model:

- 260 × 209 km DEM¹ of Von Karman crater at 1 m (MADNET 2.0²)
- Textures: 370 monocular LROC NAC³ images
- Test / train / valid datasets to avoid bias



Input:

- Camera pose and Sun position (SPICE kernels)
- 70° FoV, 1024x1024 pixel resolution, PSF
- Sample altitudes [500–1000 km] (500m => GSD⁴ ~0.5 m/pixel)
- Slopes and craters from the DEM
- Synthetic boulders are distributed on the surface with models for size, density, albedo and shapes from the scientific literature

Output:

- 11,000 images
- Label maps: slopes, craters, boulders (➡ hazards)
- Depths maps

¹ DEM: Digital Elevation Model

² UCL-MSSL_Moon_von_Karman_V1.0, <https://doi.org/10.57780/esa-fb921t3>

³ LROC NAC: Lunar Reconnaissance Orbiter Narrow Angle Camera

⁴ Ground Sample Distance

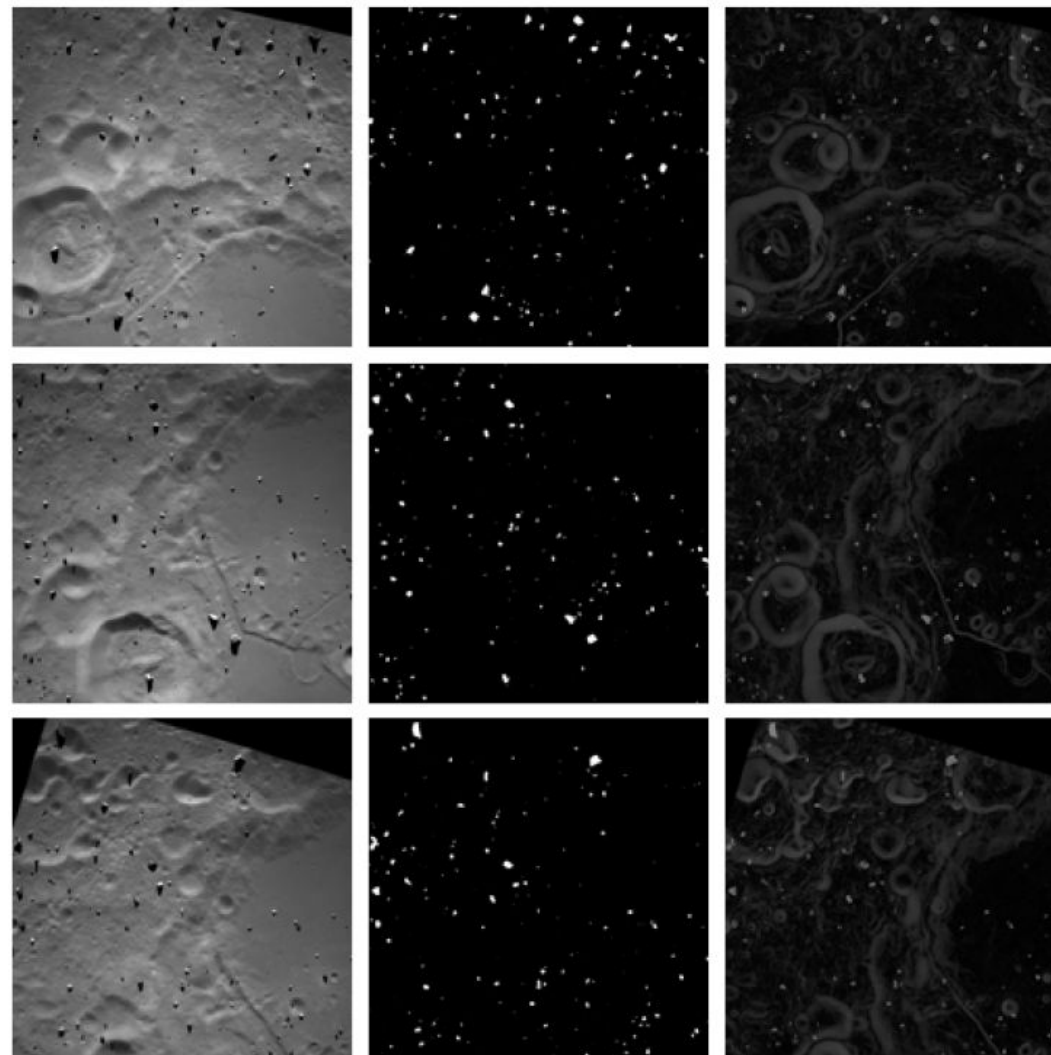


Figure 10: Examples of images, label maps and slope maps from dataset GEN_DATA_S1

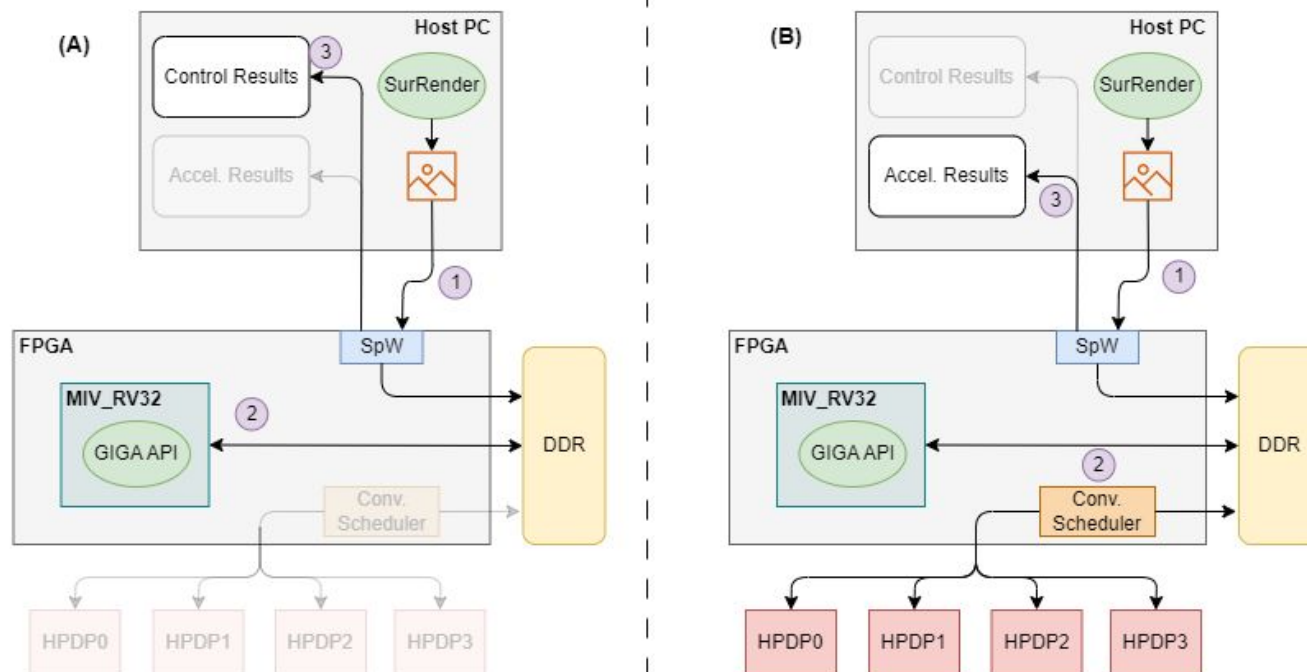
Methodology - Procedure

Procedure:

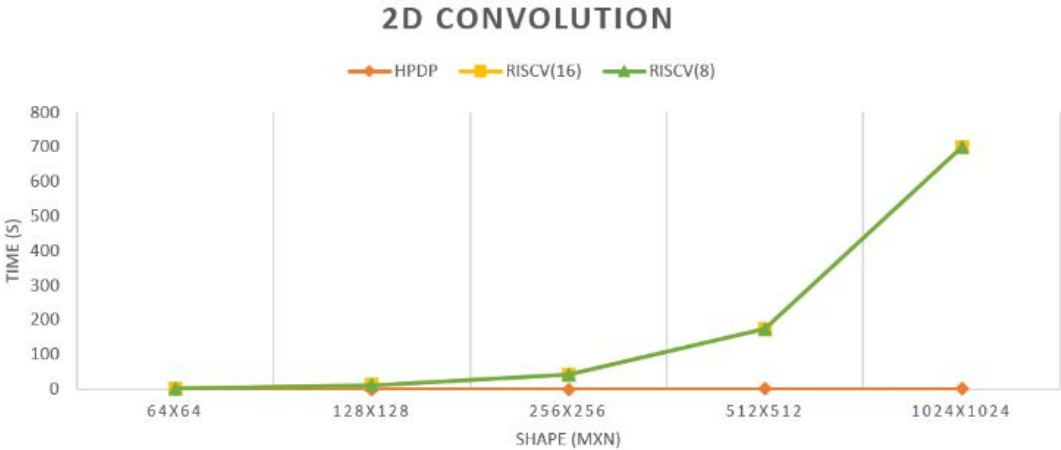
- Divided into two phases. A) control B) accelerated
- Test images common for both phases
- Execute all processing on the Risc-V and measure performance (Phase A)
- Repeat processing by offloading heavy duty to HPDP and measure performance (Phase B)
- Provide detailed report and comparison of results.

Algorithms:

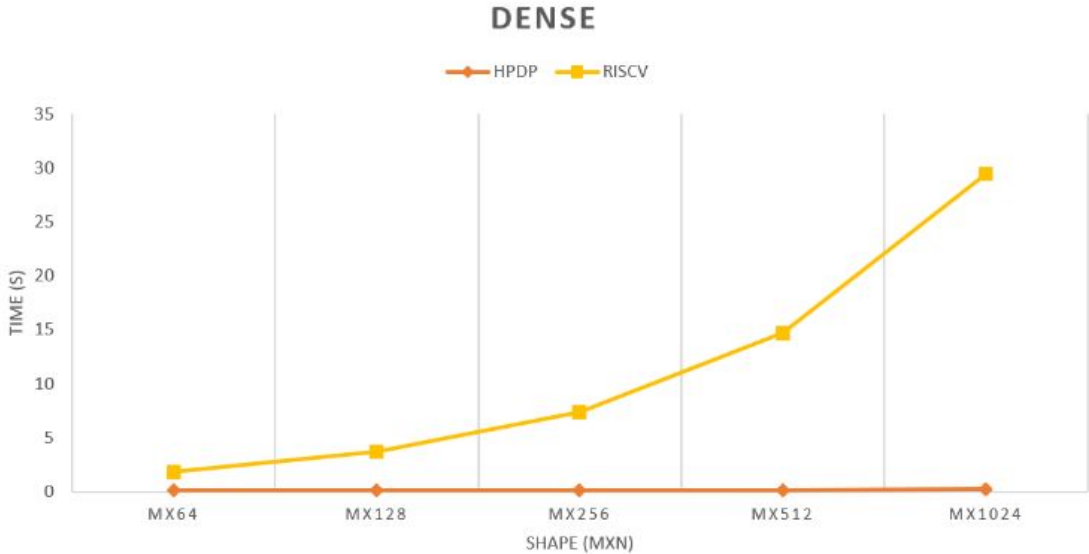
- Convolution
- Dense layer
- Bilinear Upscale
- Nearest Neighbour Upscale
- Addition



Results – RiscV vs HPDP (1/2)



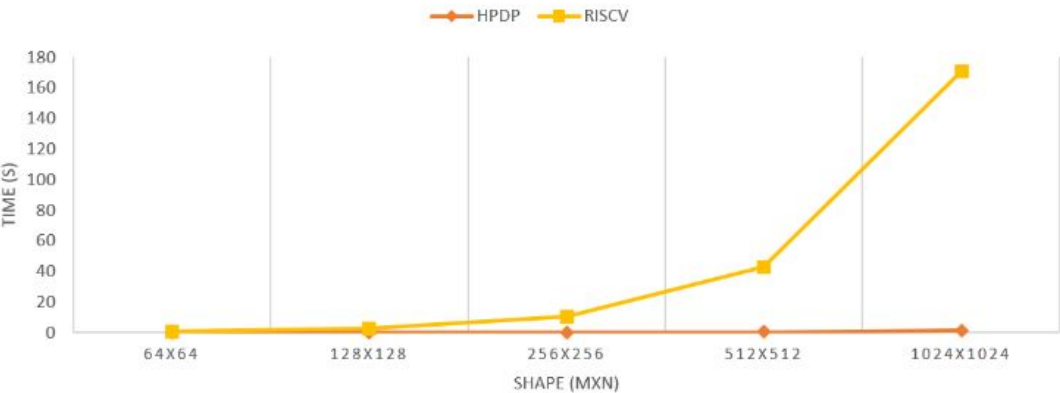
HPDP (s)	RISC-V (s)	speedup
0.18	2.56	14.22
0.19	10.56	55.58
0.23	43.24	188.00
0.36	173.9	483.06
0.79	700.3	886.46



HPDP (s)	RISC-V (s)	speedup
0.14	1.84	13.14
0.14	3.69	26.36
0.14	7.38	52.71
0.15	14.75	98.33
0.29	29.51	101.76

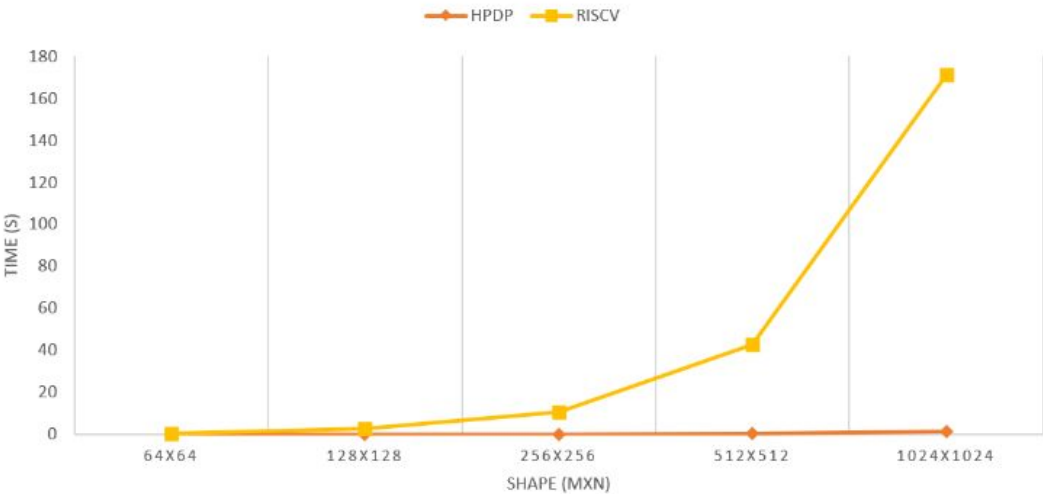
Results – RiscV vs HPDP (2/2)

NEAREST NEIGHBOUR UPSCALE



HPDP (s)	RISC-V (s)	speedup
0.14	0.67	4.79
0.16	2.67	16.69
0.21	10.71	51.00
0.41	42.82	104.44
1.28	171.26	133.80

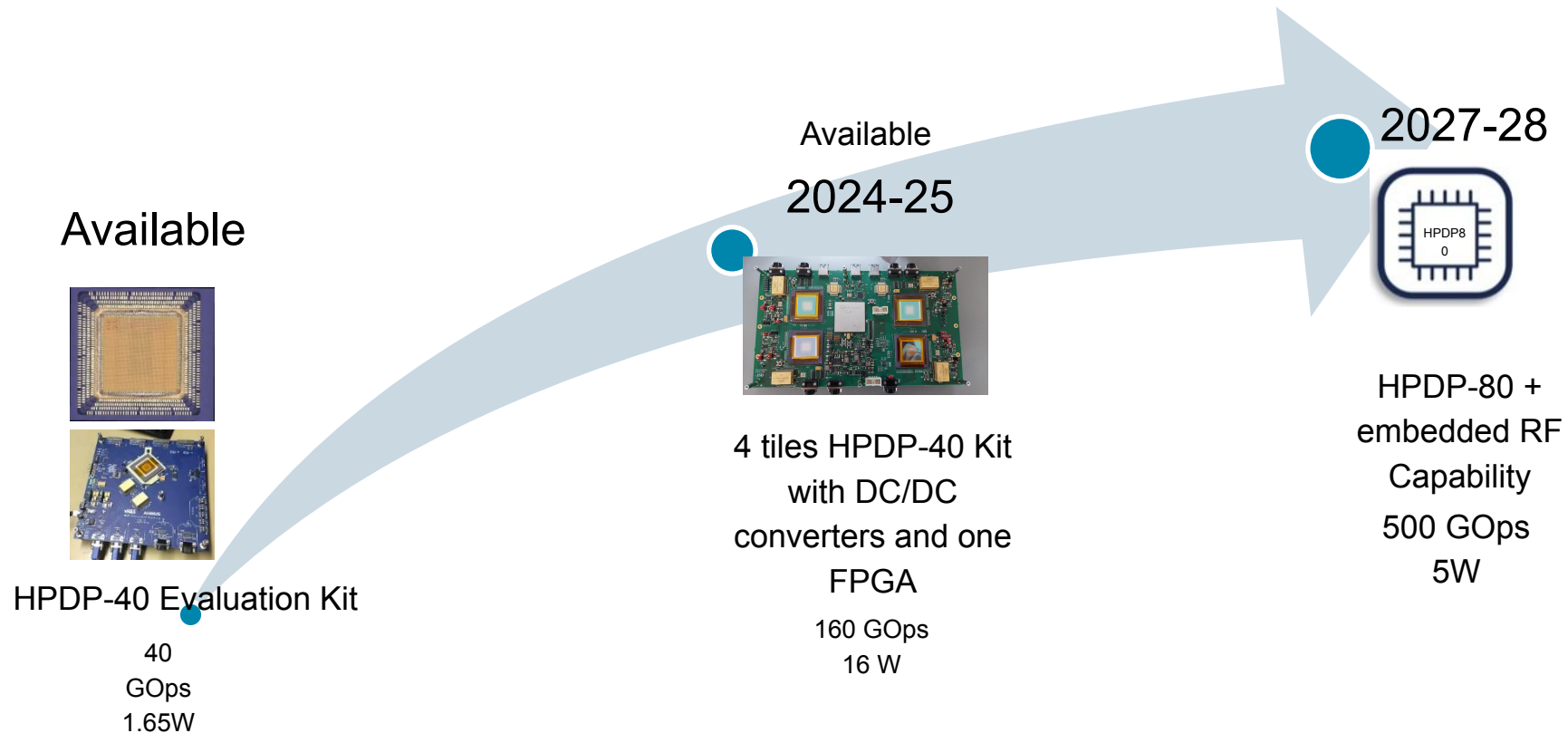
BILINEAR UPSCALE



HPDP (s)	RISC-V (s)	speedup
0.13	3.23	24.85
0.15	13.23	88.20
0.2	53.95	269.75
0.4	216.72	541.80
1.22	871.56	714.39

Conclusion

- Such technology seems to be quite promising for autonomous navigation and landers
- Over the next years with the arrival of HPDP80 these performances are expected to be further increased by a factor of 10
- Over the next years ISD will reinforce the cooperation with Klepsydra in order to get the maximum benefit from their innovative framework.



Thank you for your attention!

Questions?