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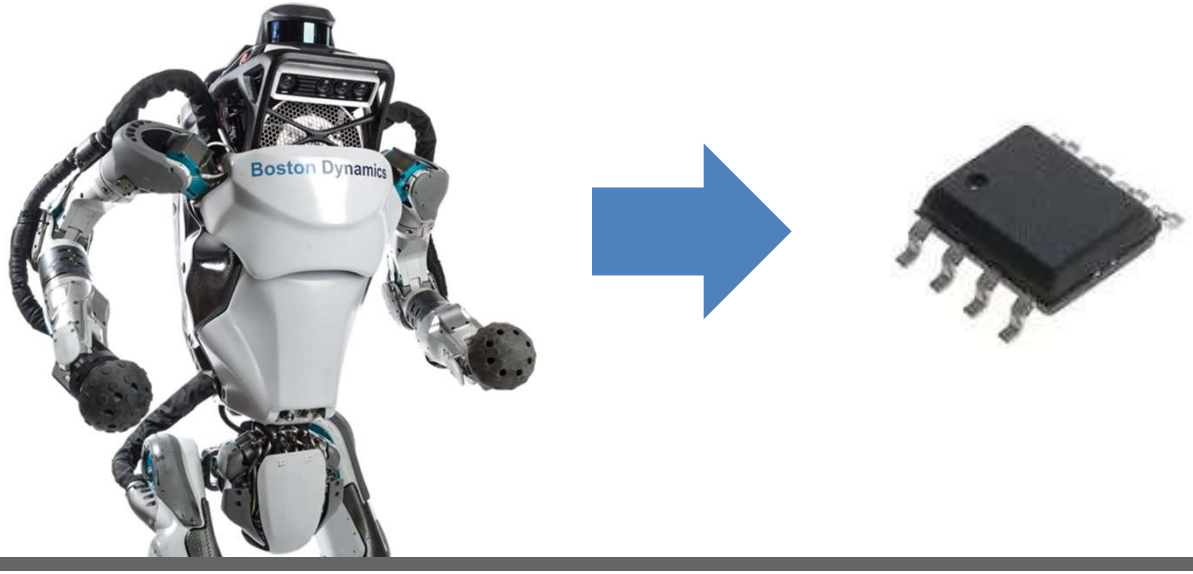
Robomorphic Computing

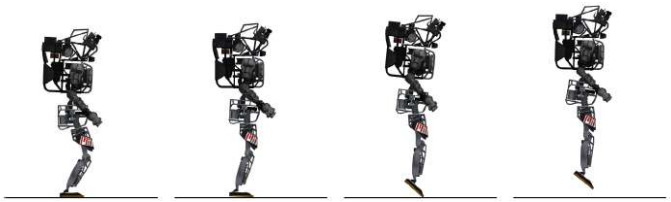
A Design Methodology for Domain-Specific Accelerators Parameterized by Robot Morphology



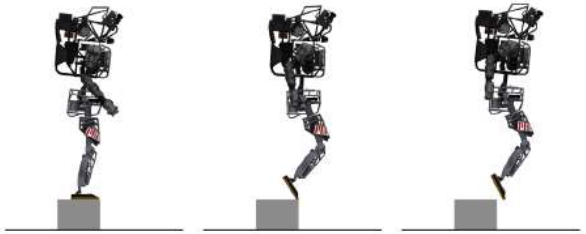
Sabrina M. Neuman, Brian Plancher, Thomas Bourgeat (MIT),
Thierry Tambe, Srinivas Devadas (MIT), and Vijay Janapa Reddi

Goal: Agile, Robust, Untethered Motion!

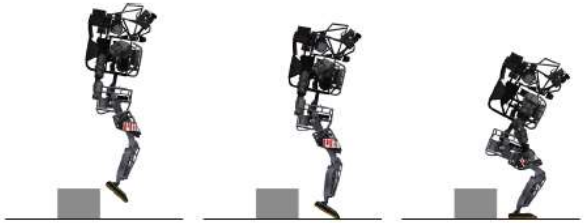
Run

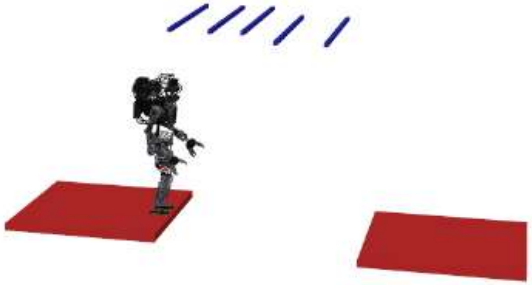


Jump

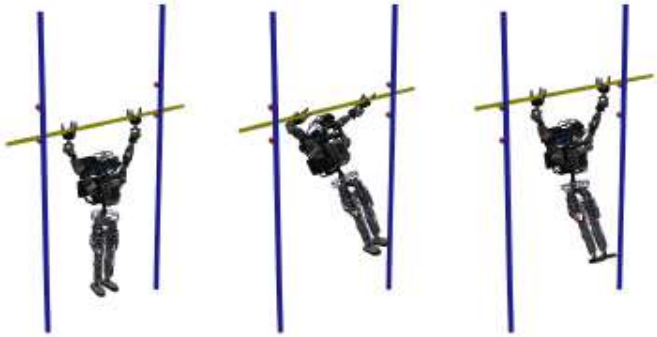


Box Jump





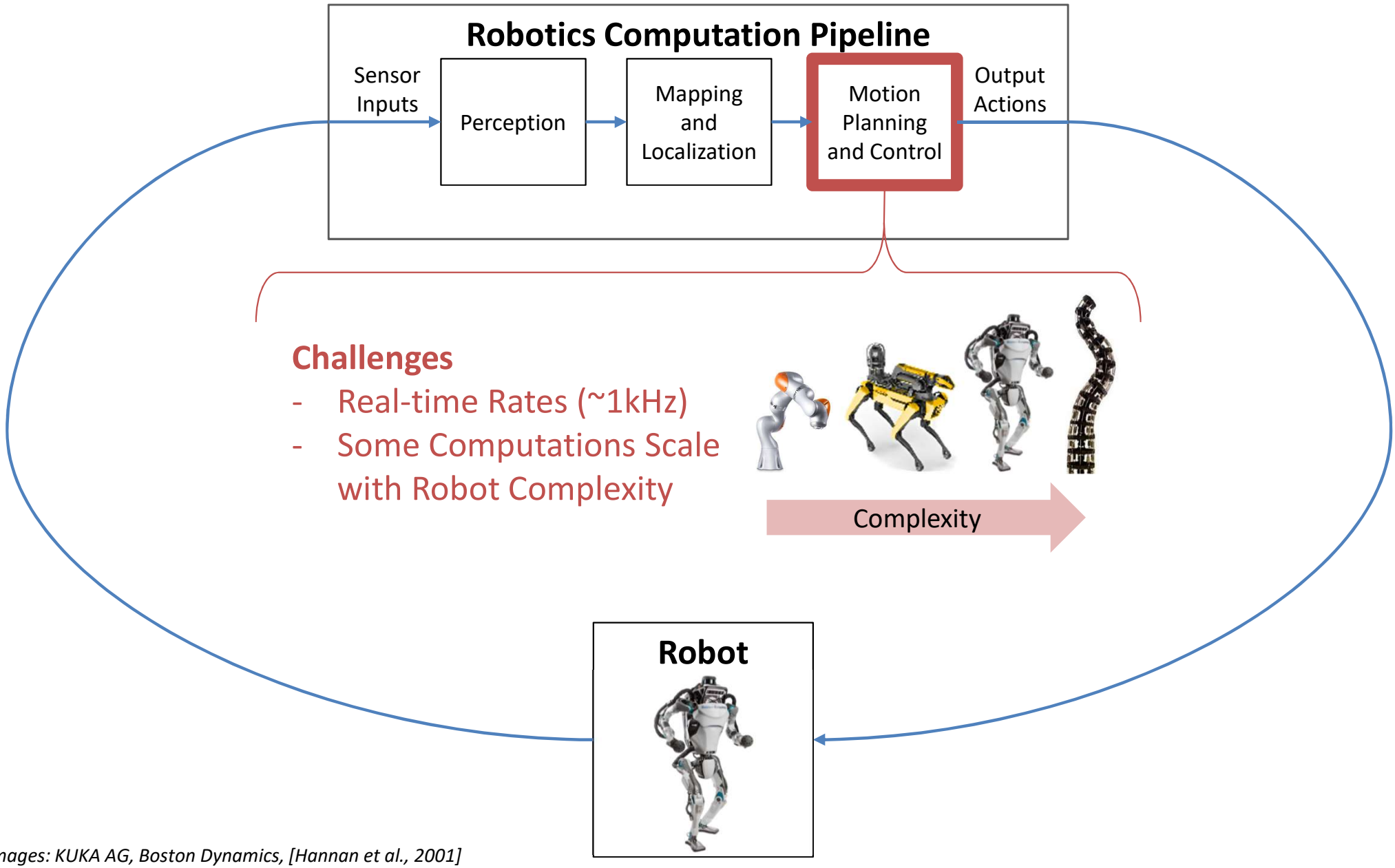
Monkey Bars



Salmon Ladder

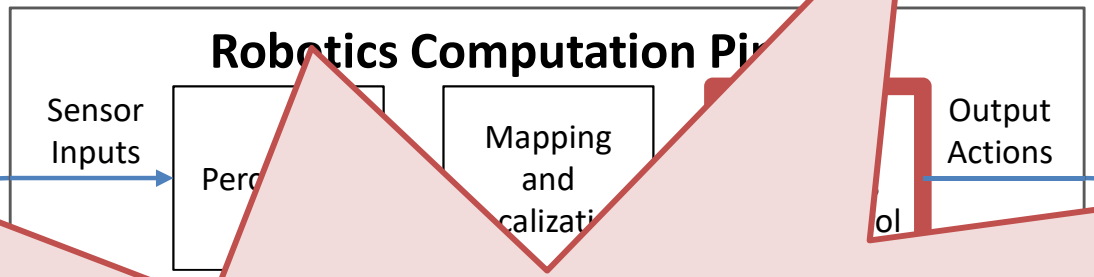
Images: [Dai et al., 2014]

Need Real-time Performance

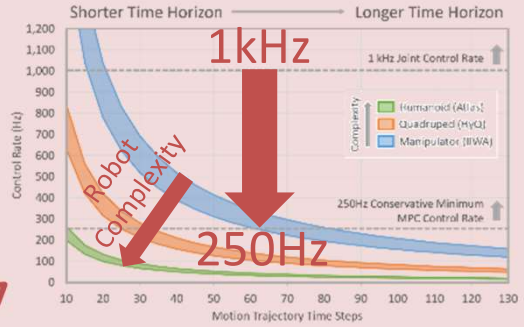


Images: KUKA AG, Boston Dynamics, [Hannan et al., 2001]

Need Real-time Performance

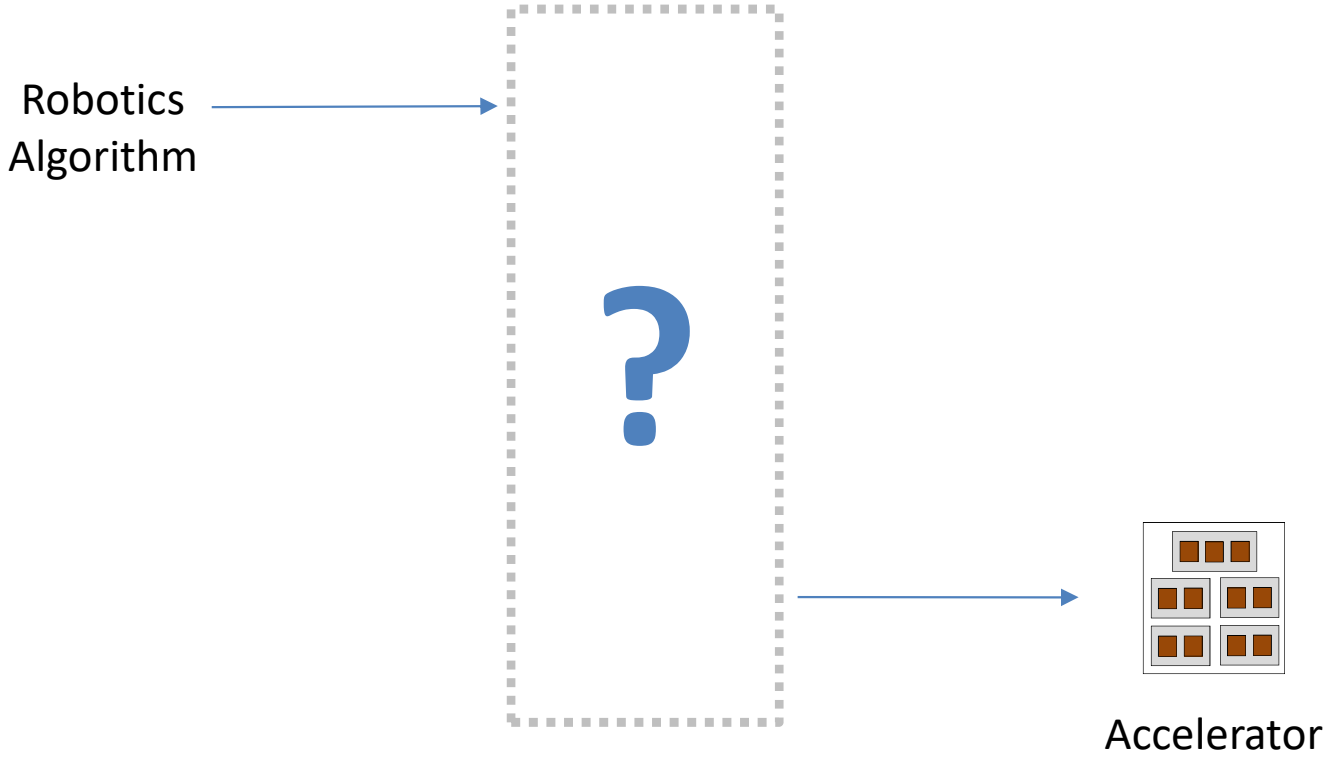


Current SW Too Slow → Performance Gap

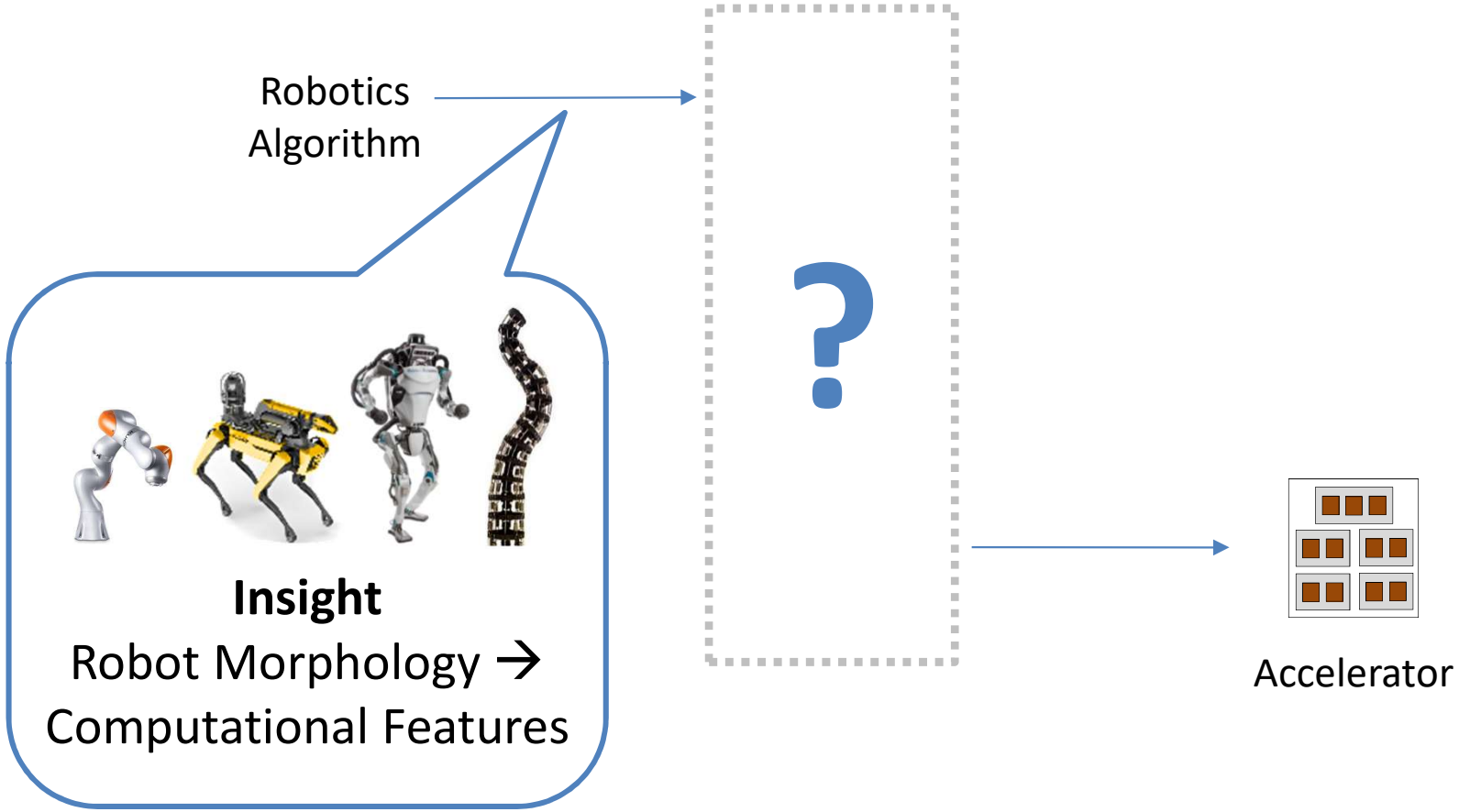


e.g., order of magnitude for Nonlinear MPC

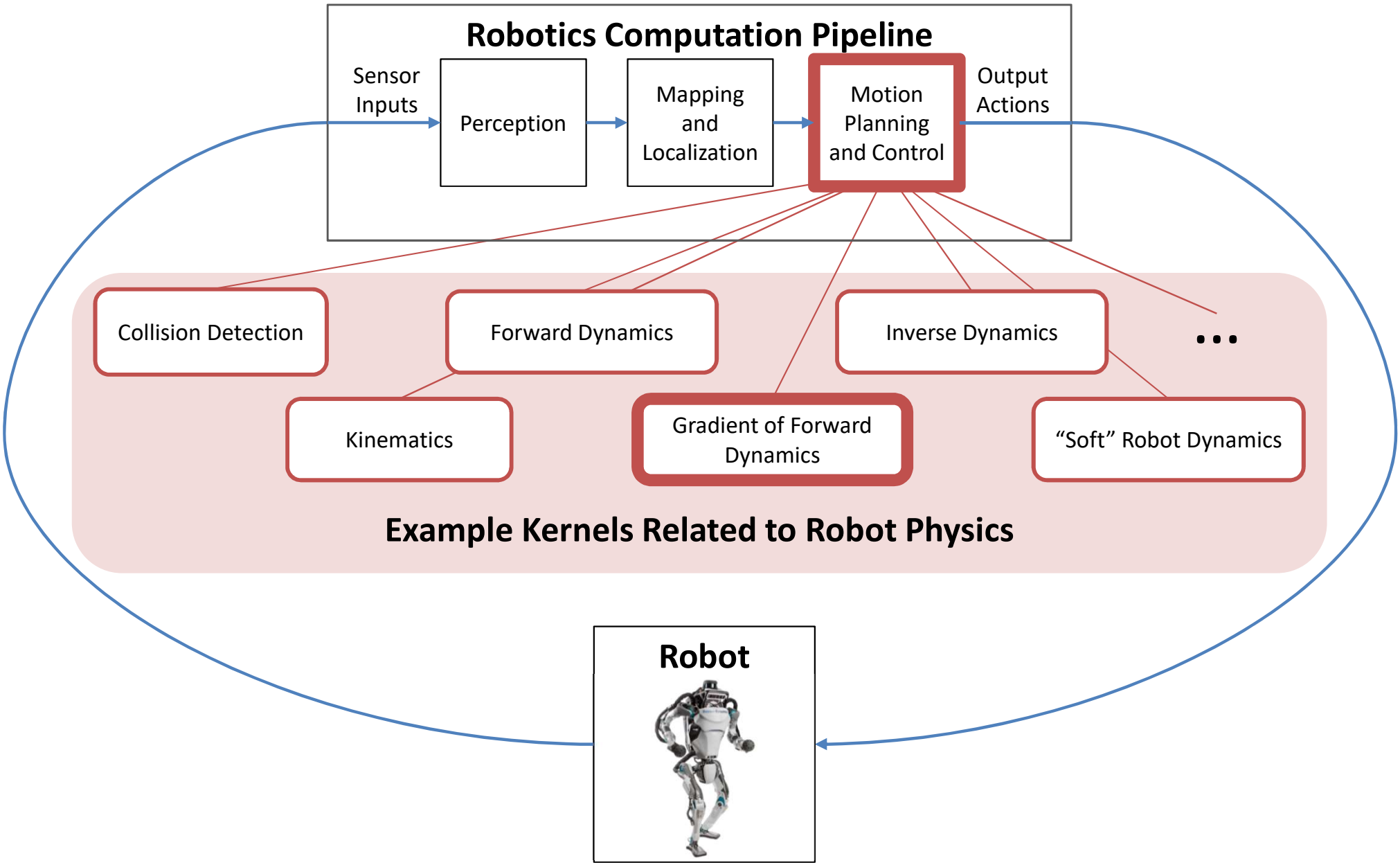
Solution: Hardware Acceleration



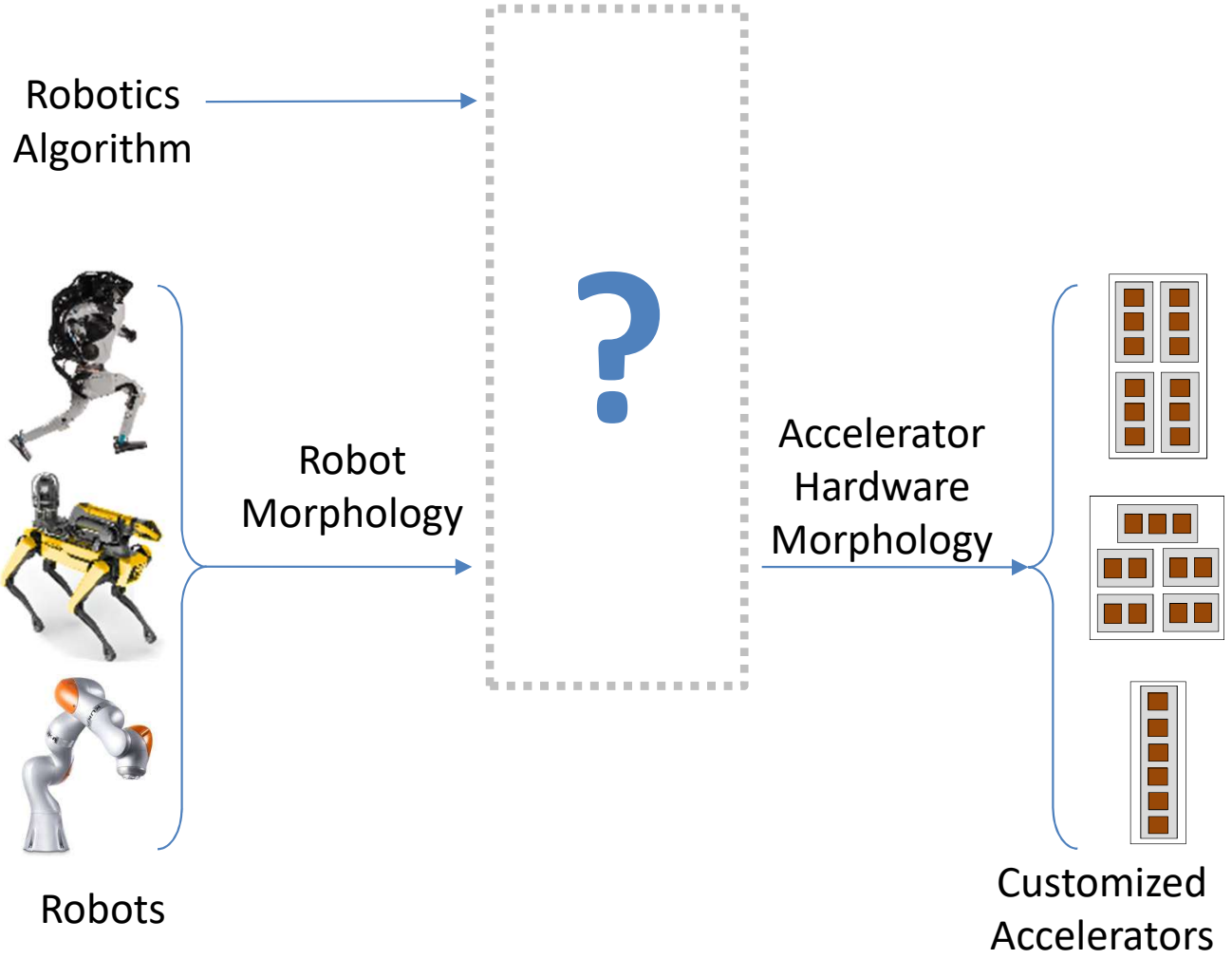
Insight: Robot Morphology



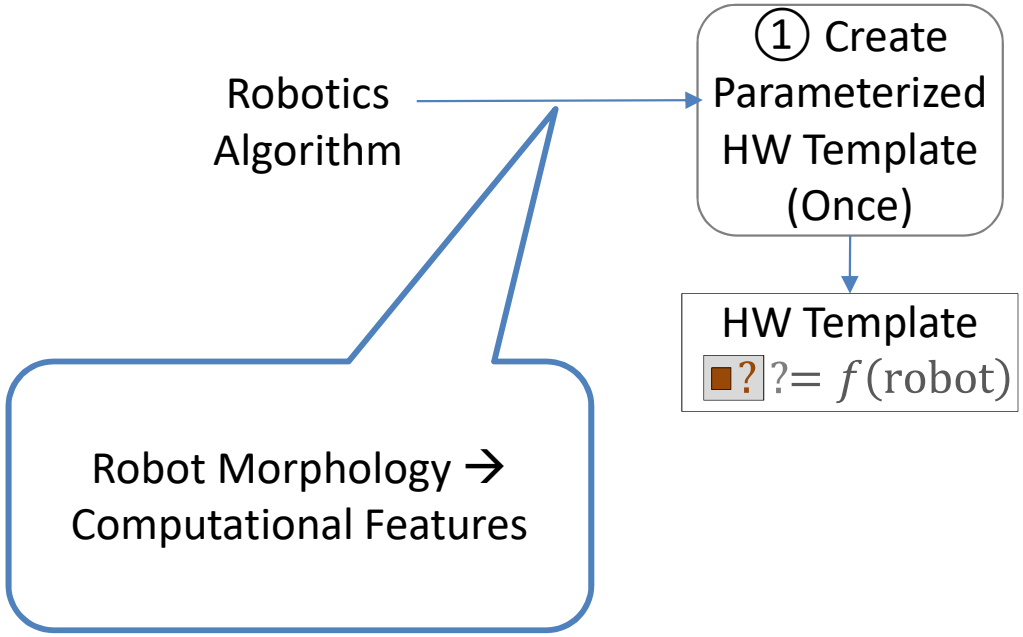
Insight: Robot Morphology



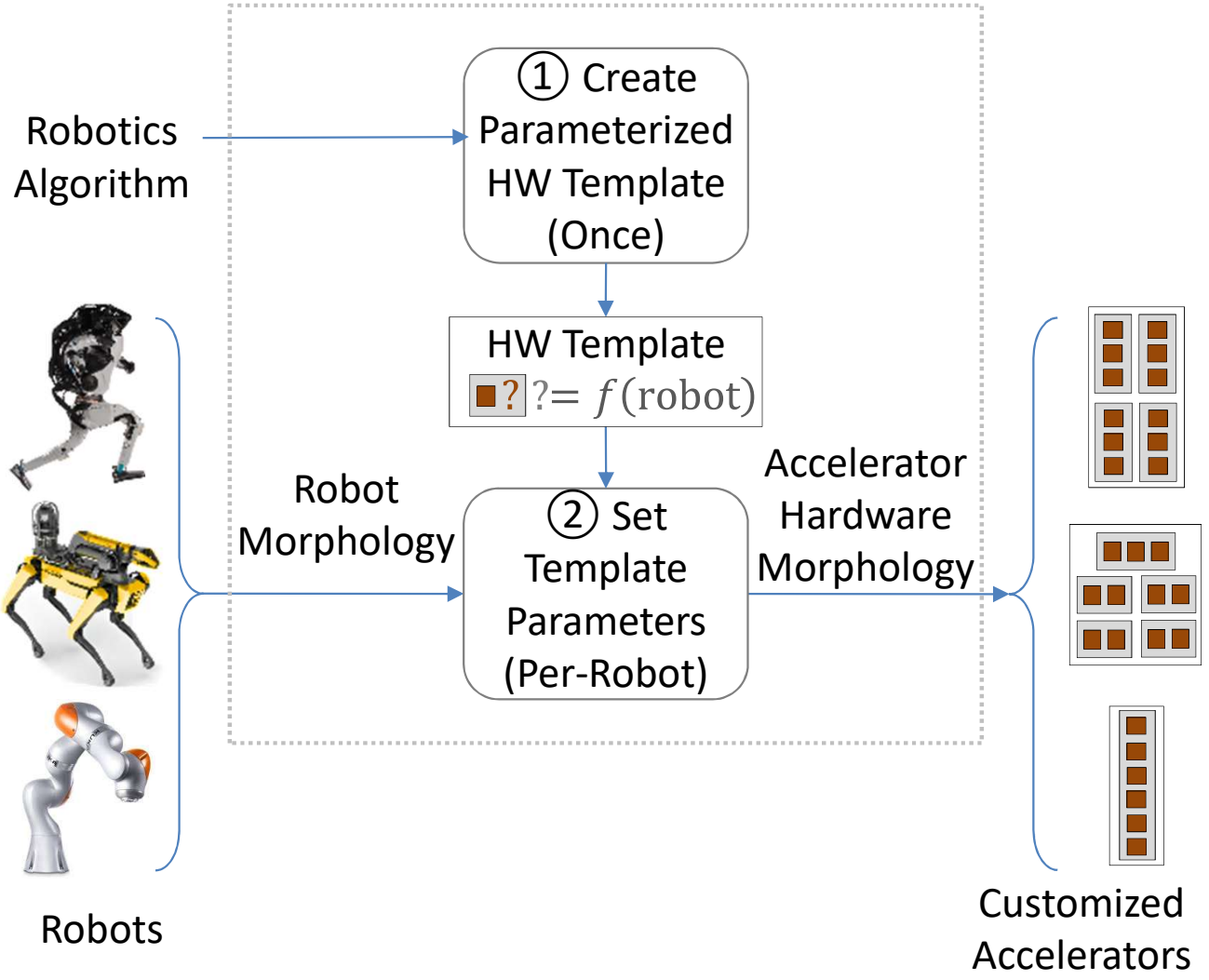
Robomorphic Computing



Robomorphic Computing



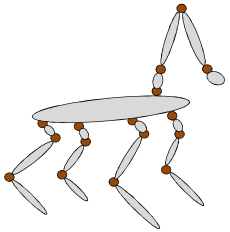
Robomorphic Computing

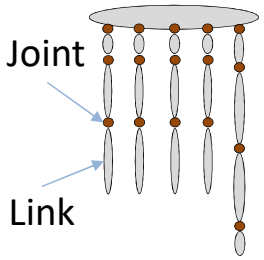


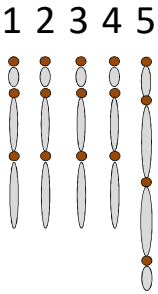
Robomorphic Design Flow

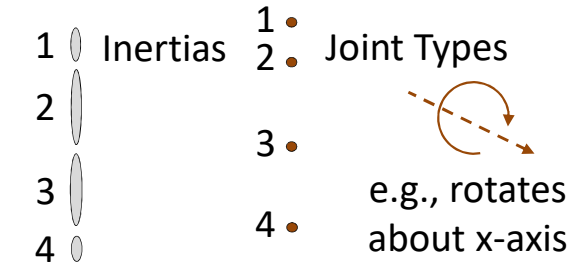
Robot Morphology

Robot → Topology → Limbs → Links and Joints



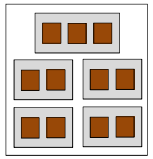






Robomorphic Computational Features

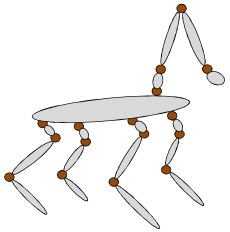
Accelerator Hardware Morphology

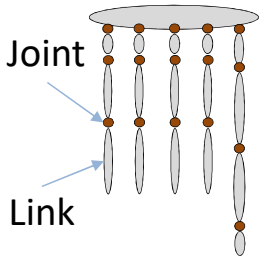


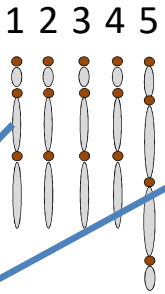
Robomorphic Design Flow

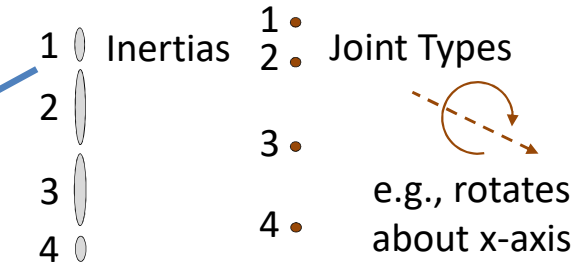
Robot Morphology

Robot → Topology → Limbs → Links and Joints





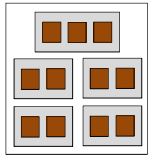


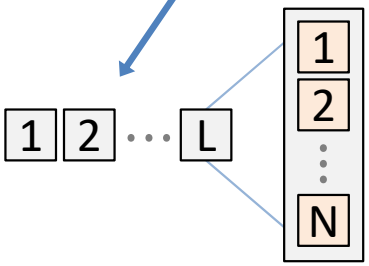


Robomorphic Computational Features

Modest Parallelism from Limbs and Links (e.g., 5 limbs with 3-4 links)

Accelerator Hardware Morphology

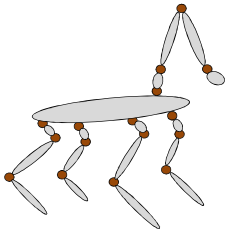


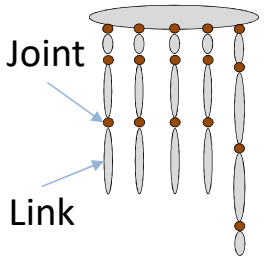


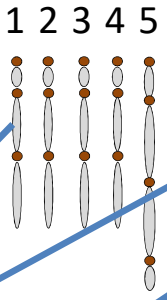
Robomorphic Design Flow

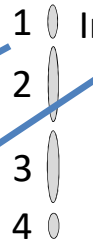
Robot Morphology

Robot → Topology → Limbs → Links and Joints









Inertias

Joint Types

e.g., rotates about x-axis

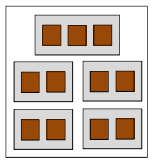
Robomorphic Computational Features

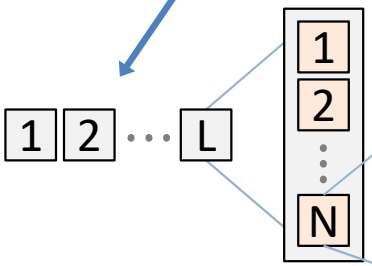
Modest Parallelism from Limbs and Links (e.g., 5 limbs with 3-4 links)

Matrix Constant Values

Small, Middlingly-Sparse Matrices (e.g., 6x6 and 30-60% sparse)

Accelerator Hardware Morphology





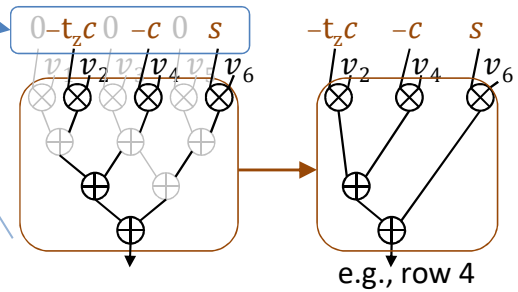
$I_{link} =$

$X_{joint} =$

$S_{joint} =$

e.g., Joint Transformation ${}^{Link2}X_{Link1} \cdot v$

$$\begin{bmatrix} -c & s & & & & \\ s & c & & & & \\ & & 1 & & & \\ & & -t_z c & -c & s & \\ & & -t_z s & s & c & \\ & & t_z & & 1 & \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \\ v_6 \end{bmatrix}$$



e.g., row 4

Example: Dynamics Gradient Accelerator

Gradient of Forward Dynamics

① Create Parameterized HW Template (Once)

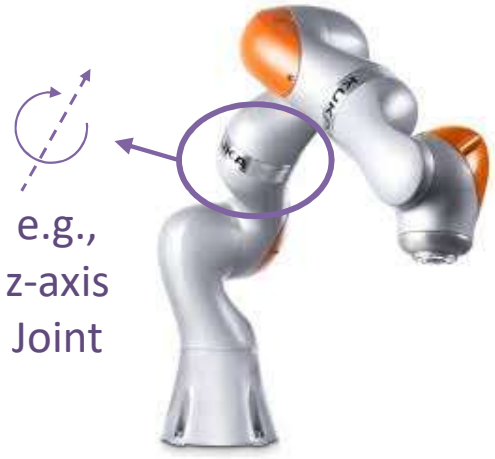
HW Template

② Set Template Parameters (Per-Robot)

Robot Morphology

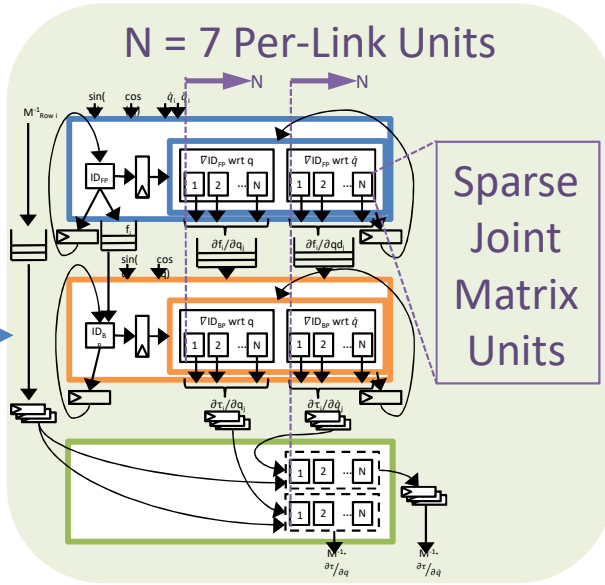
Accelerator Hardware Morphology

N = 7 Links



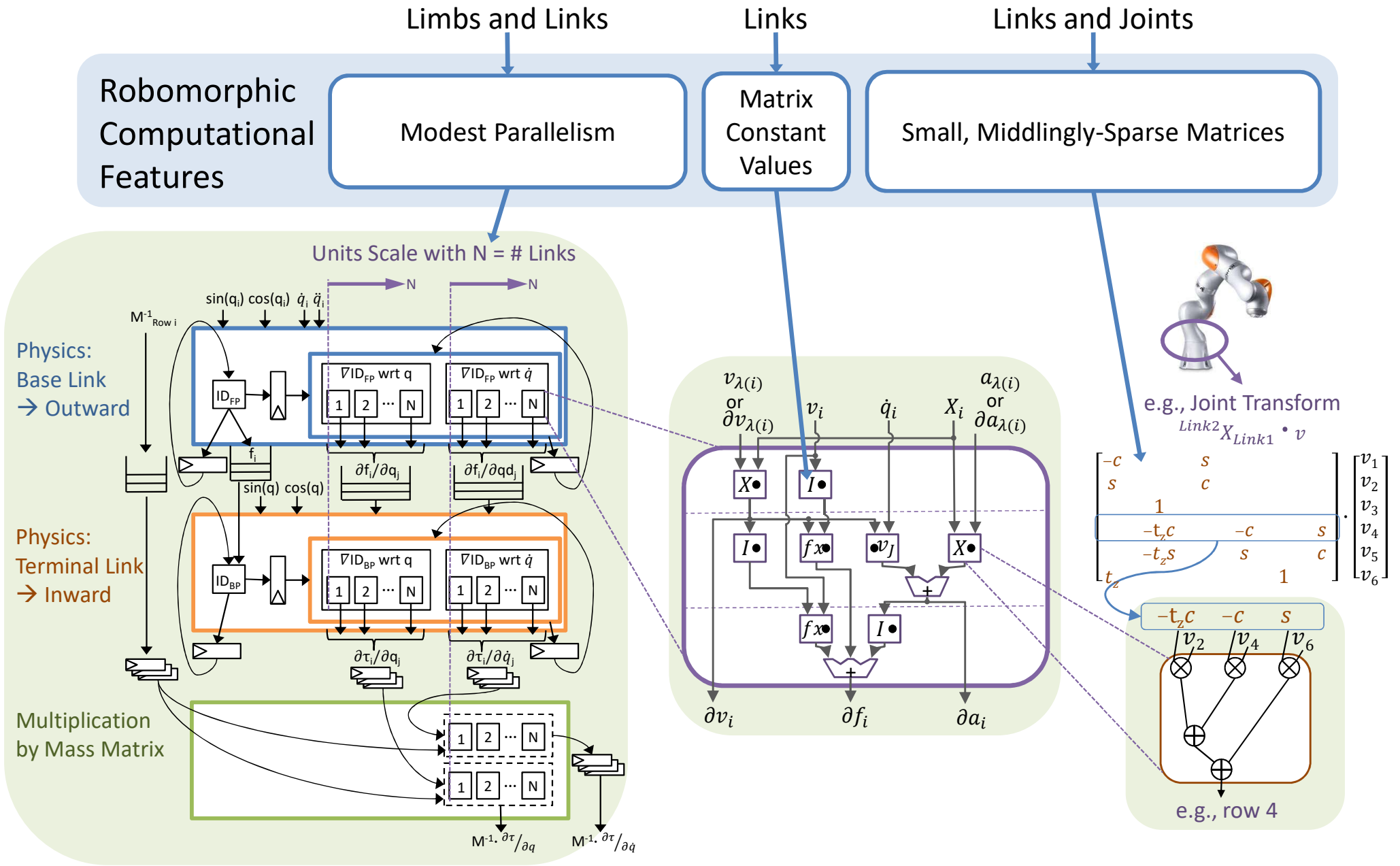
e.g., z-axis Joint

Manipulator Robot



Customized Accelerator

Example: Dynamics Gradient Accelerator



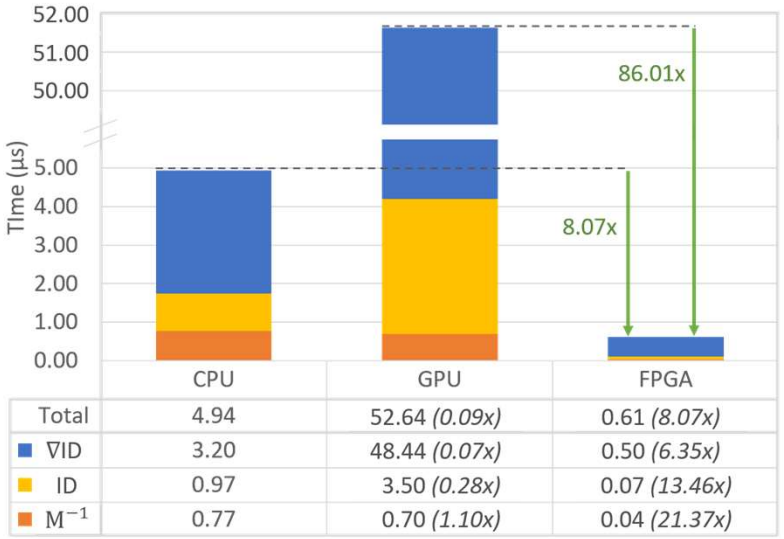
Results Highlights

Single Computation: Compute Latency

SW Baselines

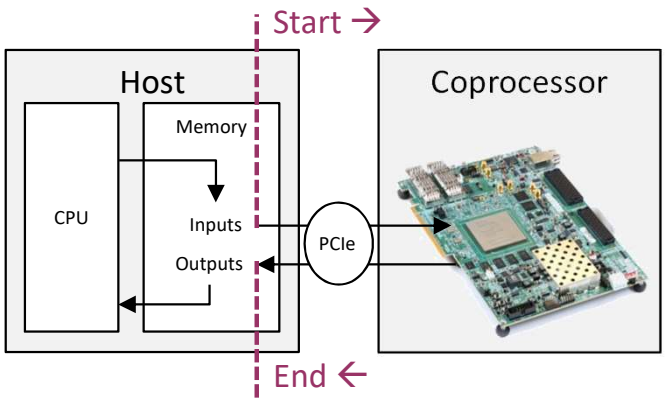
Robomorphic HW

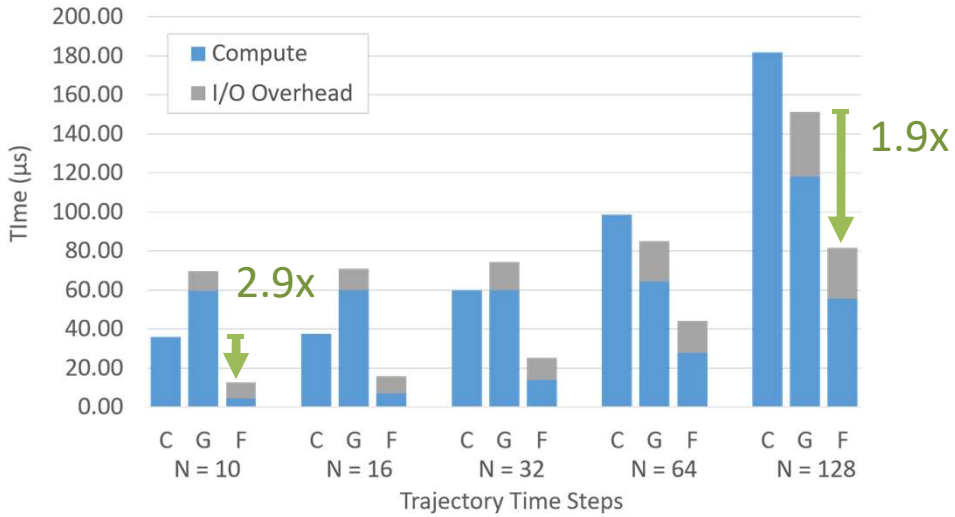
Platform	CPU	GPU	FPGA
Processor	i7-7700	RTX 2080	XCVU9P
# of Cores	4	2944 CUDA (46 SM)	N/A
Max Frequency	3.6 GHz	1.7 GHz	55.6 MHz



	CPU	GPU	FPGA
Total	4.94	52.64 *(0.09x)*	0.61 *(8.07x)*
∇ID	3.20	48.44 *(0.07x)*	0.50 *(6.35x)*
ID	0.97	3.50 *(0.28x)*	0.07 *(13.46x)*
M^{-1}	0.77	0.70 *(1.10x)*	0.04 *(21.37x)*

Multiple Computations: Compute + I/O Round-Trip Latency





Future Work

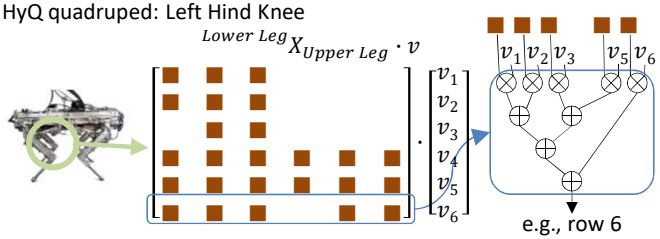
More Robots

Complexity

Other Joint Examples

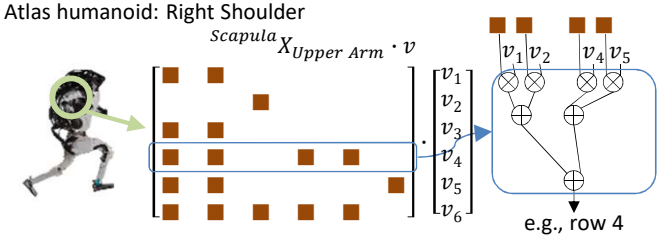
HyQ quadruped: Left Hind Knee

$^{Lower\ Leg}X_{Upper\ Leg} \cdot v$



Atlas humanoid: Right Shoulder

$^{Scapula}X_{Upper\ Arm} \cdot v$



More Algorithms

- Gradient of Forward Dynamics
- Forward Dynamics
- Inverse Dynamics
- Collision Detection
- Kinematics
- "Soft" Robot Dynamics
- • • •

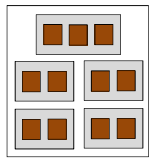
Automation

Robot Morphology

Extract Robomorphic Features

- Limb and Link Parallelism
- Constant Values
- Sparse Joint Matrices

Accelerator Hardware Morphology



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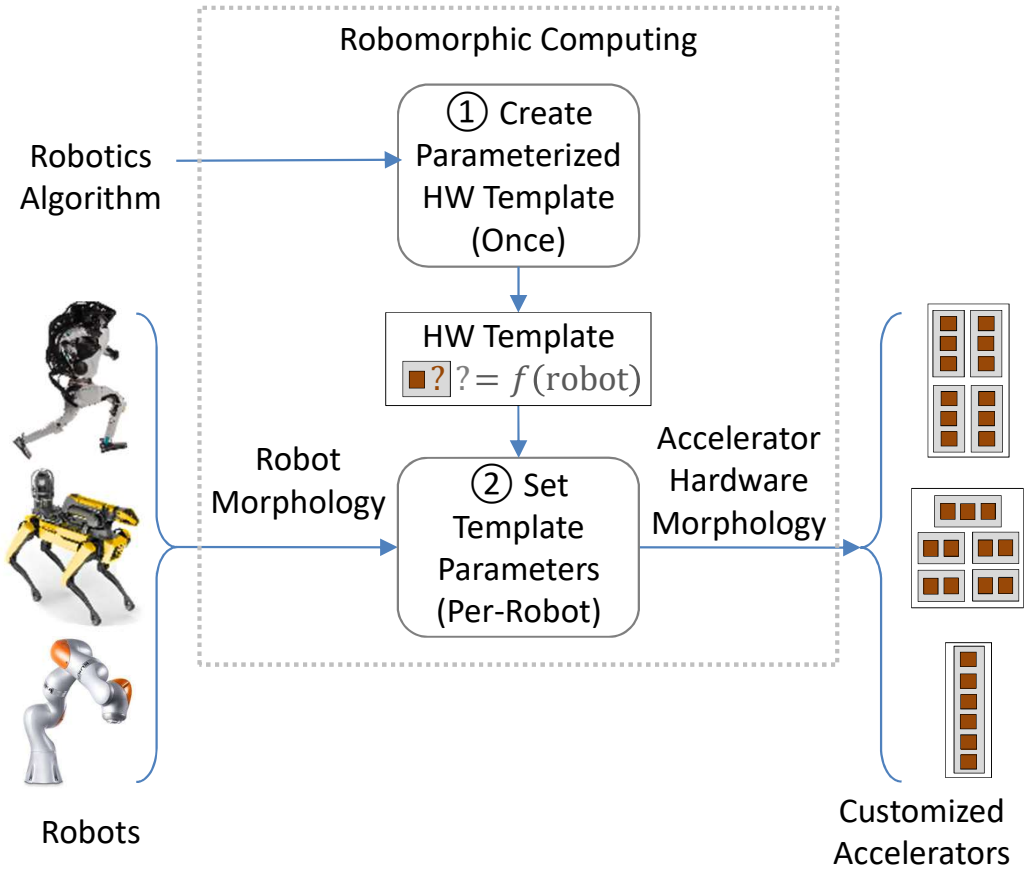

Contributions

- Robomorphic Computing
  - Systematic methodology
  - Robot → Customized Accelerator
- Dynamics Gradient Accelerator
  - Implemented for manipulator
  - FPGA speedups over CPU, GPU
  - ASIC speedup over FPGA

Future Work

- More robots
- More algorithms
- Automation

Goal: Automatically-Optimized Robotics Processors

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