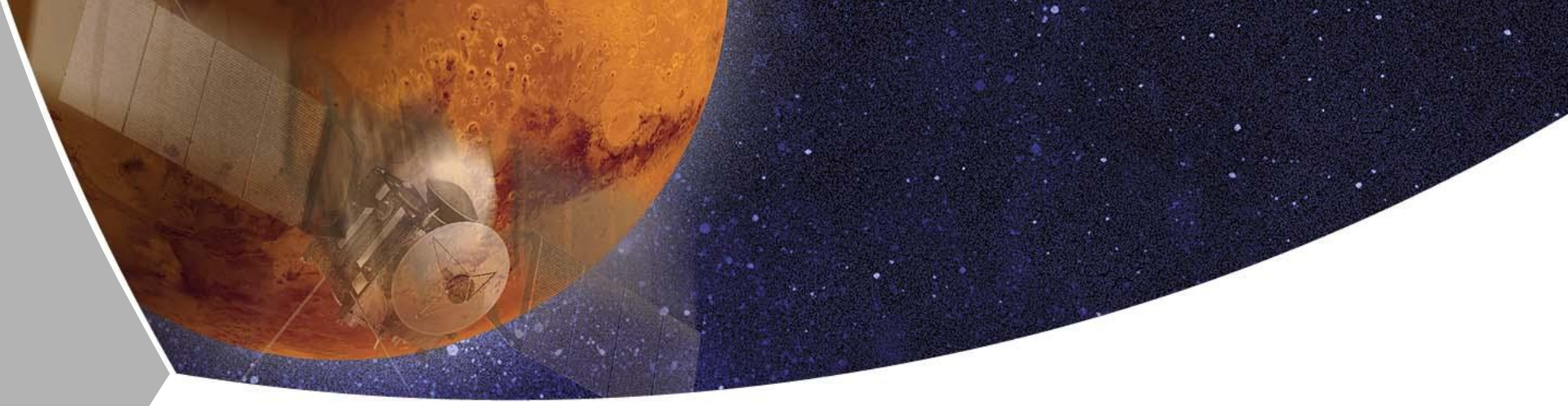
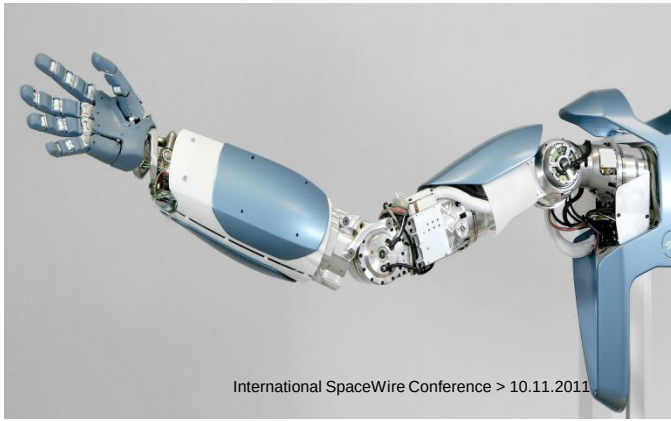


SpaceWire, a Backbone for Humanoid Robotic Systems

Mathias Nickl, ***Stefan Jörg****, Thomas Bahls, Alexander Nothhelfer, Stefan Strasser*

Robotic and Mechatronics Center,
German Aerospace Center (DLR)

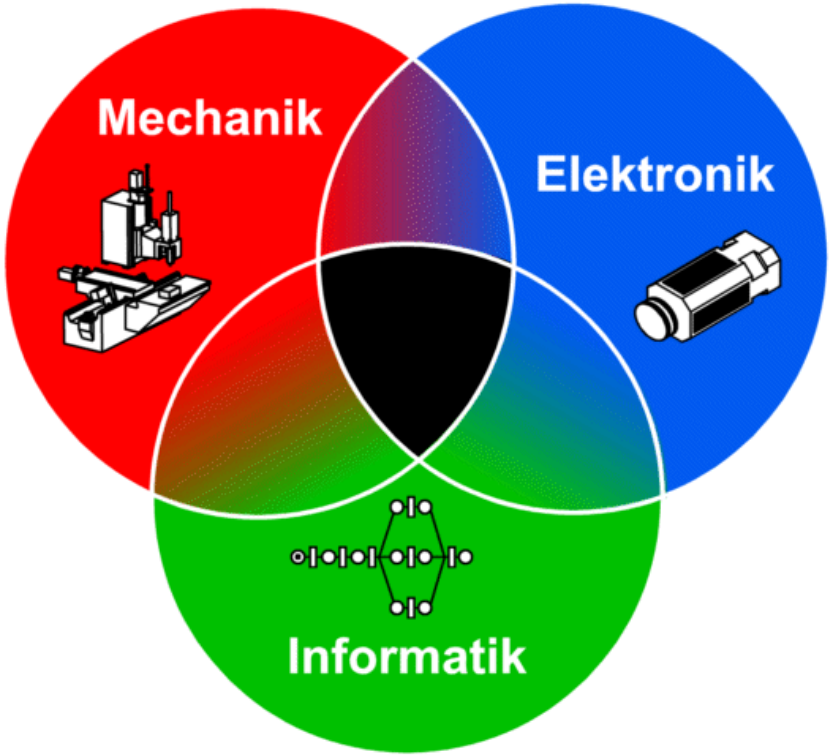


Robotics and Mechatronics Center: Competences…

Physics

Usability engineering

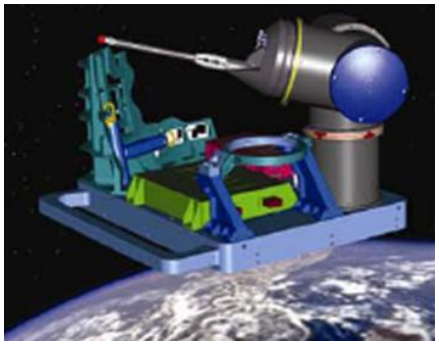
Psychology

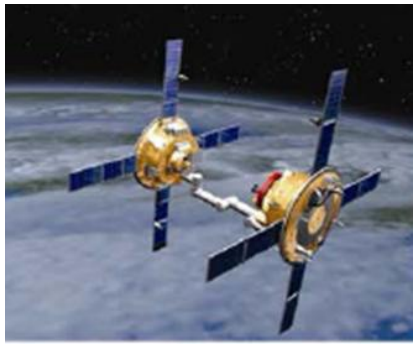


Industrial design

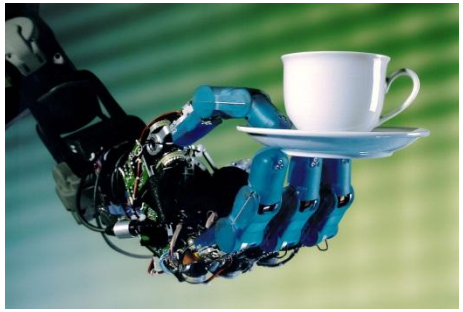
Medical engineering

Robotics and Mechatronics Center: Competences… to build highly-integrated robots



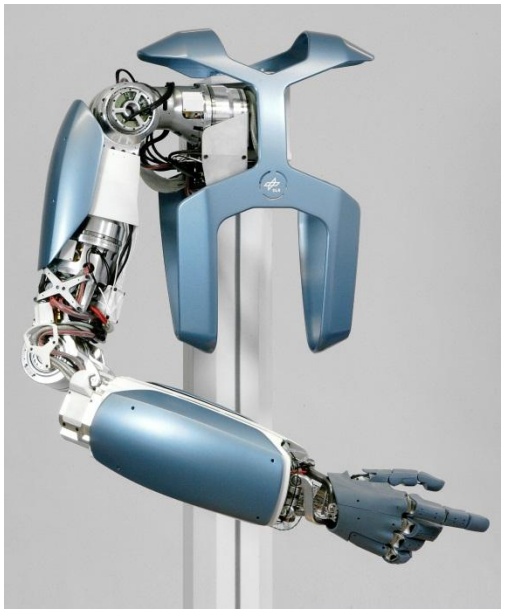


Robotics and Mechatronics Center: Systems with SpaceWire

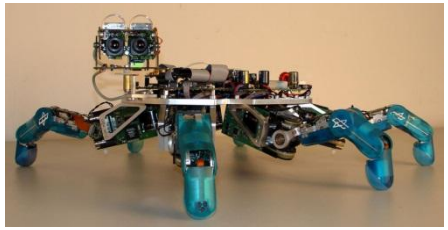


DLR Hand II 2001 (IEEE1355)

Medical Robots and Tools: Kinemedic 2005, Miro 2008, MICA 2009

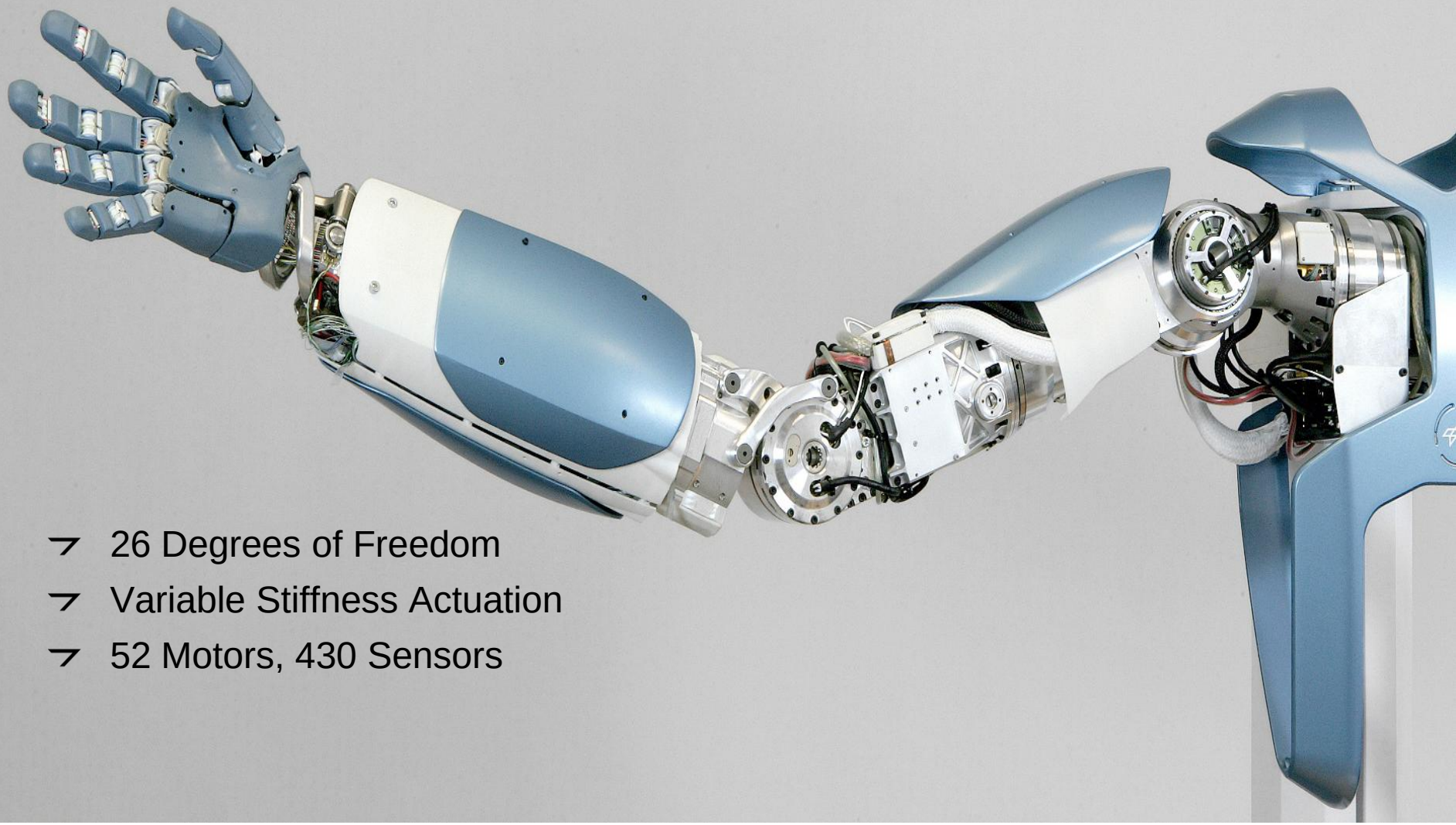


DLR Hand Arm System 2010



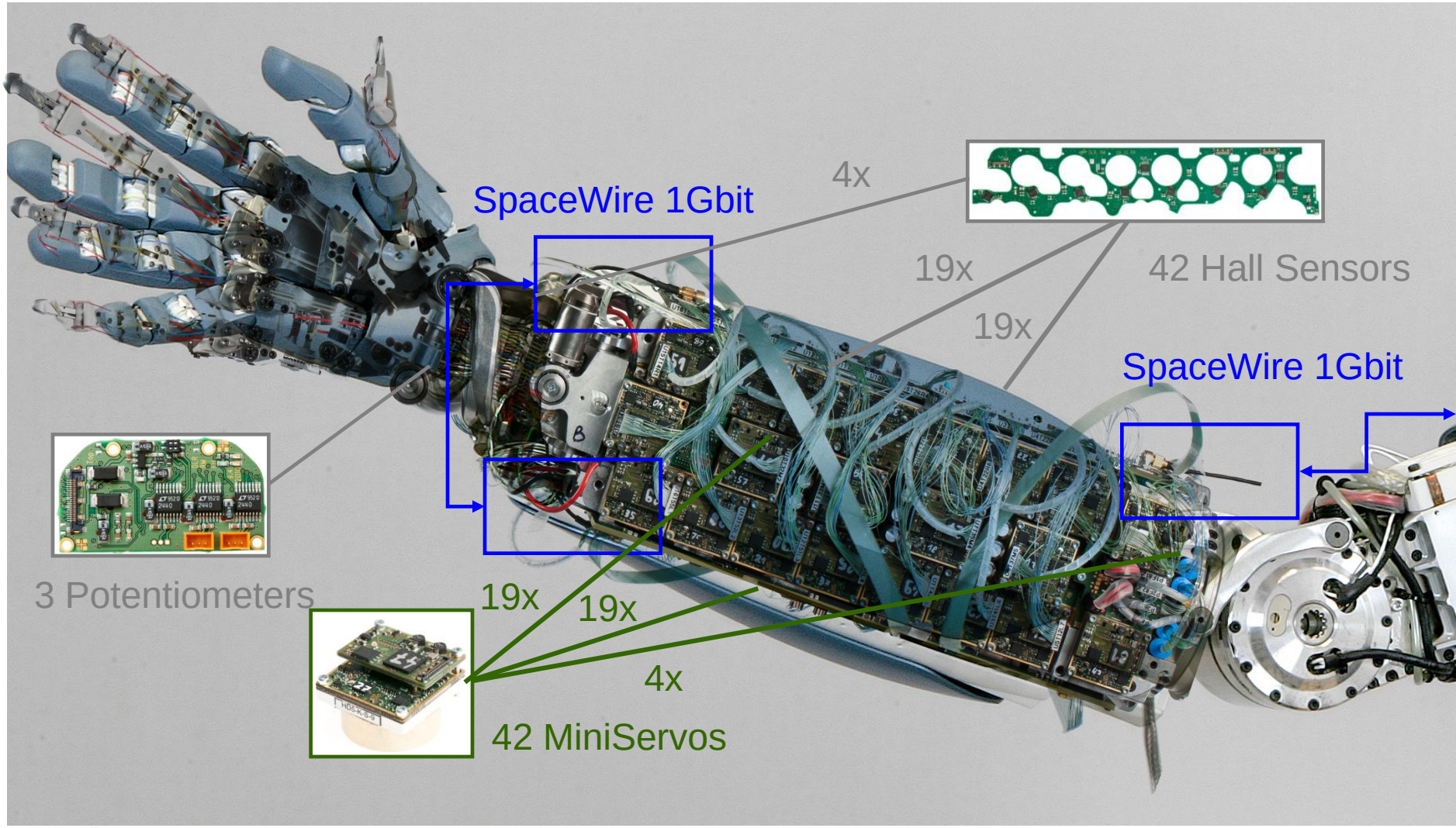
DLR Krabbler 2006

DLR Hand Arm System - A novel humanoid design

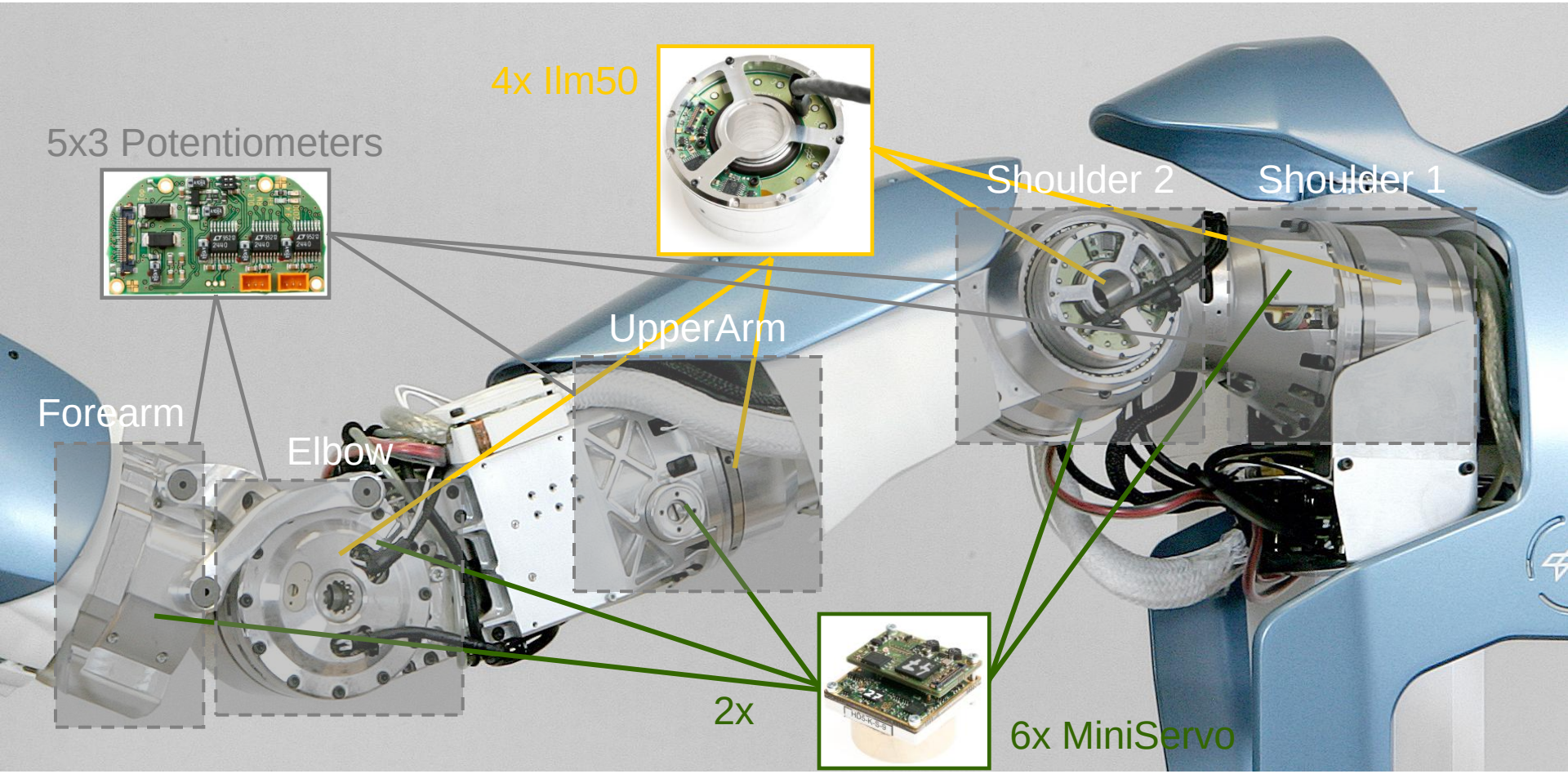


- 26 Degrees of Freedom
- Variable Stiffness Actuation
- 52 Motors, 430 Sensors

DLR Hand Arm System – Hand + Wrist (19 +2 DOF)

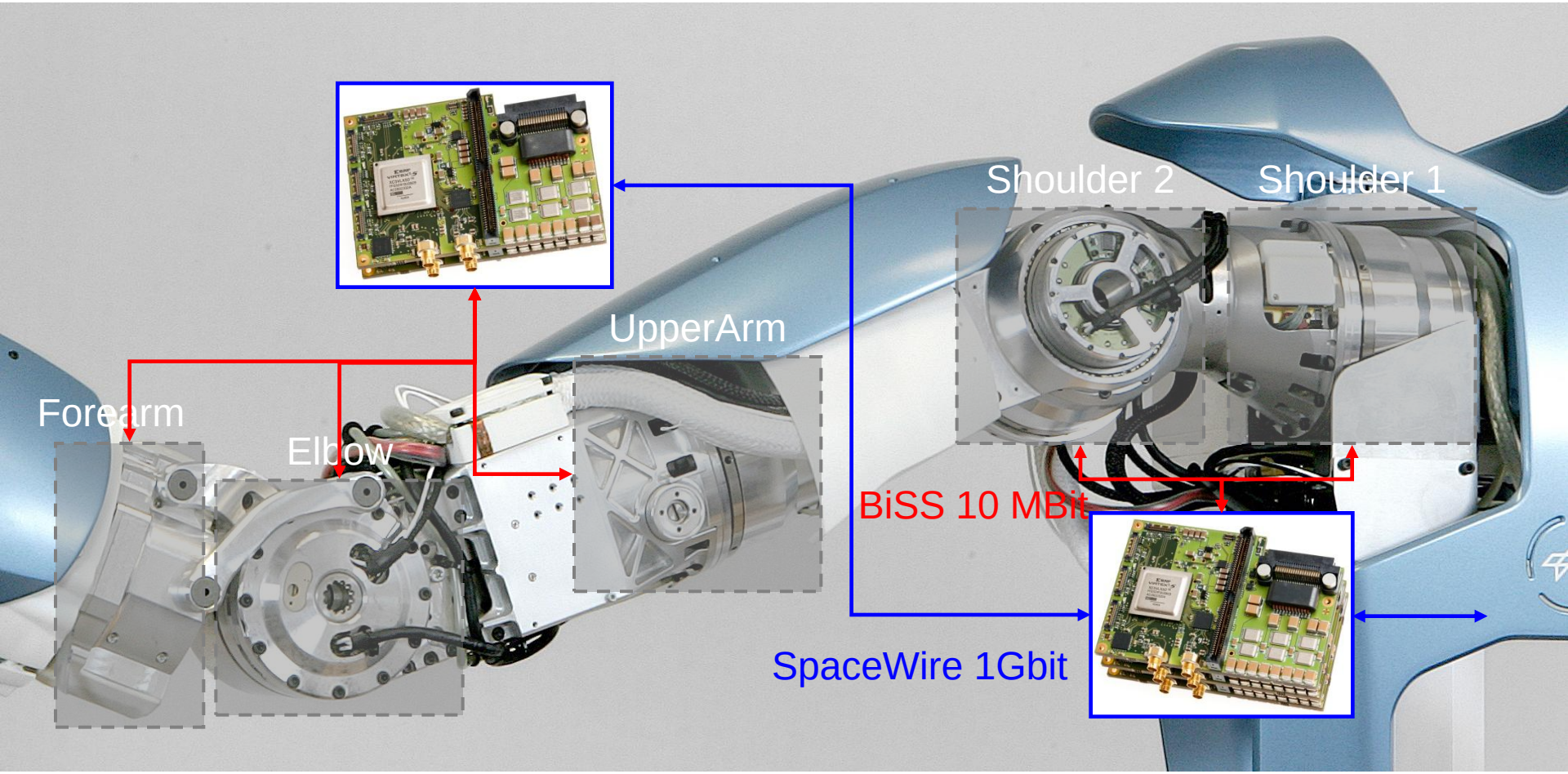


DLR Hand Arm System – The Arm (5 DOF)

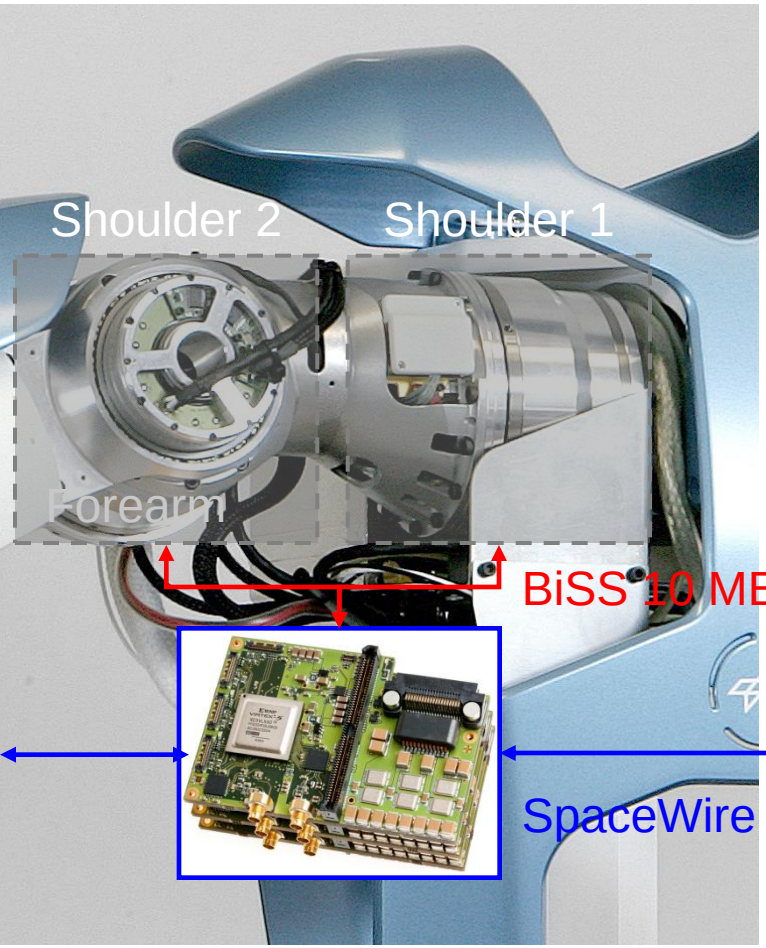


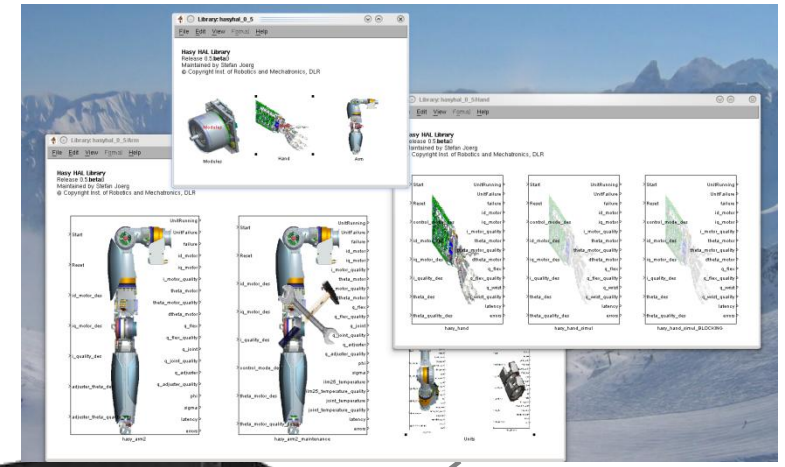
Shoulder-Elbow FSJ Mechanism [Wolf et al., ICRA 2011]
Forearm Mechanism [Friedl et al., IROS 2011]

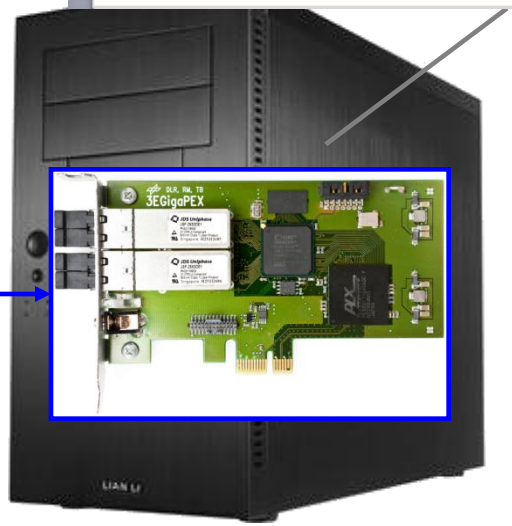
DLR Hand Arm System – Communication



DLR Hand Arm System – Rapid Prototyping



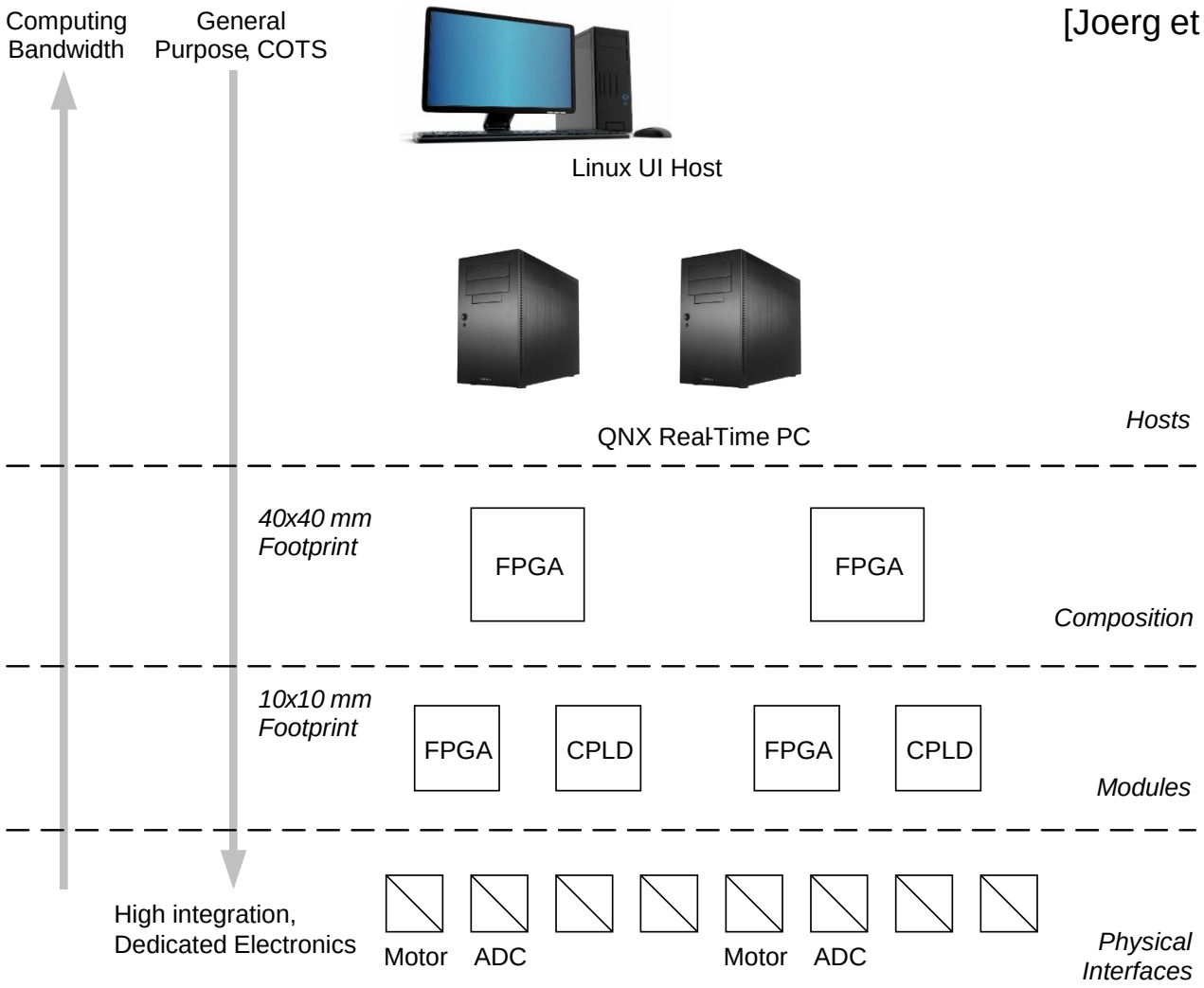




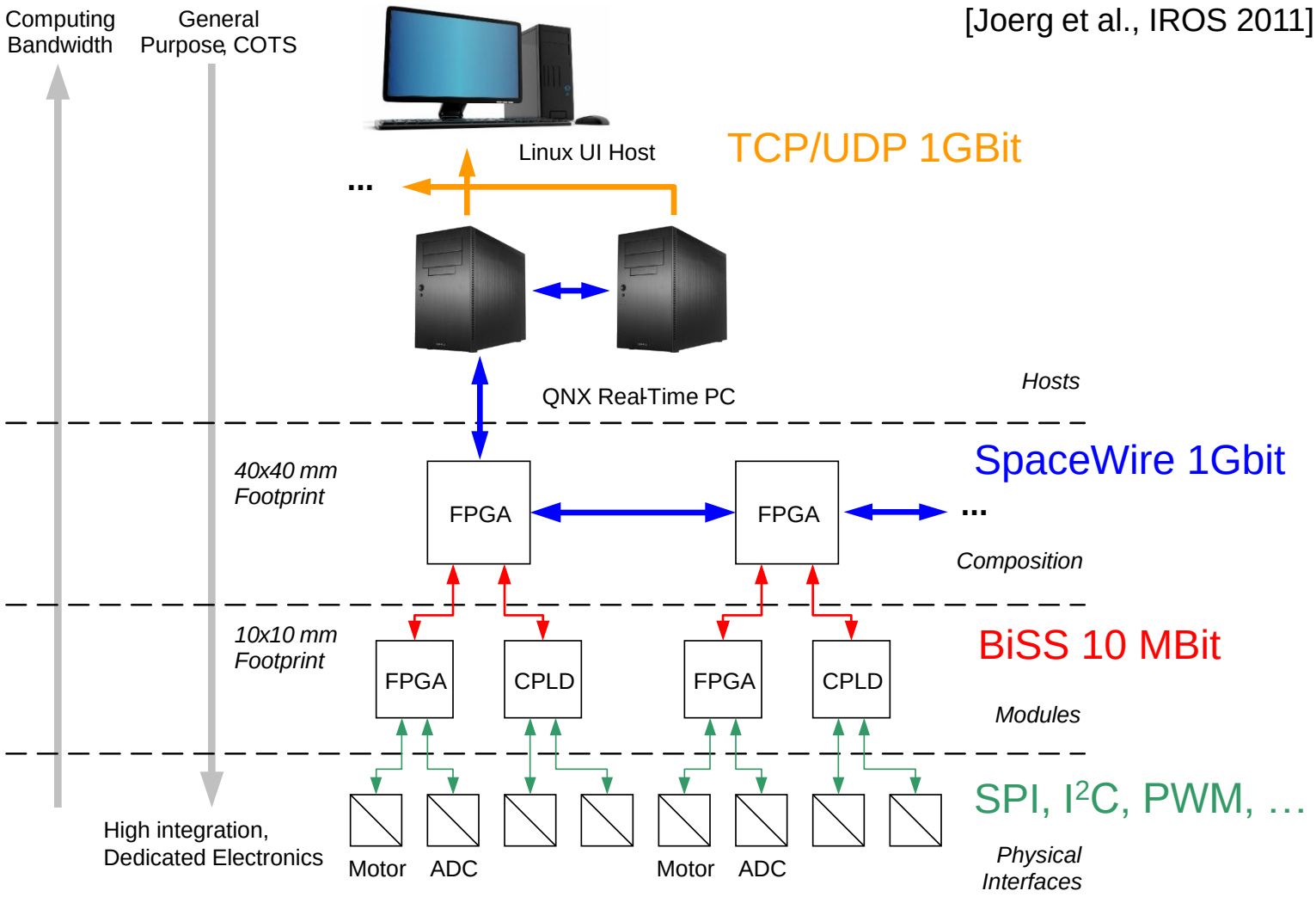
3 kHz
Host Control
Loop

The Hierarchical Architecture - Computing nodes

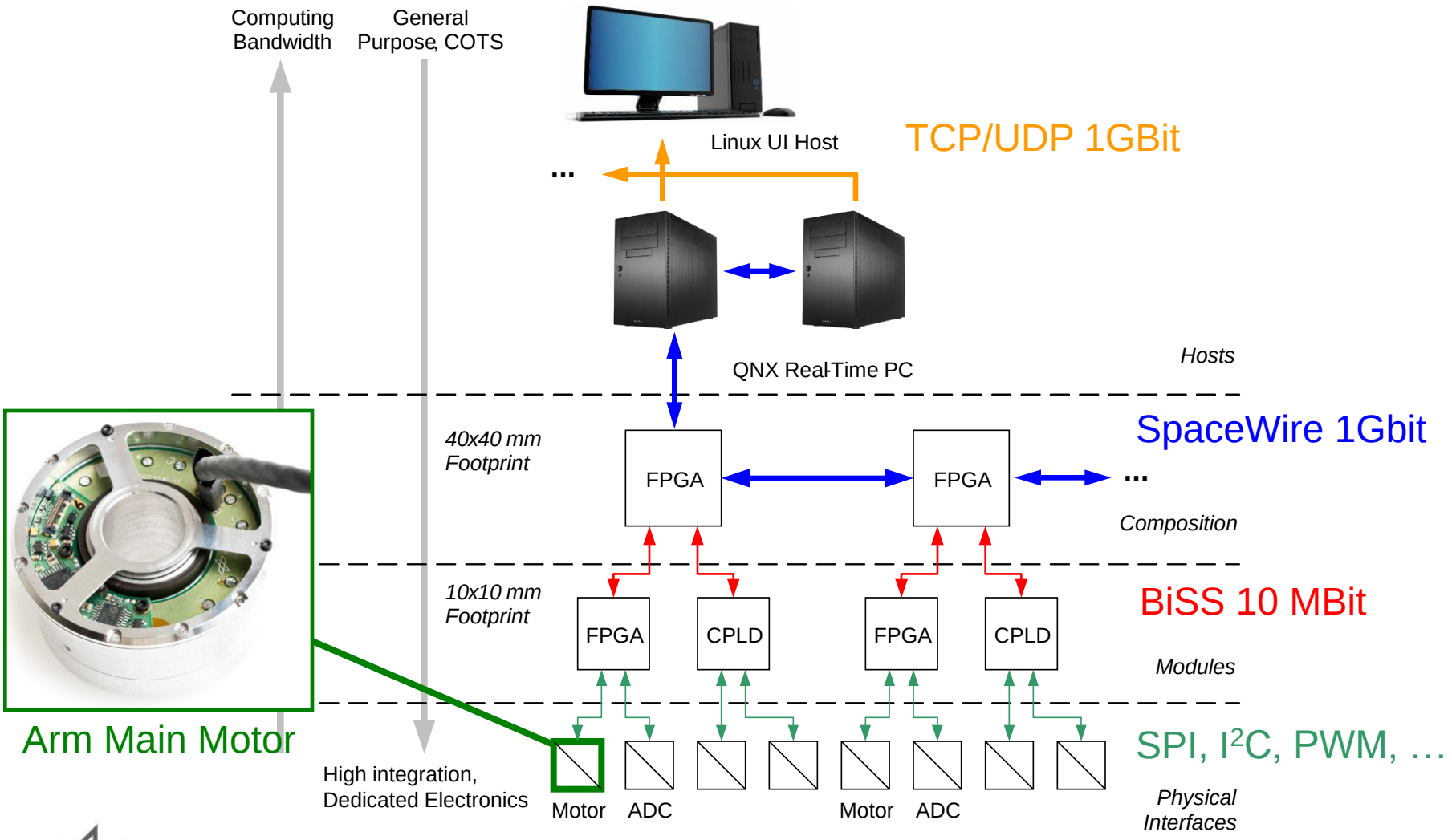
[Joerg et al., IROS 2011]



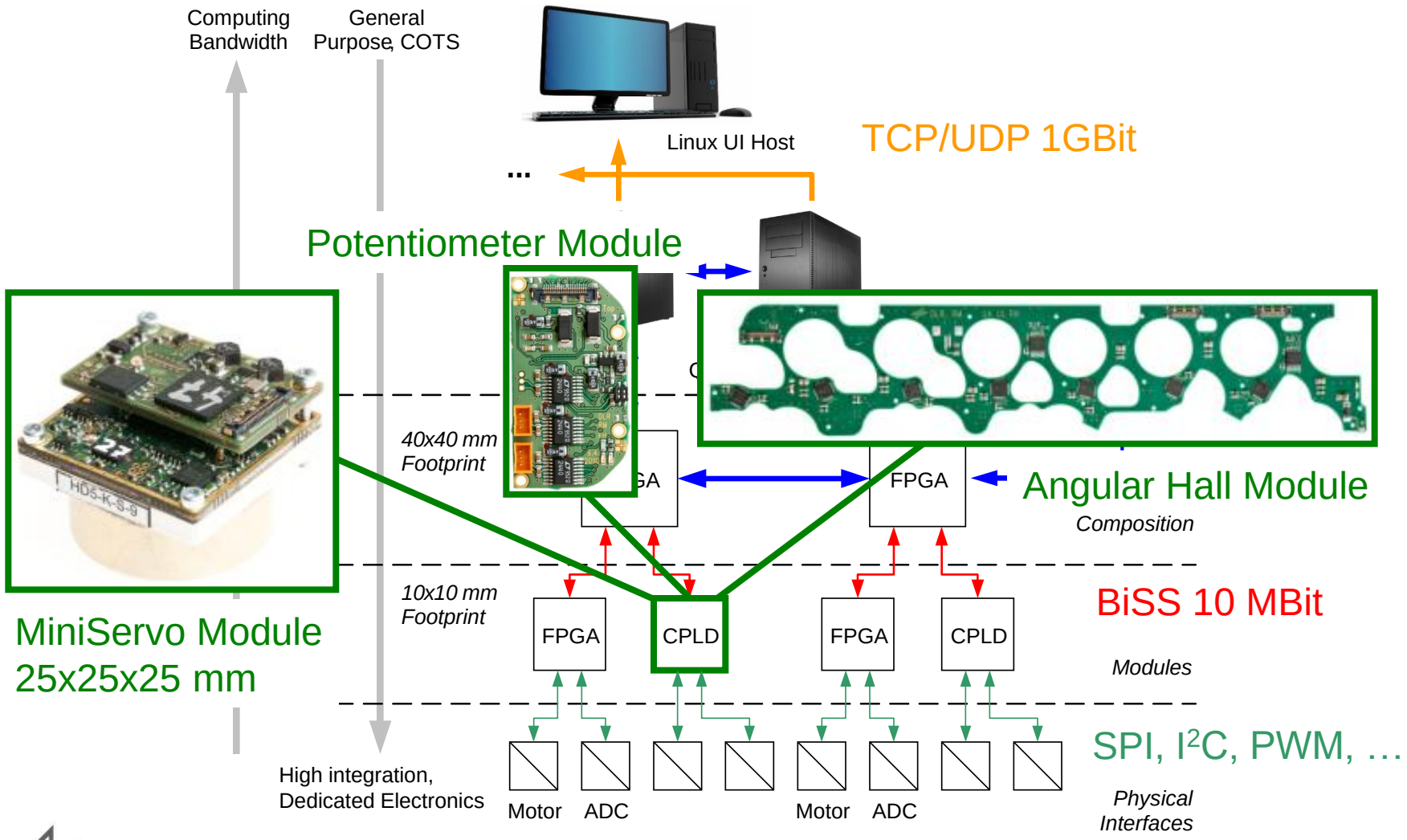
The Hierarchical Architecture



The Hierarchical Architecture - Physical Interfaces



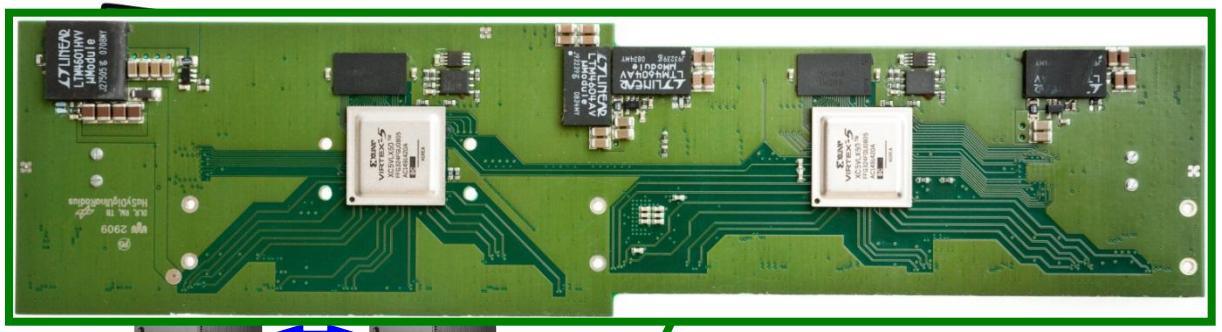
The Hierarchical Architecture - Modules



The Hierarchical Architecture - Composition

eneral
se, COTS

SpaceWire PCIe



Forearm Node

Arm Node

QNX Real-Time PC

Hosts

40x40 mm Footprint

FPGA

FPGA

...

Spacewire 1Gbit

Composition

10x10 mm Footprint

FPGA

CPLD

FPGA

CPLD

BiSS 10 MBit

Modules

High integration,
Dedicated Electronics

Motor

ADC

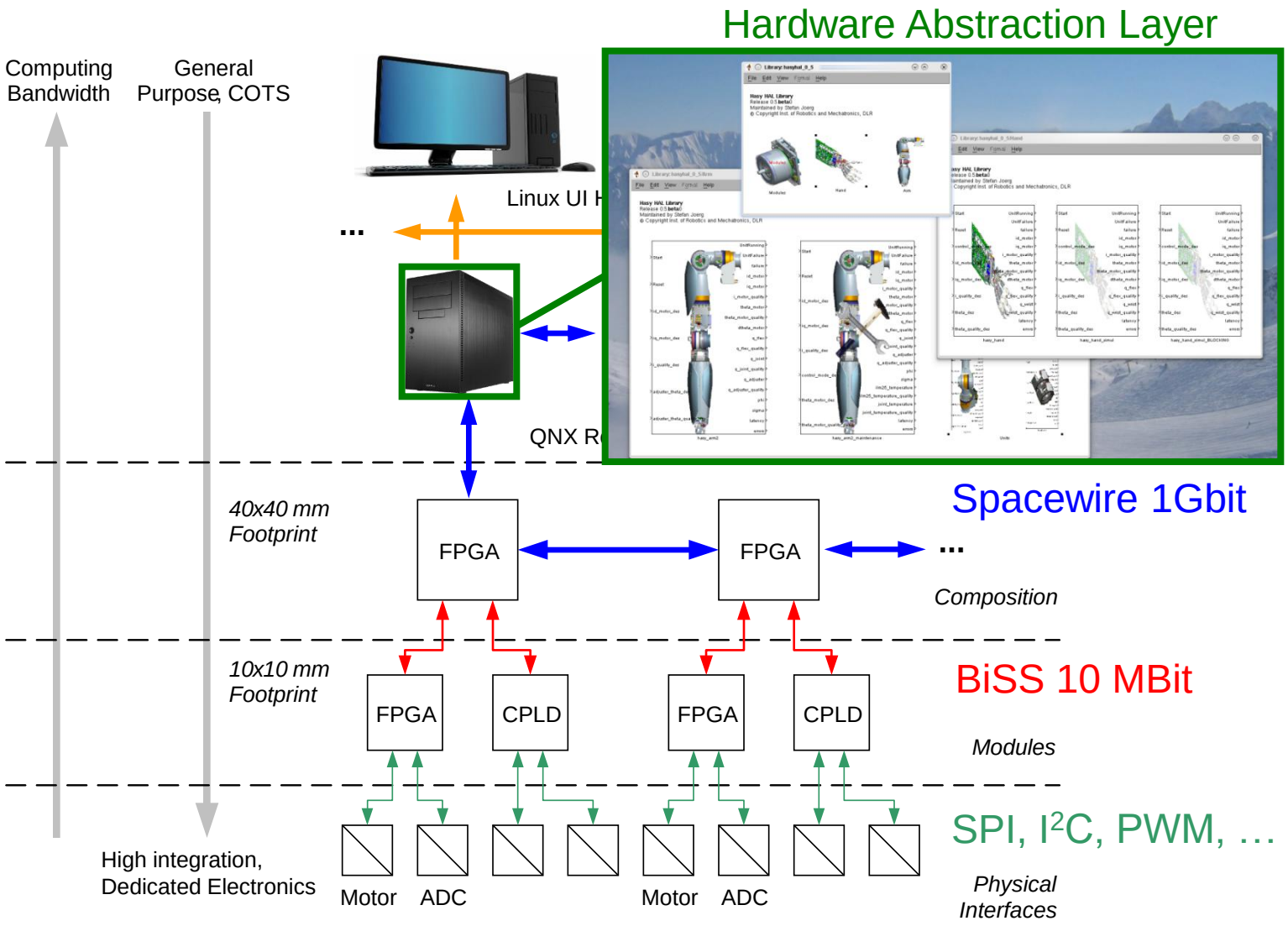
Motor

ADC

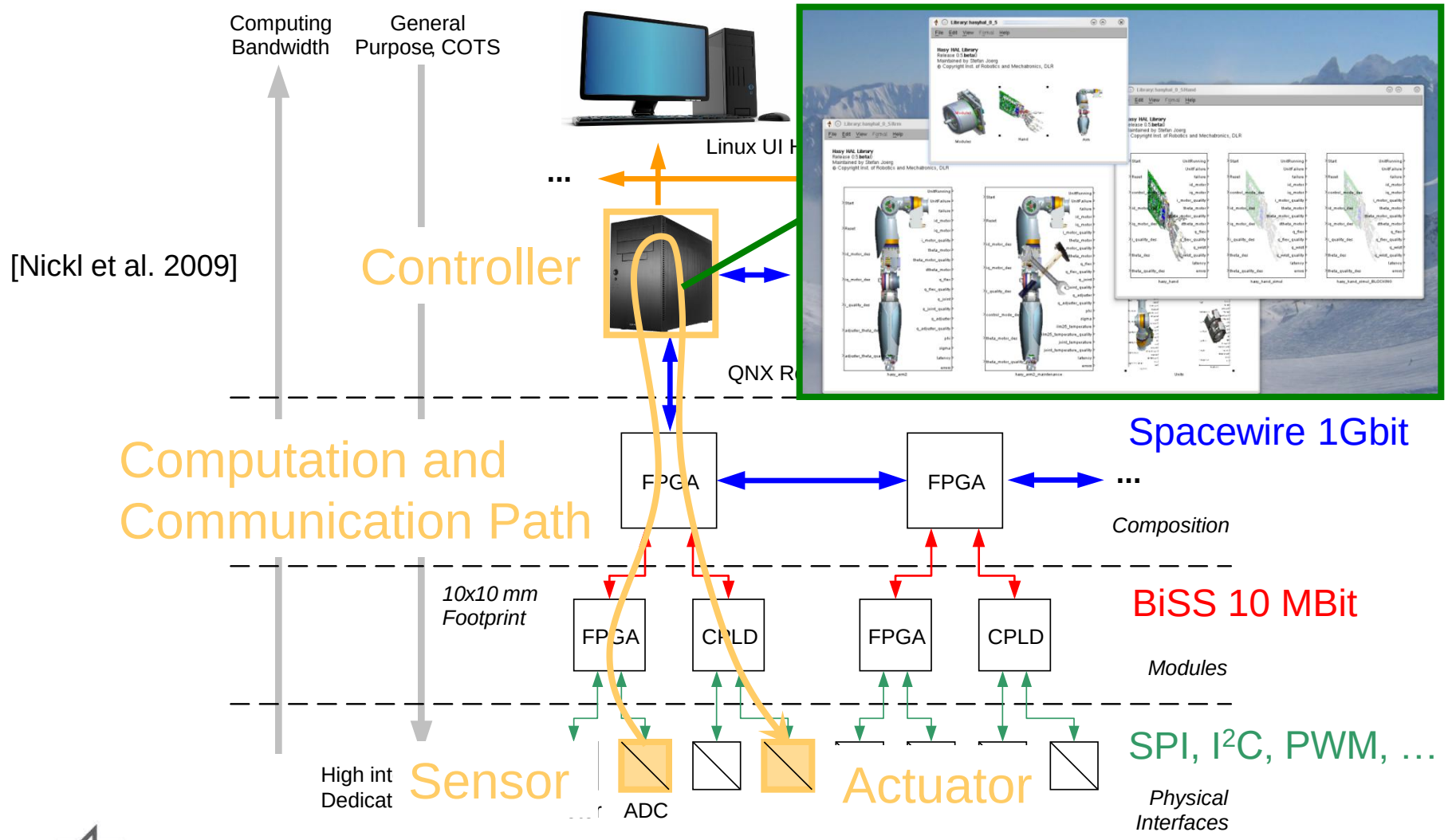
SPI, I²C, PWM, …

Physical Interfaces

The Hierarchical Architecture – The HAL

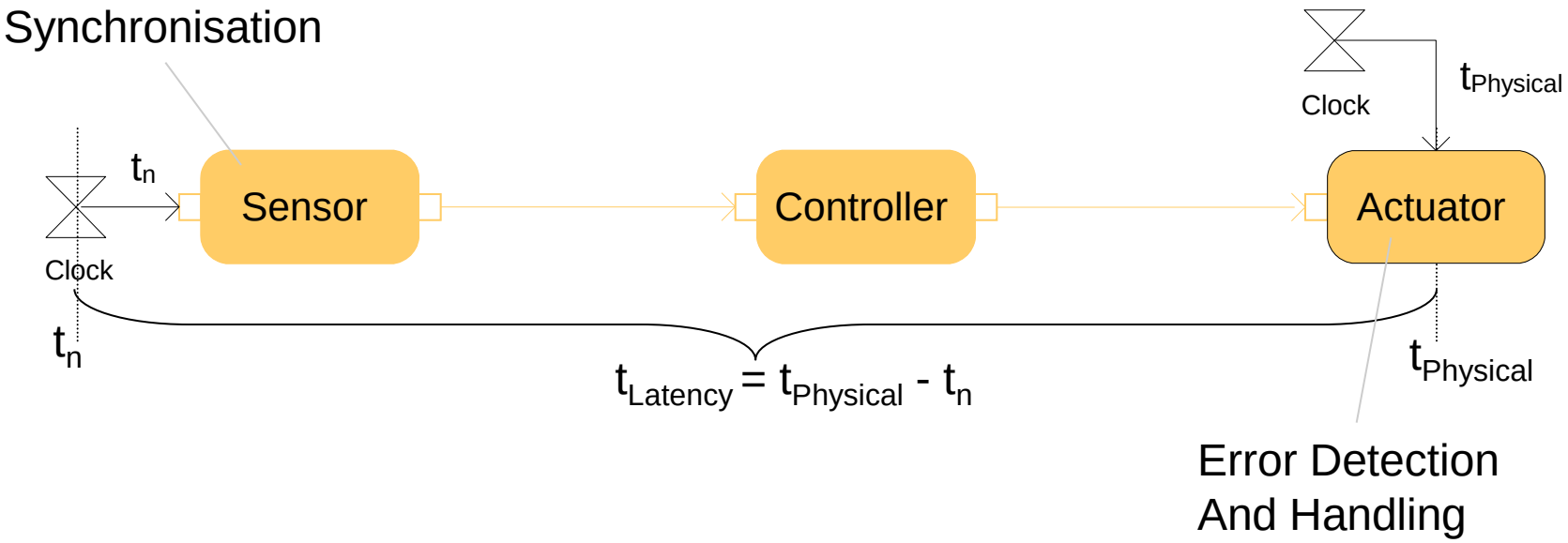


The Virtual Path – From Sensor to Actuator

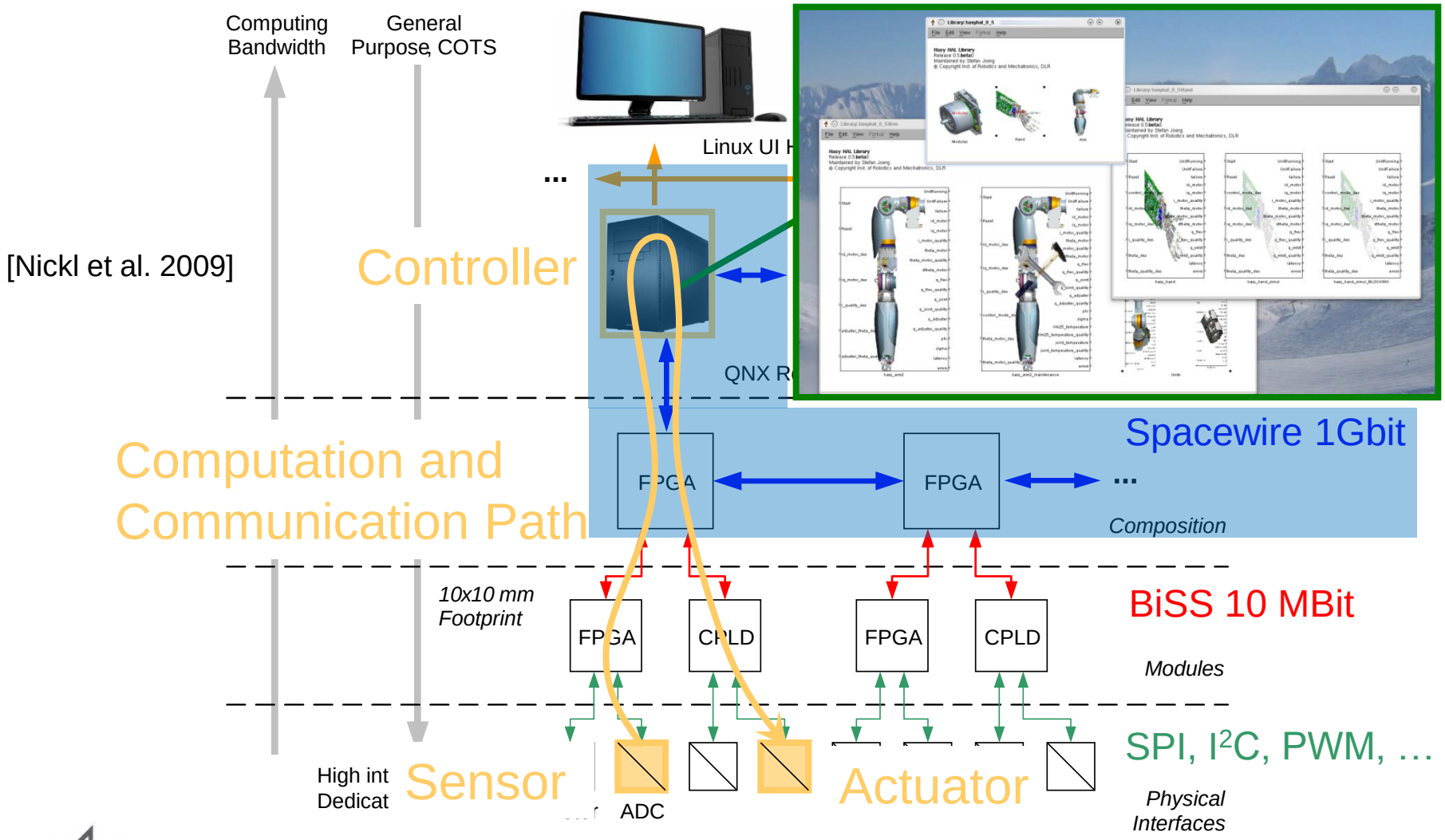


The Virtual Path – From Sensor to Actuator

The Application is synchronized by the sensor hardware (*The Virtual Path* [Nickl et al. 2009])



The Virtual Path – From Sensor to Actuator



SpaceWire-Implementation: Requirements for Robotics

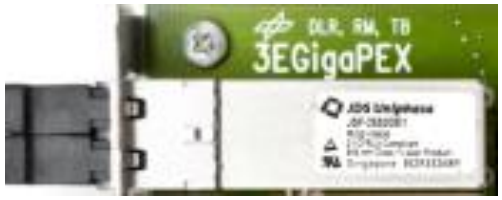
- **Deterministic**
  - Defined Topology
  - Packet length limited to 1024 bytes
  - Clock with Time Codes
- **Low latency**
  - up to 1 Gbit/s
  - FPGA implementation
  - PCIx Host adapter with drivers for QNX/VxWorks
- **High integration**
  - Own electronics (cables, connectors)
- **Manageable**
  - Configuration from file
  - Test Suite

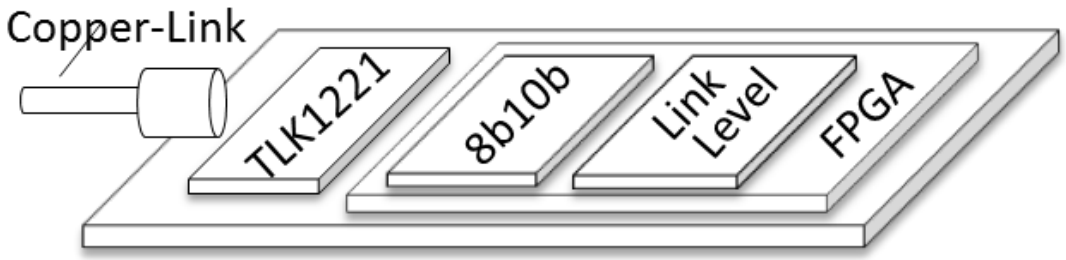
PCIx host adapter

SpaceWire-Implementation: Physical, Character, Link Layers

- LVDS and Fiber
- Up to 1 GBit/s
- 8b10b encoding (FPGA)
- Links with CRC

Kinemedic 2005





Copper Link with 8b10b

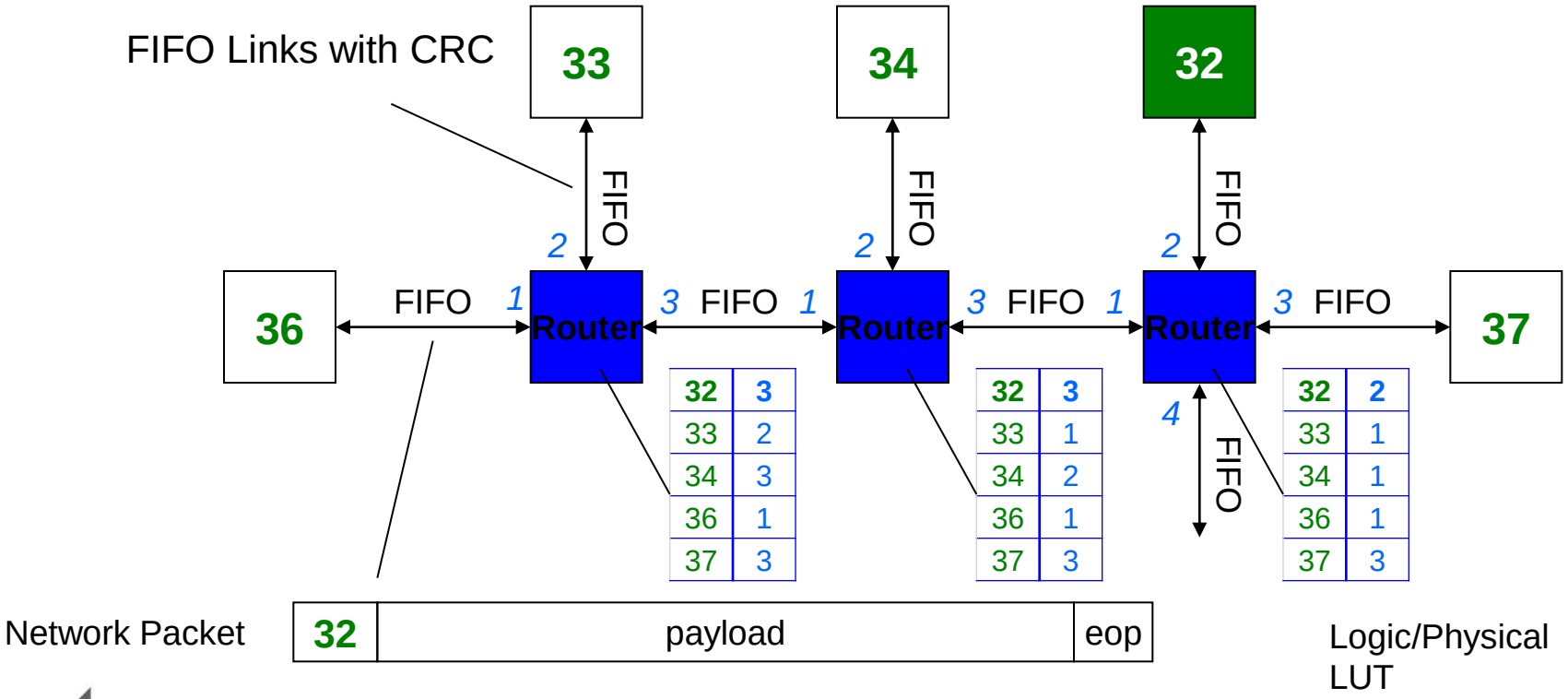
ESC	KChar
IDLE	K28.5
TC	K28.1
FCT	K28.2
EEP	K28.3
EOP	K28.4
NULL	K28.6

ESC to Kchar mapping

SpaceWire-Implementation: Standard Network Layer

- Implemented on FPGA
- Router Configuration Protocol
  (for runtime configuration of address tables)

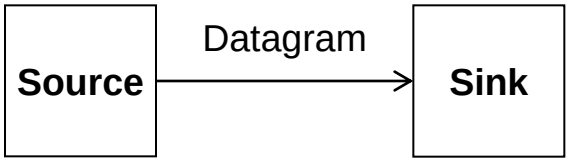
Kinemedic 2005



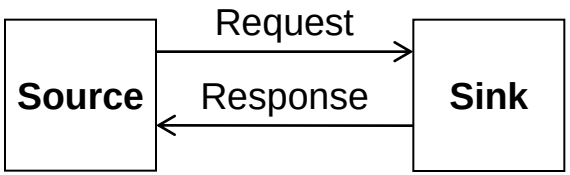
SpaceWire-Implementation: Our Transport Layer

- Connection-oriented proctocols
- CRC protected payload
- Peer Address is configured at runtime

MICA 2008



Datagram Protocol



RequestResponse Protocol

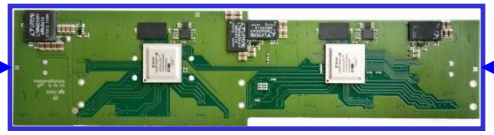
Logic. Addr.	Packet ID	payload	crc	eop

Transport Packet

Results:
DLR Hand Arm System – SpaceWire Topology

Hand

Upper Side



Lower Side

Host

Arm

Triple Joint Stack

Double Joint Stack

Host

	Router	**Nodes**
Hand	4	52
Arm	5	45
Hosts	4	4
Total	13	101

Results:
Arm Control Application – SpaceWire Packets

Triple Joint Stack

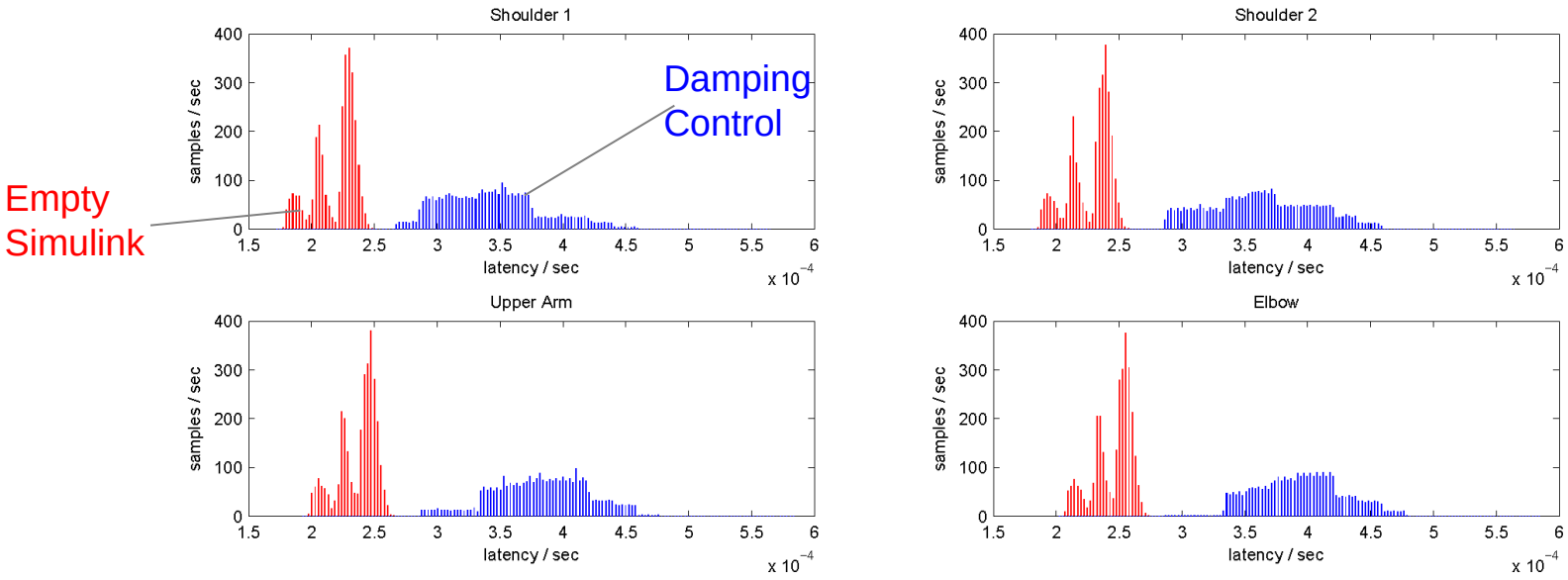
Double Joint Stack

Host

3 kHz Host Control Loop, Signals by Datagram Protocol

	Triple	Double	Total	Bytes
Actual Packets / cycle	9	8	17	600
/ sec	27000	24000	51000	1758k
Desired Packets / cycle	5	4	9	171
/ sec	15000	12000	27000	501k
Total / cycle	14	12	26	771
/ sec	42000	36000	78000	2259k

Results:
Arm Control Application - Latency of 3kHz Loop



Application		*Shoulder1*	*Shoulder2*	*Upper Arm*	*Elbow*	*mean*
HAL only	mean [µs]	219.34	227.65	237.23	245.99	**232.55**
(empty Simulink model)	std [µs]	16.53	16.53	15.00	15.01	15.77
Damping Control	mean [µs]	343.24	363.09	382.50	393.48	**370.57**
[Petit et al., ICRA 2011]	std [µs]	39.34	41.50	37.21	34.10	38.04

deadline: 2 cycles = **667µs**

Conclusions & Outlook

- Experiments prove stability and determinism (Latency < 667us)
- Hierarchical architecture enables high integration at manageable effort
- SpaceWire has been succesfully utilized as communication backbone for robotic systems of increasing complexity

Further work:

- Complete humanoid robot
- Experiment with highly distributed algorithms (safety, reflex actions)


Thank you!