

**RESEARCH HIGHLIGHTS IN  
MECHATRONICS  
LABORATORY OF INTELLIGENT MACHINES  
LUT UNIVERSITY**

Professor, D.Sc (Tech.) Heikki Handroos

# LUT UNIVERSITY IN NUTSHELL

Founded

**1969**

**1545**

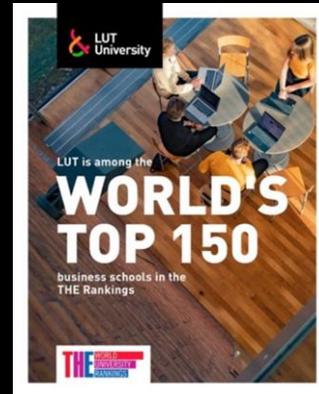
Staff  
members

**9000**

Students

**2300**

International  
students



**€133,3**

Funding

**1148**

Publications  
in 2024

**94%**

Employment rate  
one year  
after graduation

**102**

Nationalities

## LUT School of **ENGINEERING SCIENCES**

- » Separation technology
- » Physics
- » Computational engineering
- » Software engineering
- » Industrial engineering and management
- » Social sciences

## LUT School of **ENERGY SYSTEMS**

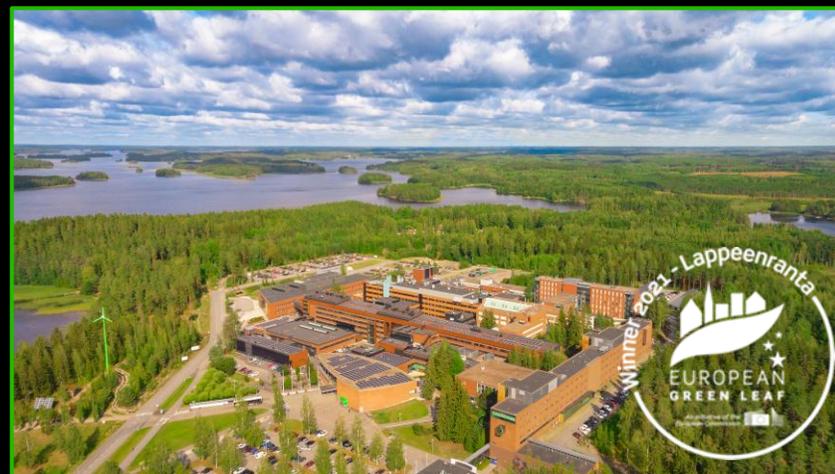
- » Energy technology
- » Electrical engineering
- » Sustainability science
- » Mechanical engineering

## LUT **BUSINESS SCHOOL**

- » Driving sustainable growth
- » Creating value in a digital economy



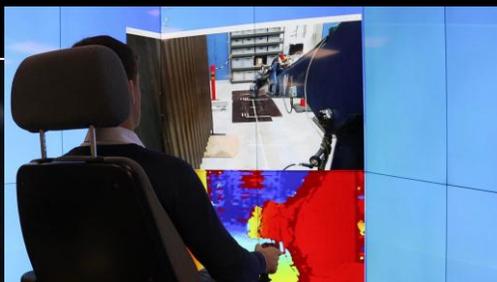
# CAMPUSES IN LAPPEENRANTA AND LAHTI



# LABORATORY OF INTELLIGENT MACHINES – MOST IMPORTANT RESEARCH IMPACTS



- Advance Modelling and Simulation methods for Mechatronic Systems
- Advanced Robotics technologies with Special Reference to Nuclear and Hazardous Environments (more than 20 years in EUROfusion programs)
- More than 300 scientific publications and 40 doctoral dissertations (end of 2024)
- Spin-offs
  - Mevea Oy (Training & R&D simulators)
  - THT Robotics (Robotic Handling for Web-Grocery)
  - Flowgait Oy (Horseback Riding Simulators)
  - Haptronics Oy (Haptic Interfaces for Heavy Machinery)





# LIM PERSONNEL 12/2024

1 professor 2 associate professors, 3 post docs, 7Ph.D students + 5 research assistants

# PARALLEL KINEMATIC MOTION PLATFORMS

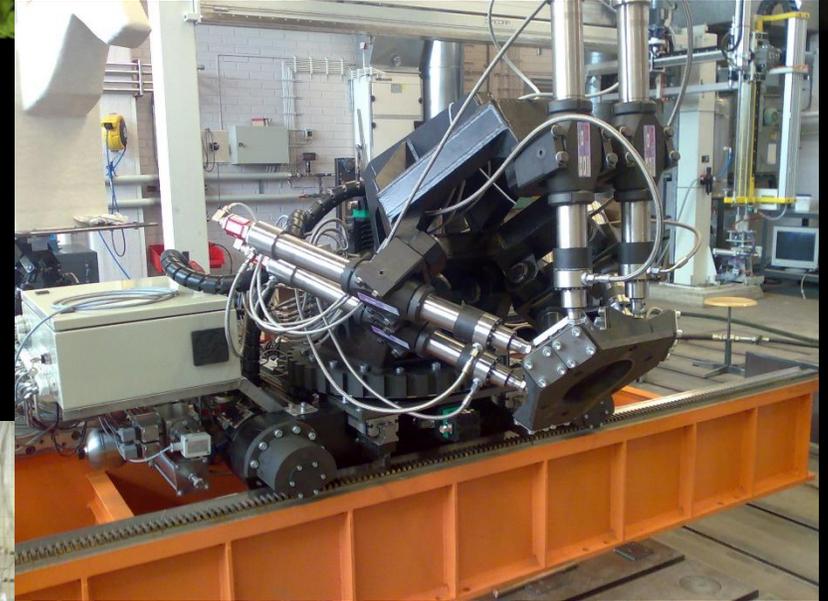
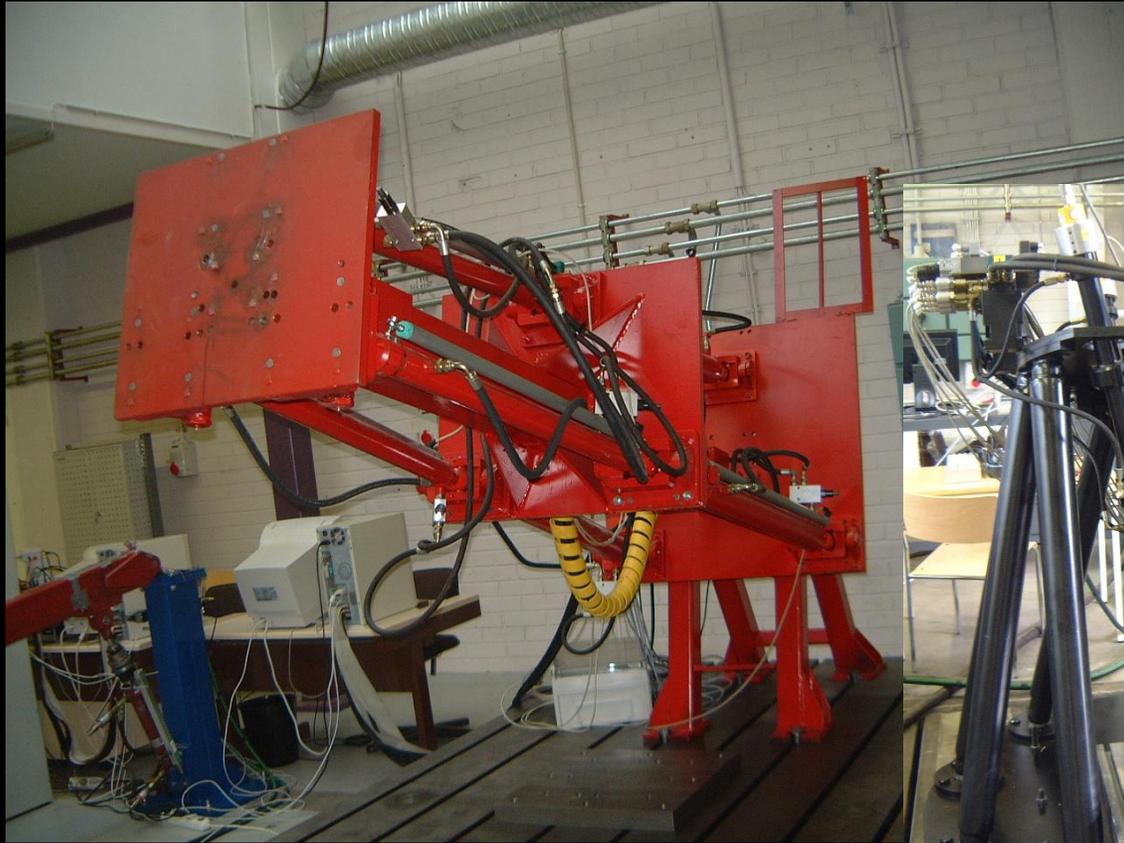
HYDRAULIC



ELECTRIC



# RESEARCH IN HEAVY DUTY PARALLEL ROBOTICS



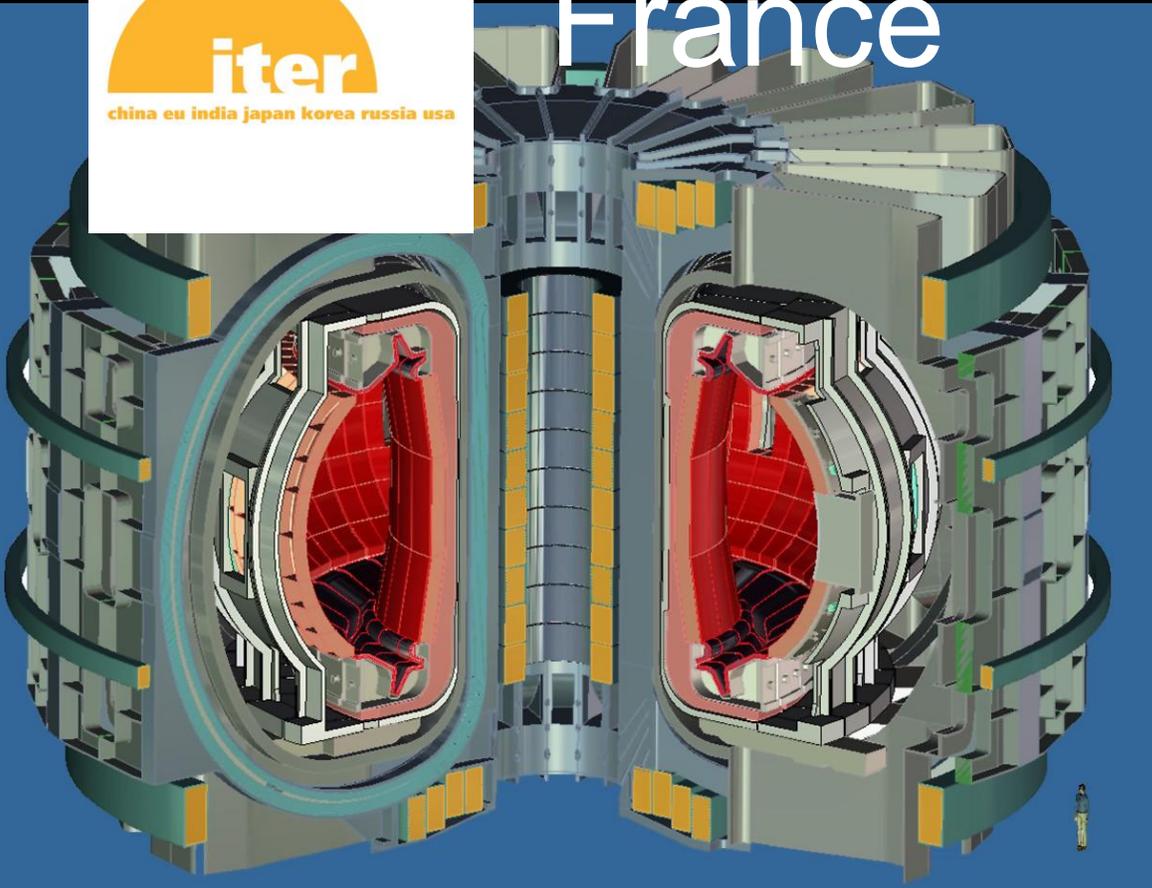


EUROfusion



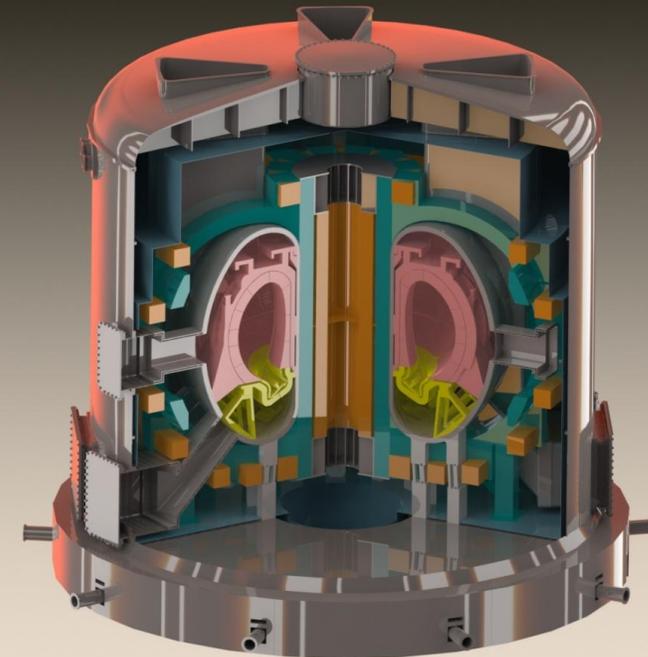
# TOKAMAK EXPERIMENTS

## Cadarache, France

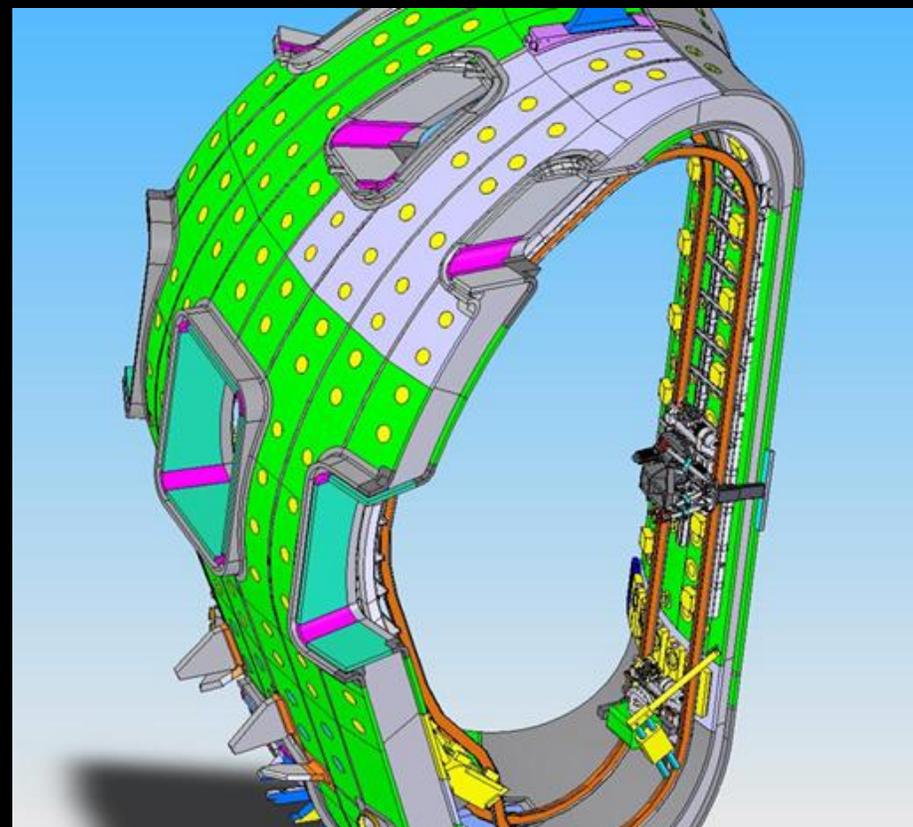


Institute Of Plasma Physics  
Chinese Academy Of Sciences

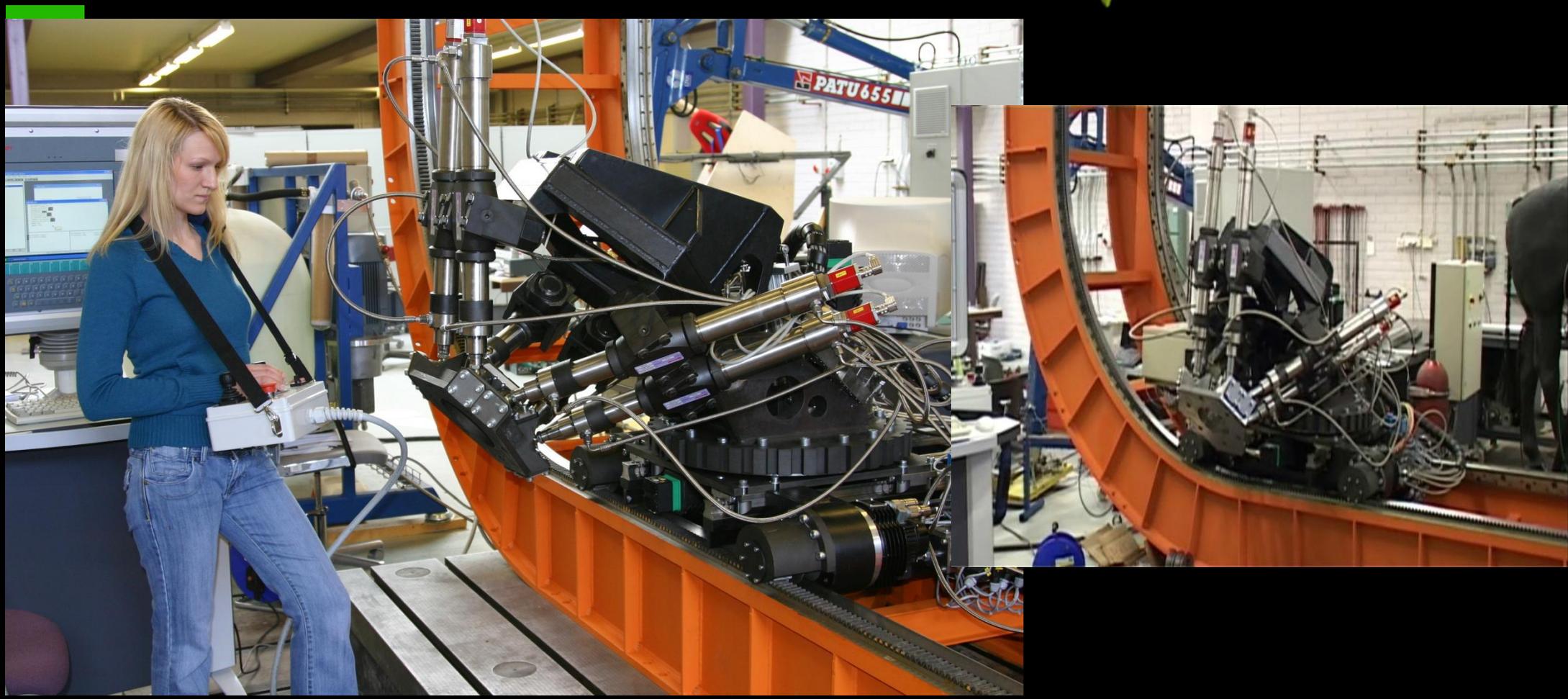
## CFETR, Hefei



# 1. OILHYDRAULIC PROTOTYPE OF INTERSECTOR WELD/CUT ROBOT



# 2. 10-AXIS WATERHYDRAULIC PROTOTYPE



# 3. 10-AXIS ELECTRICALLY ACTUATED IWR

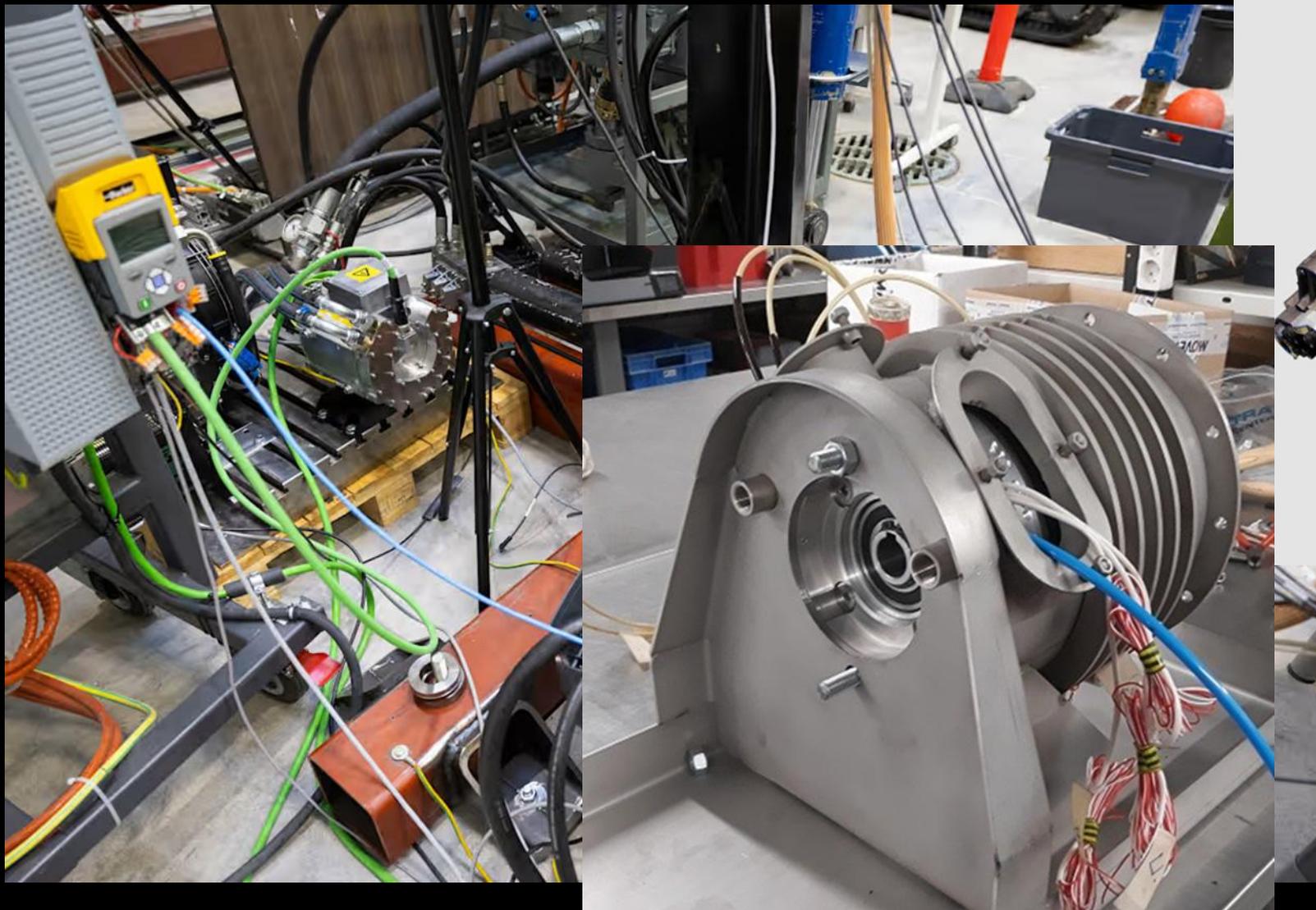


# RESEARCH ON MODELLING, IDENTIFICATION, OBSERVATION AND CONTROL OF HYDRAULIC SERVOSYSTEMS

- Robust control (Sliding Mode, Backstepping)
- Identification (Differential Evolution, Monte Carlo Markov Chain)
- Observation (Extended and uncentered Kalman Filters, Particle Filters)
- Fuzzy and neural control
- Tuning of controllers by AI



# RESEARCH ON MORE ELECTRIC TRANSMISSION



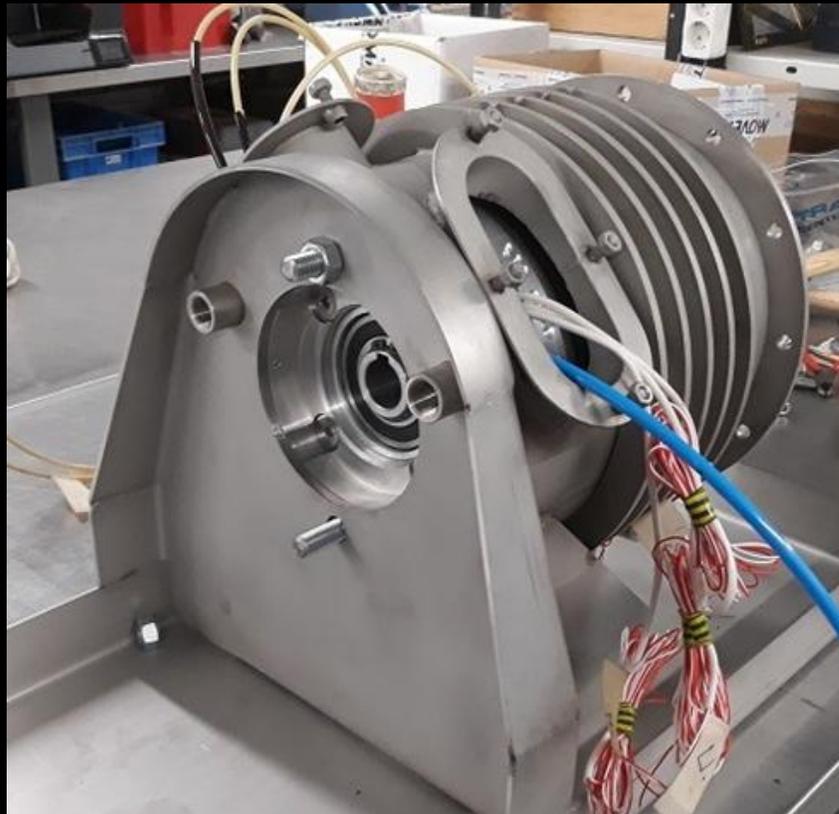
# INTEGRATED ELECTRO-HYDRAULIC ENERGY CONVERTERS – LUT IEHEC



- Supply hydraulic circuit with hydraulic power
- Energy regeneration (hydraulic energy → electrical energy)
- Maximum efficiency up to 90 %. Inverter efficiency is not included.

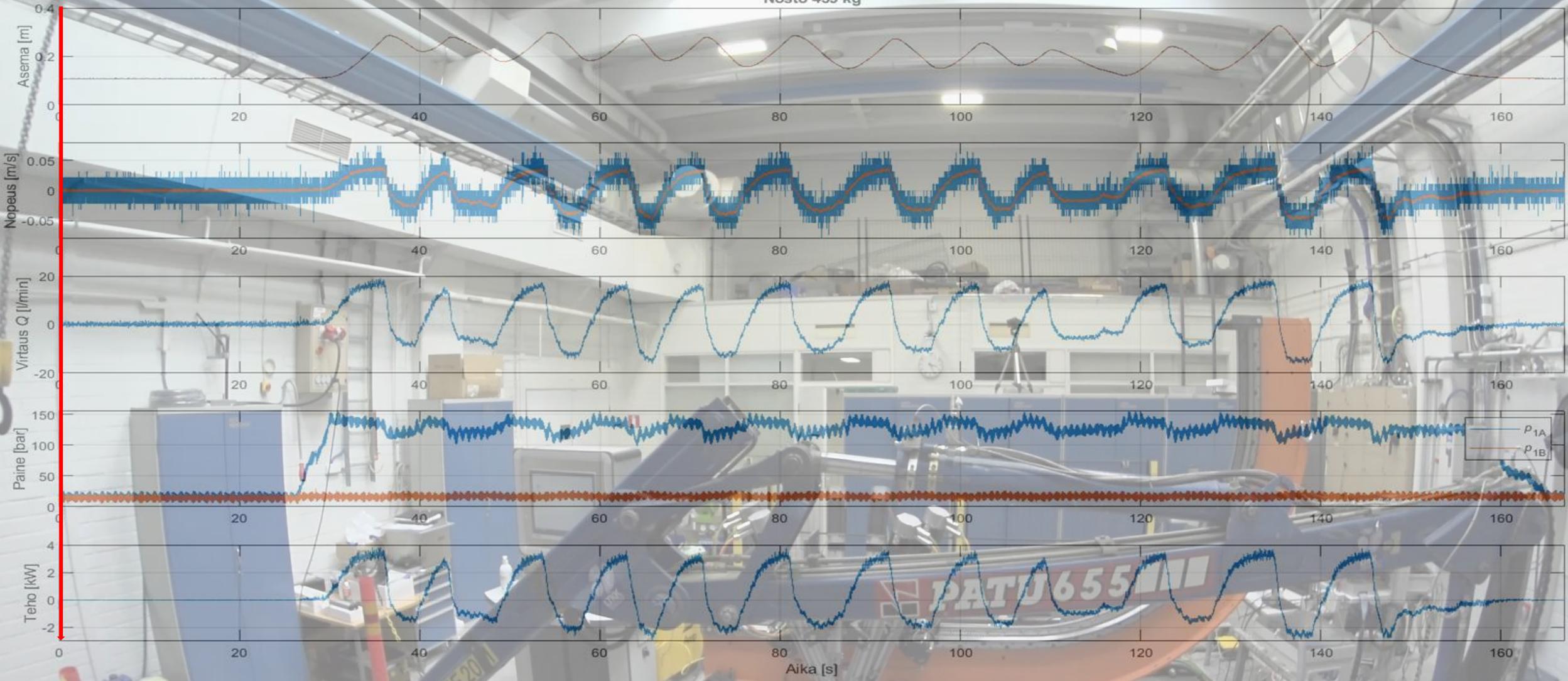
Parameter	Value
Output power	30 kW
Flow rate	100 lpm
Speed max	3000 rpm
Pressure max	380 bar
Weight	110 kg

# INTEGRATED ELECTRO-HYDRAULIC ENERGY CONVERTERS – LUT COMEHEC

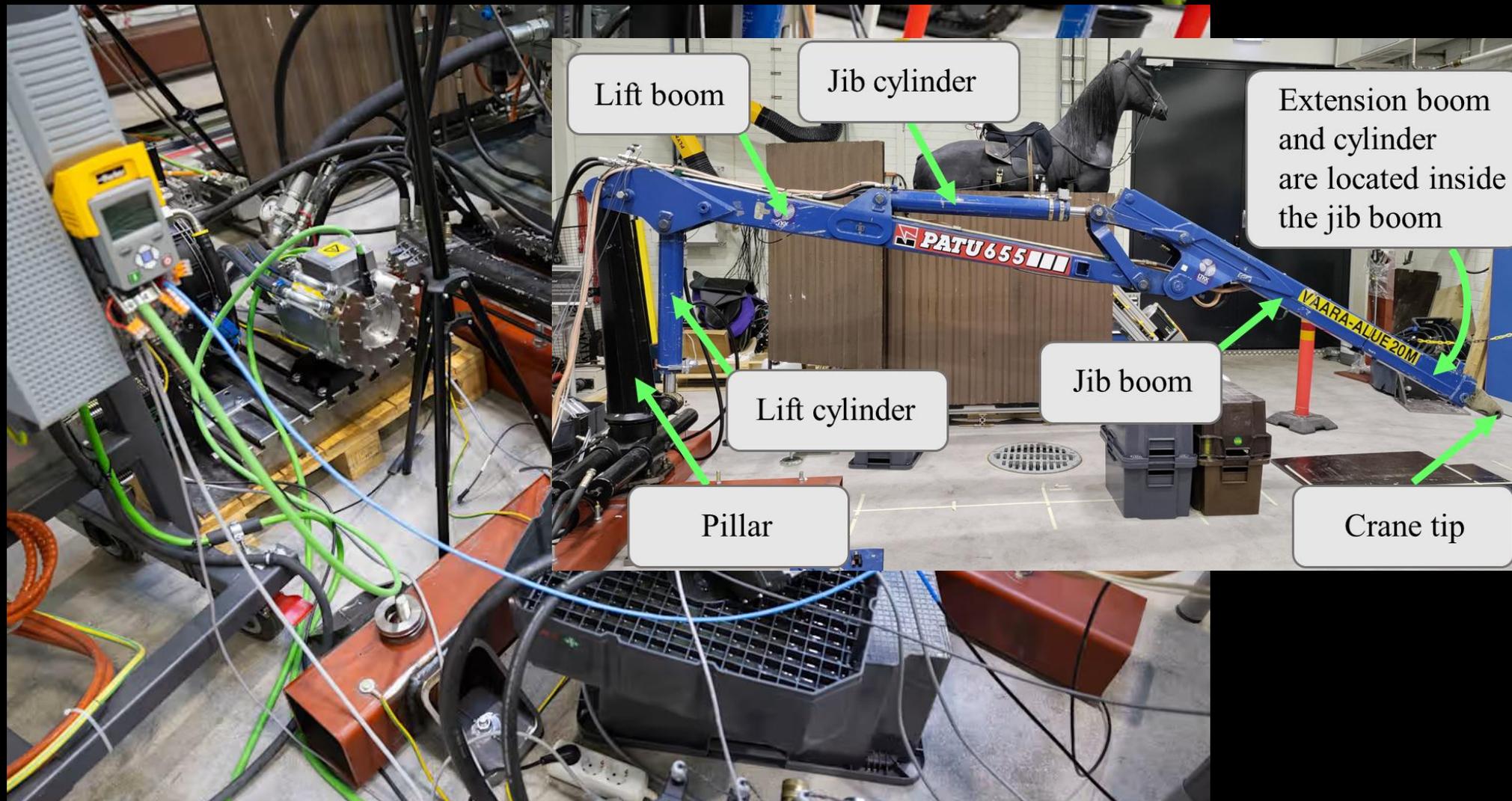


Nominal pressure, bar	200
Hydraulic machine displacement cm <sup>3</sup> /rev	19
Nominal flow rated, l/min	34.2
Hydraulic machine speed, n r/min	2000
Hydraulic machine rated power	7 kW (1000 r/min)
Hydraulic machine type	Fixed displacement bent axis motor/pump
Rated hydraulic machine Torque, TN	68 Nm
Gear ratio	1:3
Gear efficiency estimate	0.95
Electric motor power	7 kW, S3 70 %
Electric motor speed range	0 – 6000 r/min
Electric motor type	24-20 tooth-coil PMSM
Pole pair number, p	10
Electric motor max speed n <sub>Nmax</sub> , r/min	6000
Rated line-to-line voltage U	300 V @ 3000 r/min 400 V in field weakn.

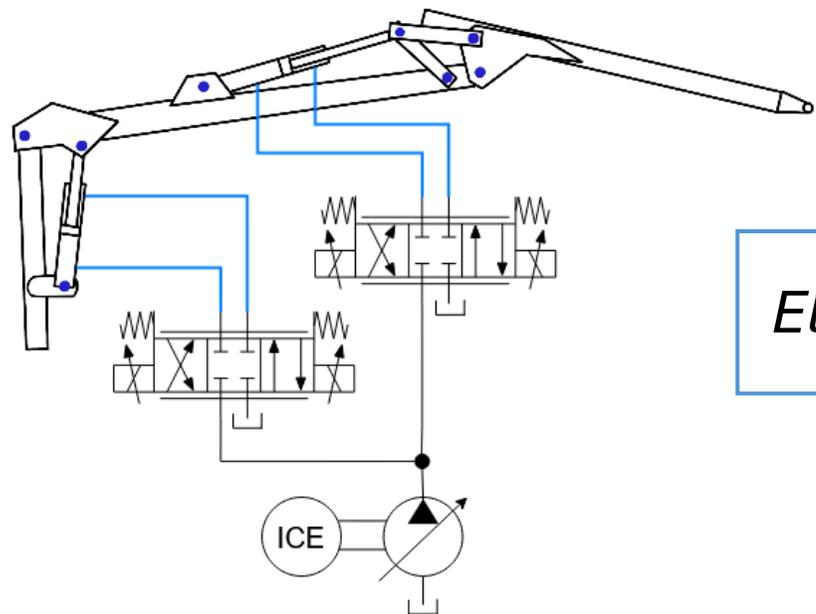
# Nosto 439 kg



## Electro-hydraulic Actuator (Parker) under test

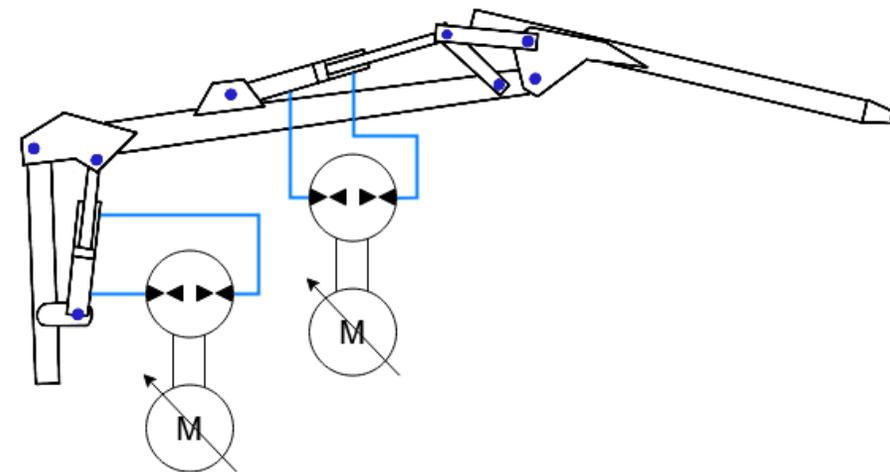
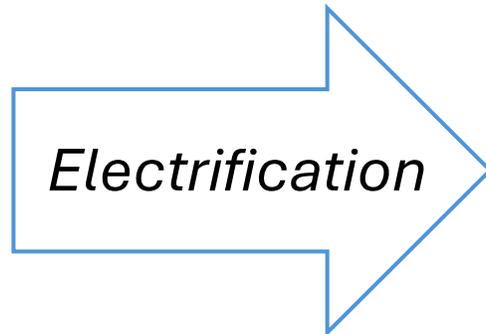


# Electrification is the key, but



*Conventional hydraulic system  
~35% efficiency*

Up to 8 actuators



*Electro-hydraulic system  
~80% efficiency*

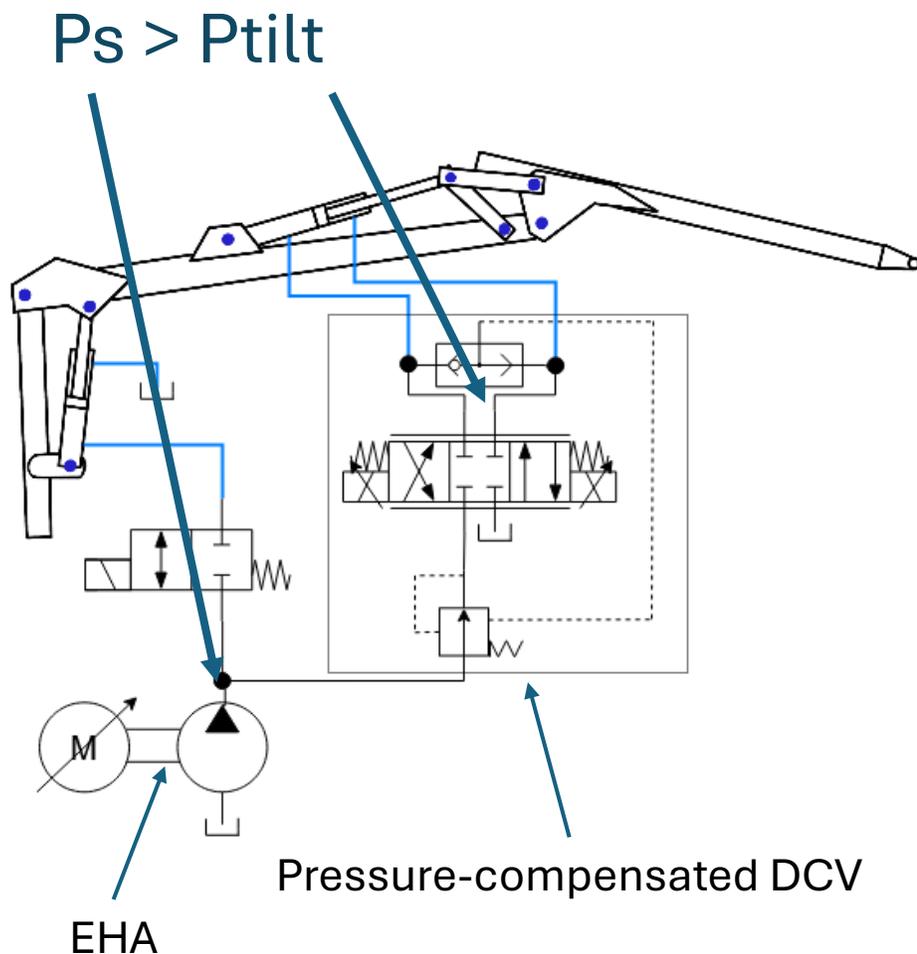
Up to 8 pump-motor units



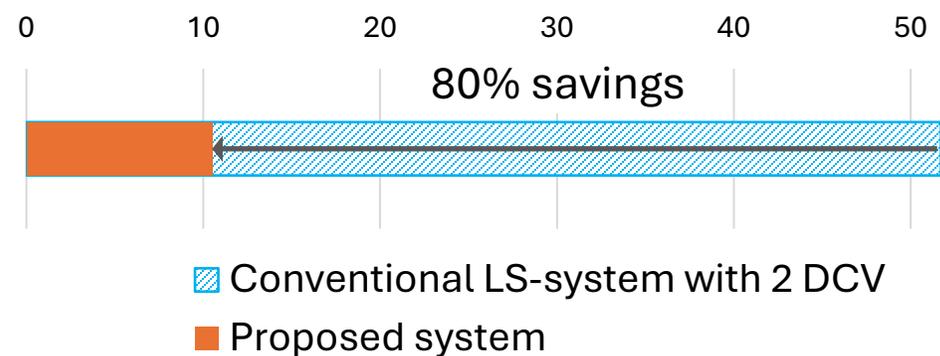
Costly and massive. How to optimize it?

# Solution 1: Valveless actuation of the lift cylinder

## Limitation:



## Energy consumption, kJ



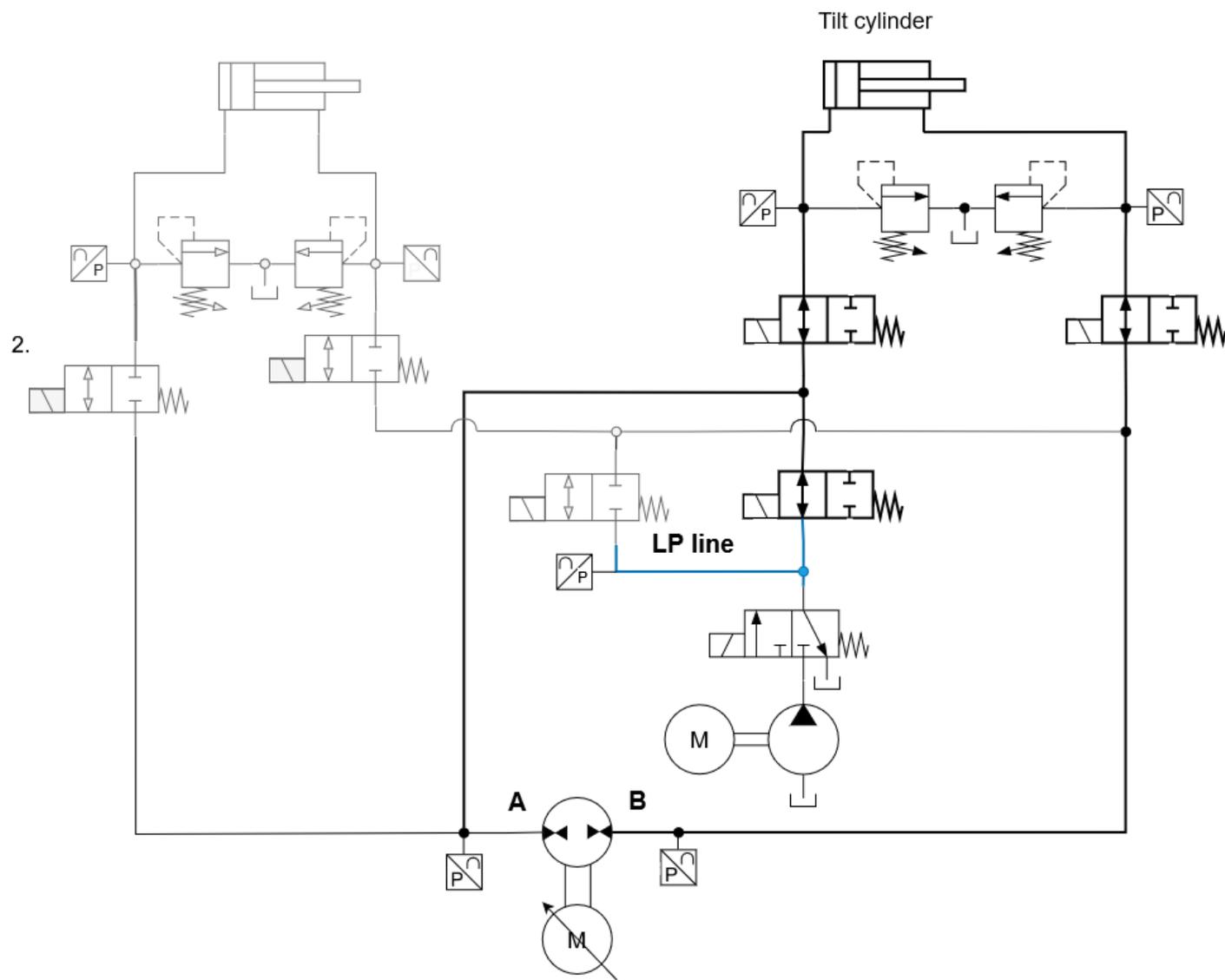
## Advantages:

- Simplicity
- Compactness
- High efficiency
- Recuperation capabilities

## Disadvantages:

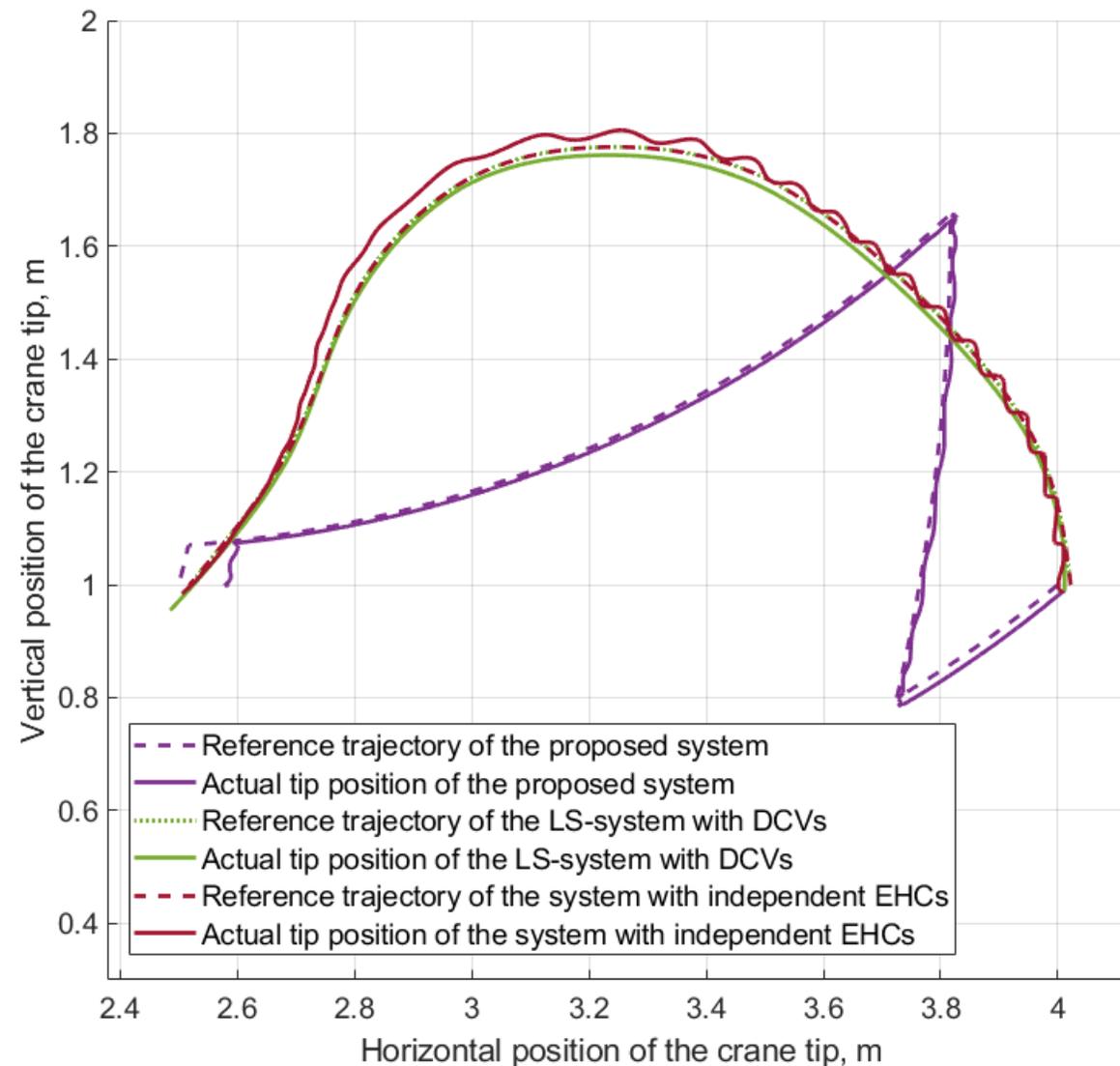
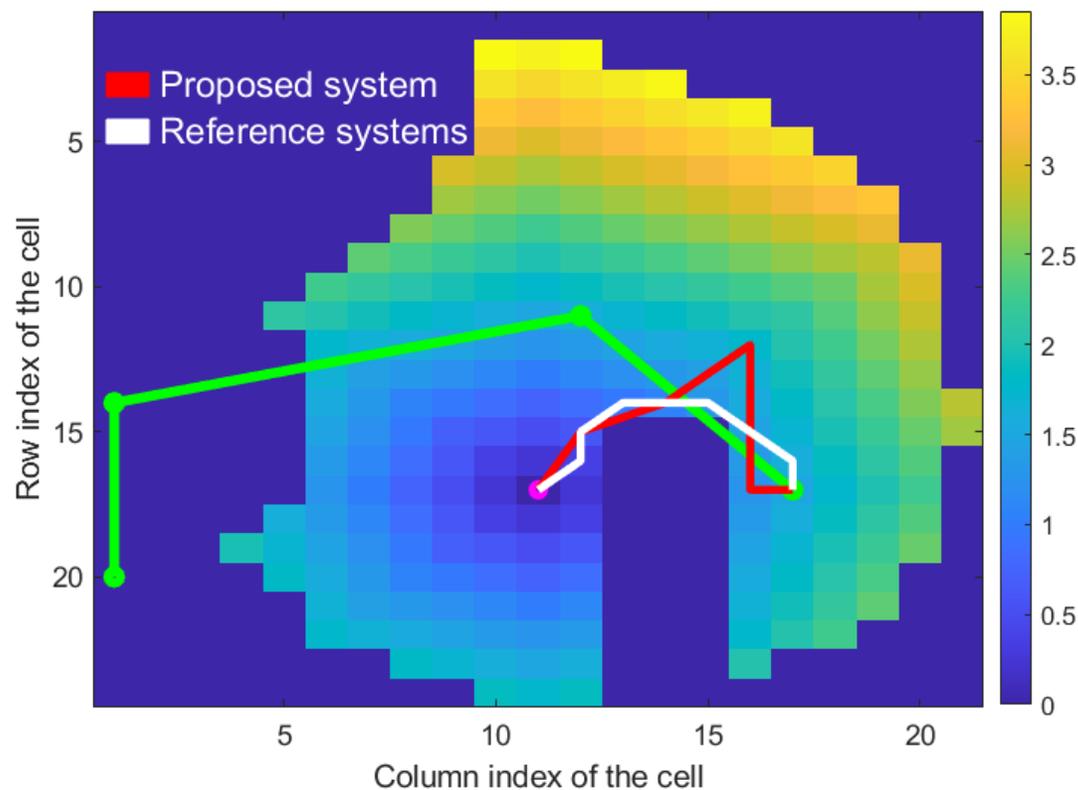
- DCV throttling losses
- Puts a limitation on system pressure

# Solution 2: Sequential actuation



- 1 – EHA
- 2 – On/off valve
- 3 – Lift cylinder
- 4 – Tilt cylinder
- 5 – Pressure sensor
- 6 – Pressure-relief valve
- 7 – Directional control valve
- 8 – Boost pump

# Solution 2: Sequential actuation



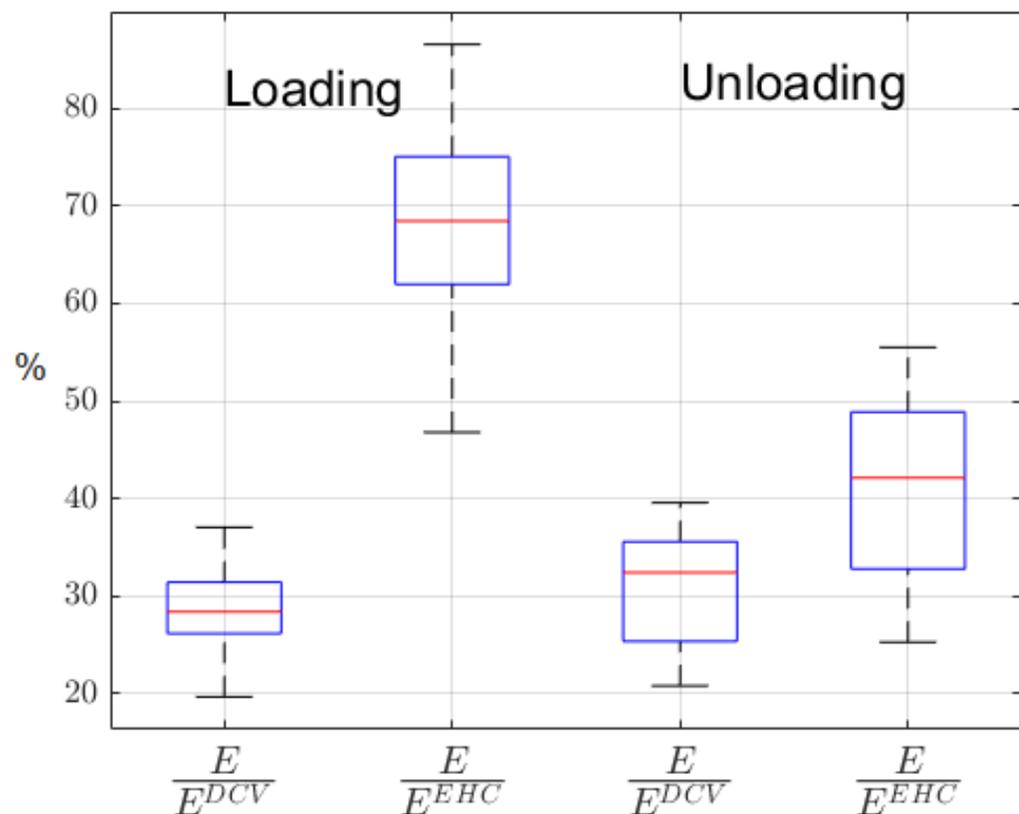
# Solution 2: Sequential actuation with a single EHA

Energy consumption per cycle

$E$  - proposed system

$E^{DCV}$  - LS-system with DCVs

$E^{EHC}$  - system with independent EHCs



## Advantages:

- Compactness
- High efficiency
- EHA operation within high-efficiency range

## Disadvantages:

- Cycle duration increases without switching optimization.

# Path planning algorithm (modified A\*)

*Learning phase*

Evaluation function:  $f(n) = g(n) + h(n)$

Energy consumed by a cylinder:

$$E_{cyl} = \int_0^T P(t)Q(t) dt$$

Cost of the path

Heuristic  
(distance to the goal)

Normalized energy:

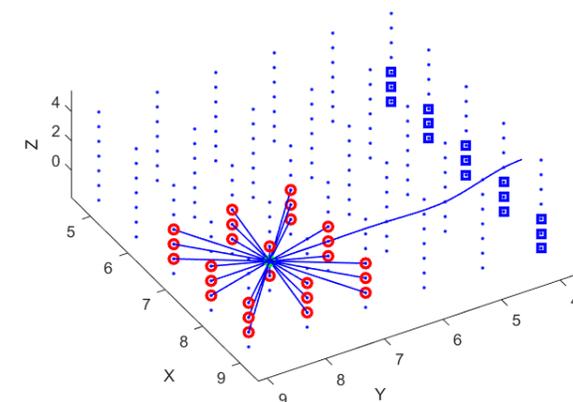
$$E_{K,R,L}[i, j, k] = \frac{E_{K,R,L}[i, j, k] + |\min_{\forall K,R,L}(E_{K,R,L})|}{|\min_{\forall K,R,L}(E_{K,R,L})| + \max_{\forall K,R,L}(E_{K,R,L})}$$

1) Define the space of the possible crane tip positions

2) Mesh the space

3) Obtain energy matrices using simulations

26 3D matrices containing energy needed to move to a neighbor cell



# THE MOST EFFICIENT PATH IN MANIPULATION



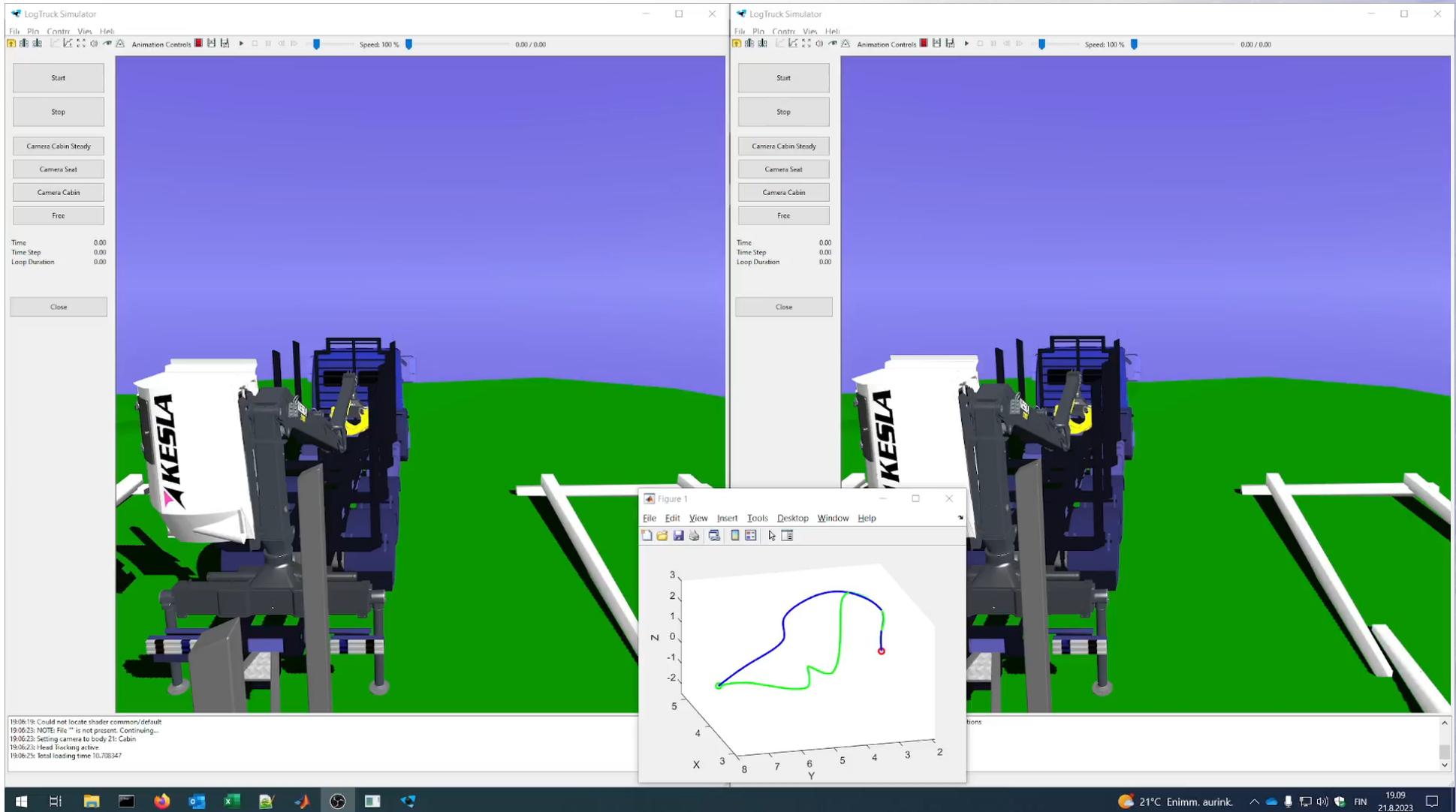
# 3-D Experiment example

ASME  
FPMC 2023

ASME/BATH Symposium on Fluid Power and Motion Control



Efficient path



Shortest path

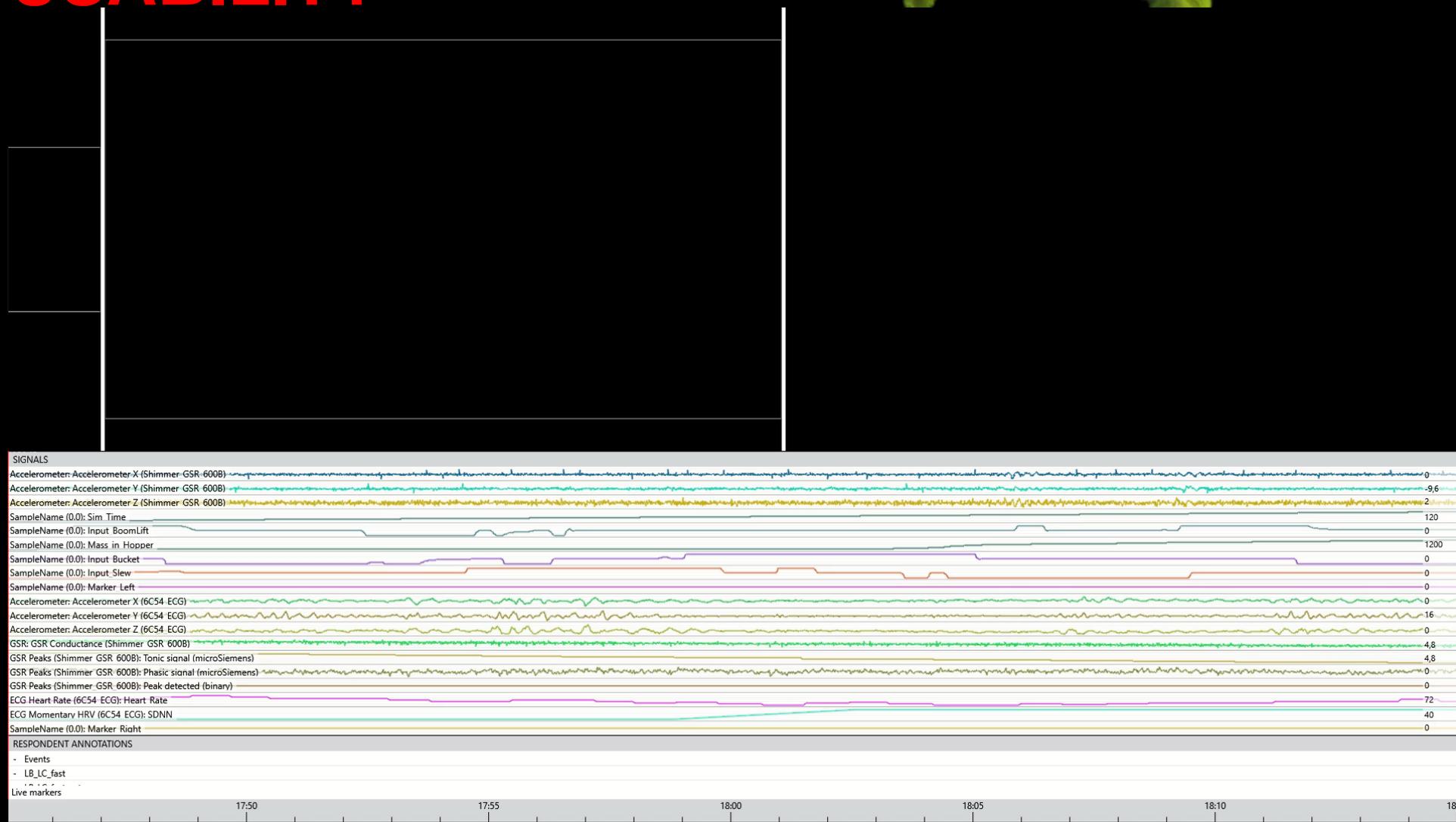
# RESEARCH ON MODELLING AND SIMULATION OF HEAVY MACHINES

- Development of computational efficient models for hydraulic components
- Development of computational efficient models for electric components
- Combining multibody models and hydraulic/electric system models
- Hardware-in-the-loop simulation

# RESEARCH ON MODELLING AND SIMULATION OF HEAVY MACHINES

- Embedded simulators in IIoT-systems
- Machine design by real-time digital twins
- Usability and Human-Machine-interface design
- Training AI with simulated data
- Mental and physical load assessment by using bio-signals and AI

# LUTERGO LABORATORY R&D INCLUDING USABILITY



# LUTERGO LABORATORY

- Studying multimodal feedback for remote operation (haptic and vibrational)
- Human-centric HMI-UX development using bio-signals (EMG, ECG, EEG etc.)
- Log crane and mini-excavator remote operation demonstrators

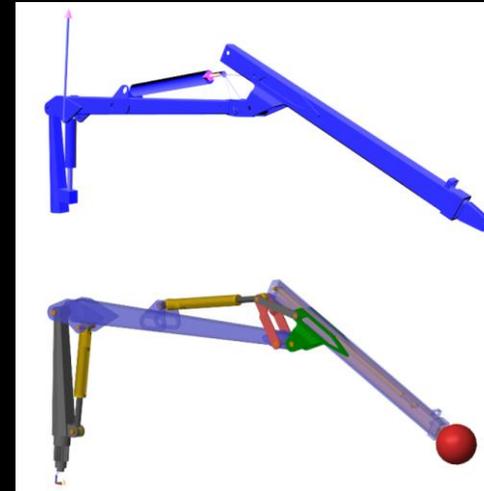


# EMBEDDED DIGITAL TWINS IN IIOT-SYSTEMS

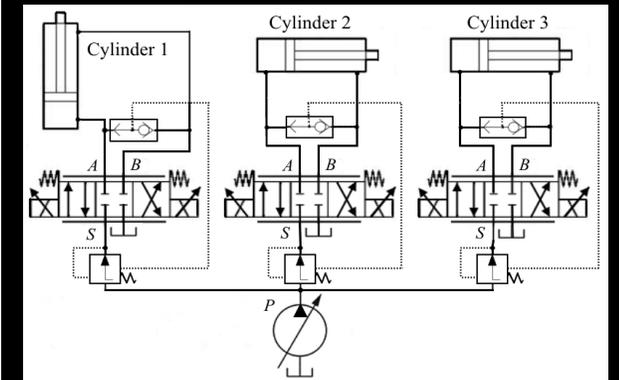


Use case: mobile log crane

Multi-body models



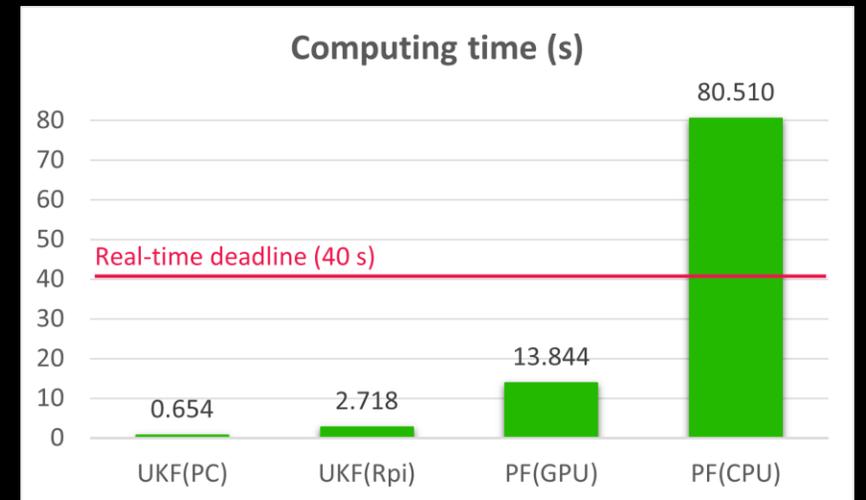
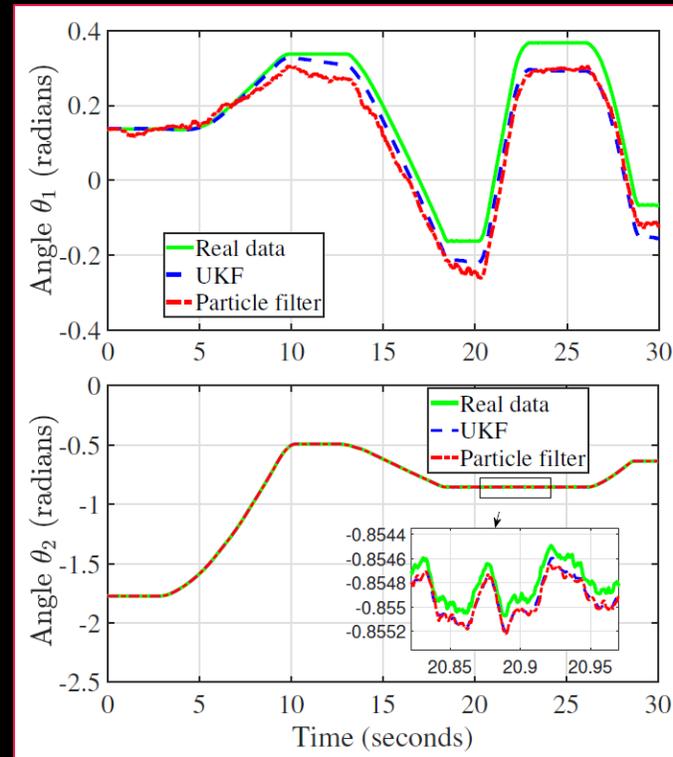
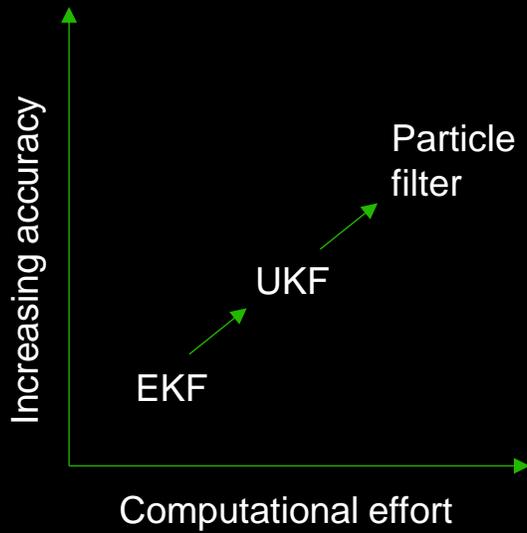
Hydraulic system model



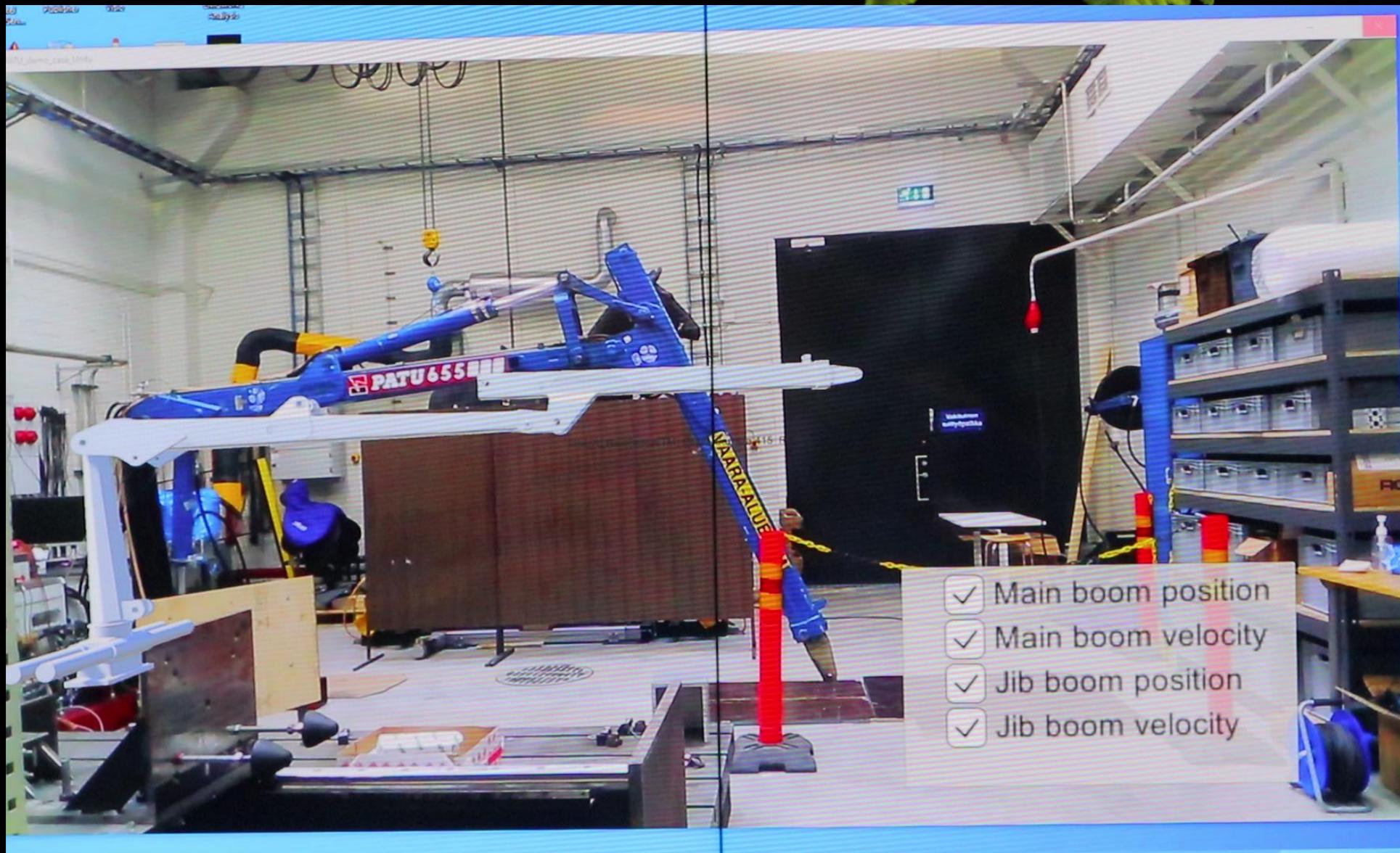
Digital twin

DigiBuzz project (2019-2021)

# NONLINEAR FILTERING



# DIGITAL TWIN WITH PARTICLE FILTER





LOGSET

Junttan



HEVTEC



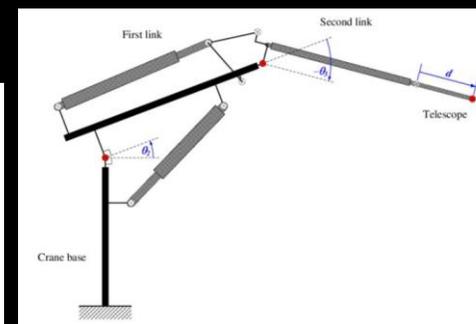
**DYNAMIC MODELLING & REAL – TIME SIMULATION OF ELECTRO-HYDRAULIC ACTUATORS**

Nitin Panwar

Doctoral Researcher

Supervisors: Prof. Heikki Handroos

(DSc.) Victor Zhidhchenko



VALTRA

normet



Mevea  
Simulation solutions



## Research Outlook and Applications

# REAL-TIME MODELS FOR EHAS

### ➤ Current Focus:

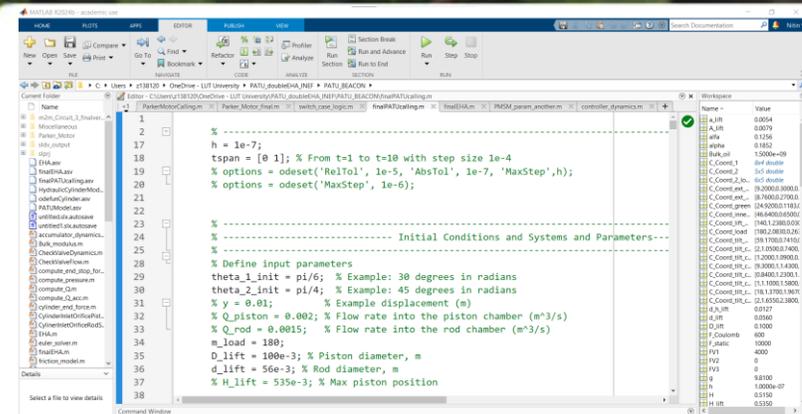
- Building high-fidelity real-time models of EHAs
- Integrating PMSM models with hydraulic subsystems
- Preparing for future HIL simulation

### ➤ Applications:

- Off – road construction equipment (e.g. PATU Crane)
- Energy – efficient hybrid systems

### ➤ Next Steps:

- Experimental validation with real hardware
- Integration with machine learning for adaptive control



```

1 %
2
3 %
4
5 %
6
7 %
8
9 %
10 %
11 %
12 %
13 %
14 %
15 %
16 %
17 h = 1e-7;
18 tspan = [0 1]; % From t=1 to t=10 with step size 1e-4
19 % options = odeset('RelTol', 1e-5, 'AbsTol', 1e-7, 'MaxStep',h);
20 % options = odeset('MaxStep', 1e-6);
21
22 % ----- Initial Conditions and Systems and Parameters-----
23 %
24 %
25 % Define input parameters
26 % theta_1_init = pi/6; % Example: 30 degrees in radians
27 % theta_2_init = pi/4; % Example: 45 degrees in radians
28 % y = 0.01; % Example displacement (m)
29 % Q_piston = 0.002; % Flow rate into the piston chamber (m^3/s)
30 % Q_rod = 0.0015; % Flow rate into the rod chamber (m^3/s)
31 % I_load = 100; % Load
32 % d_lift = 100e-3; % Piston diameter, m
33 % d_rod = 56e-3; % Rod diameter, m
34 % H_lift = 535e-3; % Max piston position
35
36
37
38

```



CAD Model, Laboratory of Intelligent Machines, LUT University

# REMOTE OPERATION



# HAPTIC INTERFACE

- Haptic joysticks with user interface
- Adjustable vibration frequency and amplitude
- Adjustable continuous force feedback
- Can be used in simulators and real machine control
- Blindfolded operation of a log crane demonstrated



# HAPTIC INTERFACE

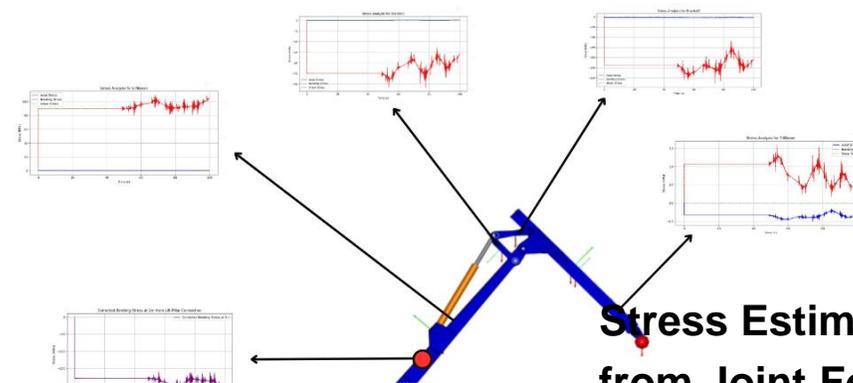


Laboratory of Intelligent Machines

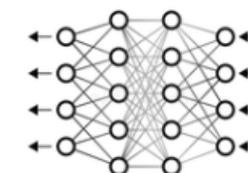
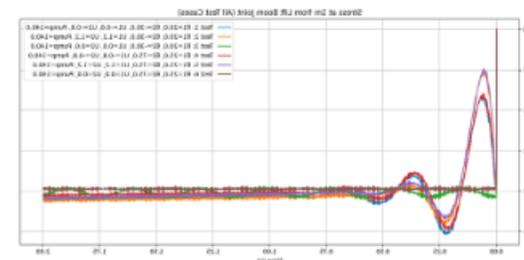
# INTELLIGENT CONTROL TECHNIQUE FOR FATIGUE LIFE ENHANCEMENT

## Real-time Stress Estimation in a Hydraulic Crane

- Patu crane was used as a reference to develop a flexible multibody FEM model based simulation in Exudyn
- Critical stress points are identified
- Joint forces/torques were used to compute stress at critical locations for various payloads
- The resulting stress datasets were collected and stored, capturing the relationship between kinematic inputs and structural stress response.



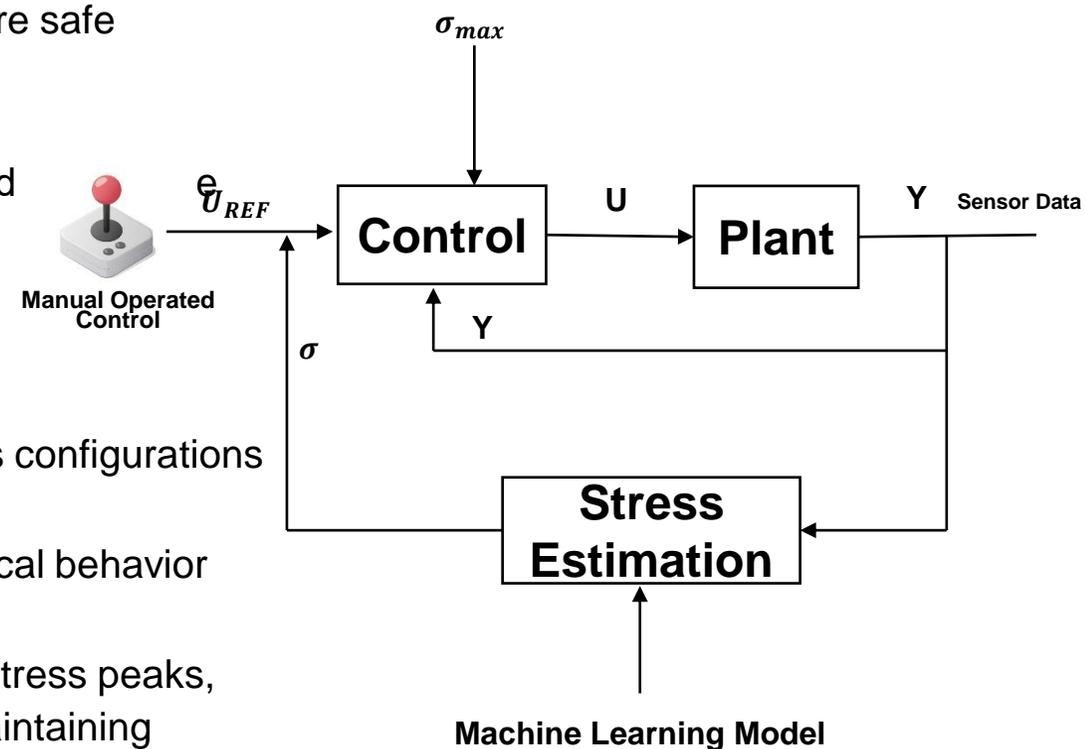
Stress Estimation from Joint Forces and Torques Using ML



Laboratory of Intelligent Machines

## STRESS-CONSTRAINED MANUAL CONTROL VIA POSITION & VELOCITY

- The control system constrains position and velocity commands to ensure safe operation within the allowable stress limits.
- When the estimated stress ( $\sigma$ ) nears the predefined maximum threshold controller:
  - Limits the maximum velocity to reduce dynamic loading during motion
  - Restricts position commands to keep the system away from high-stress configurations
  - Adjusts or suppresses operator inputs if they would result in stress-critical behavior
- This strategy enables safe and responsive manual control that avoids stress peaks, ensures smooth operation, and prevents fatigue buildup — all while maintaining continuous and controllable movement.



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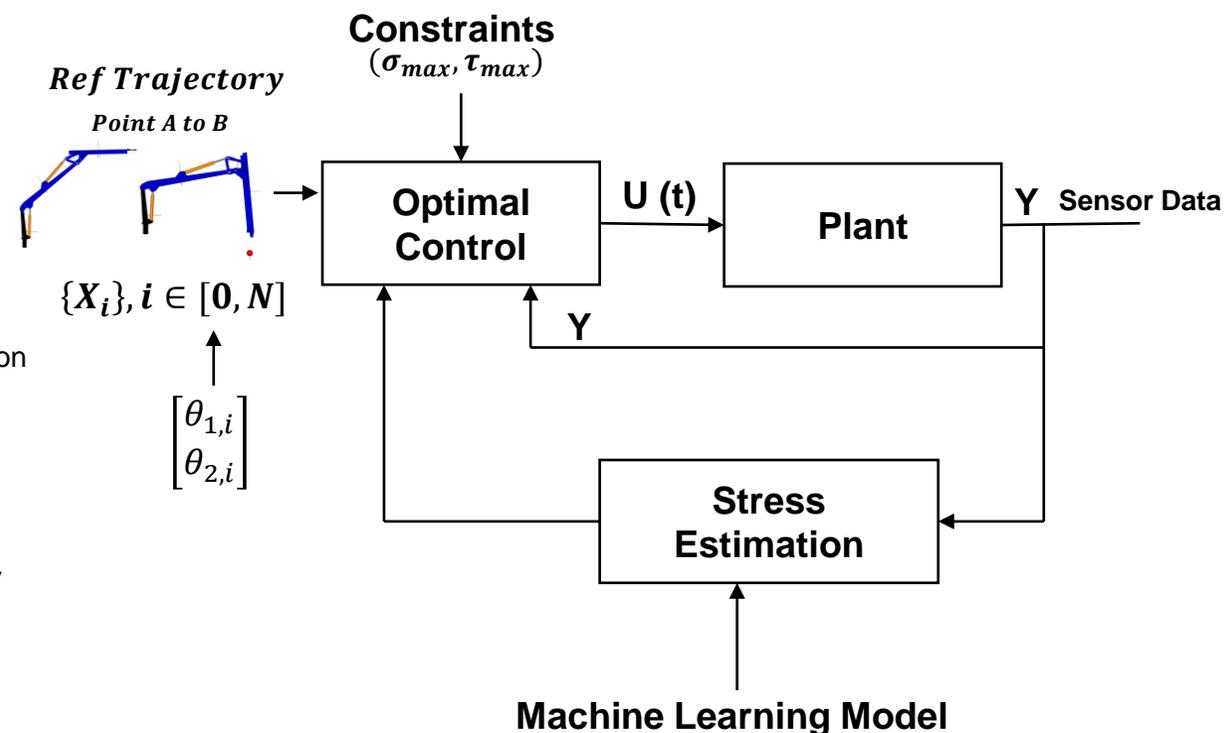
## OPTIMAL AUTOMATIC CONTROL WITH STRESS-AWARE CONSTRAINTS

- The controller receives a reference trajectory  $\{X_i\}$ ,  $i \in [0, N]$ , where each target point includes joint states:

$$X_i = \begin{bmatrix} \theta_{1,i} \\ \theta_{2,i} \end{bmatrix}$$

(Lift and tilt angles over time)

- The control law computes a time-varying control input  $U(t)$  that drives the crane smoothly from the initial to final state, while satisfying system dynamics.
- Real-time system output  $Y$  is used by a machine learning–based stress estimation model to compute the internal stress  $\sigma$ .
- The controller enforces hard constraints on:
  1. Maximum estimated stress ( $\sigma \leq \sigma_{max}$ )
  2. Maximum acceleration/torque ( $\tau \leq \tau_{max}$ )
- Compared to manual control (which reacts to velocity and position), this strategy ensures:
  - I. Predictive stress avoidance
  - II. Precise timing of motion execution
  - III. Fatigue-optimal trajectories across the entire motion plan



# Thank you for your attention!



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