A 20 Years Research Journey in Fluid Power along with Deep Respect and Friendship with Monika

Prof. Dr.-Ing. Jürgen Weber,
Chair of Fluid Mechatronic Systems (Fluidtronics)
West Lafayette, June 5, 2019

Contents

- Introduction – A New Idea 1998
- IBIS 2002 - 2005
  Displacement Control, Independent Metering
- TEAM 2012 - 2015
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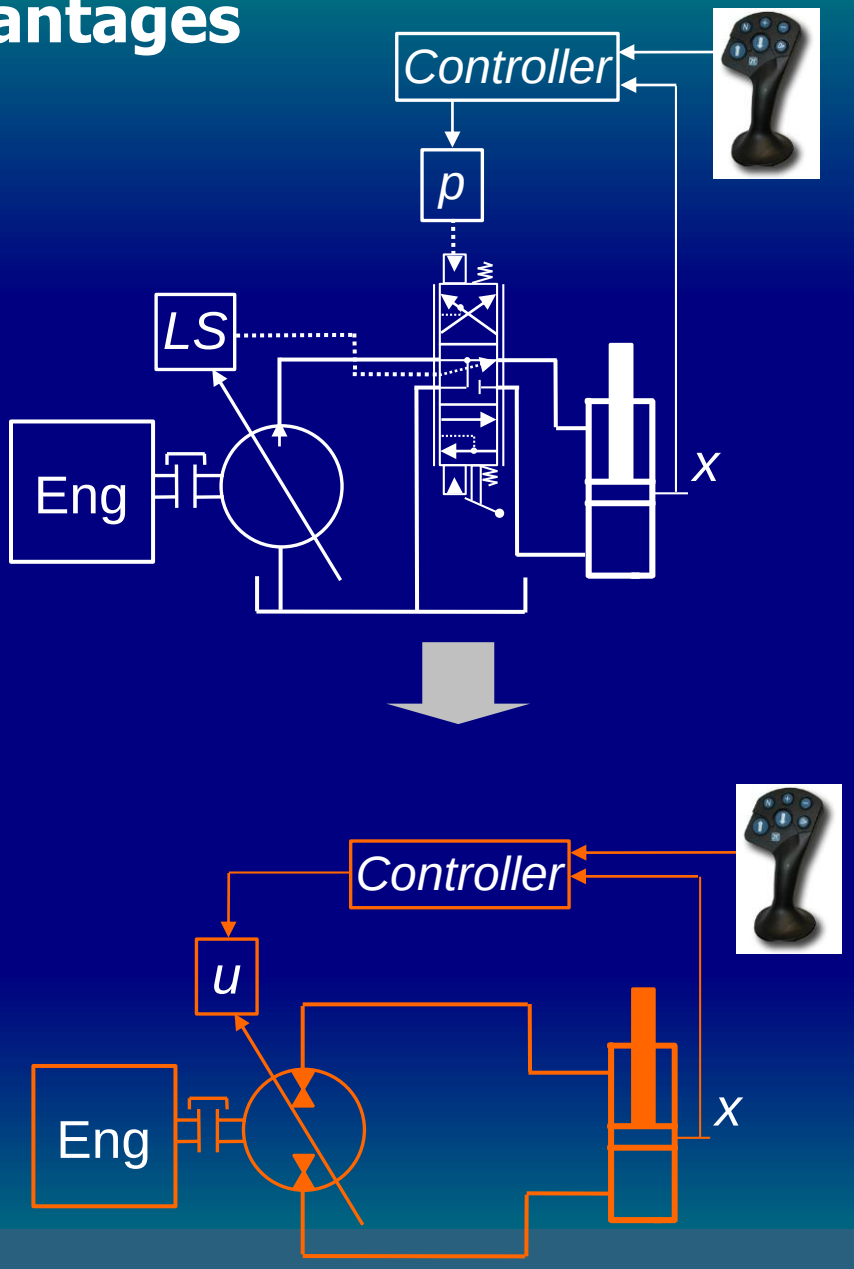
- Independent Metering – 2019 State of the Art
- Back to the Future (Bauen 4.0)
- Summary and Conclusion

Displacement Controlled Wheel Loader a simple and clever Solution

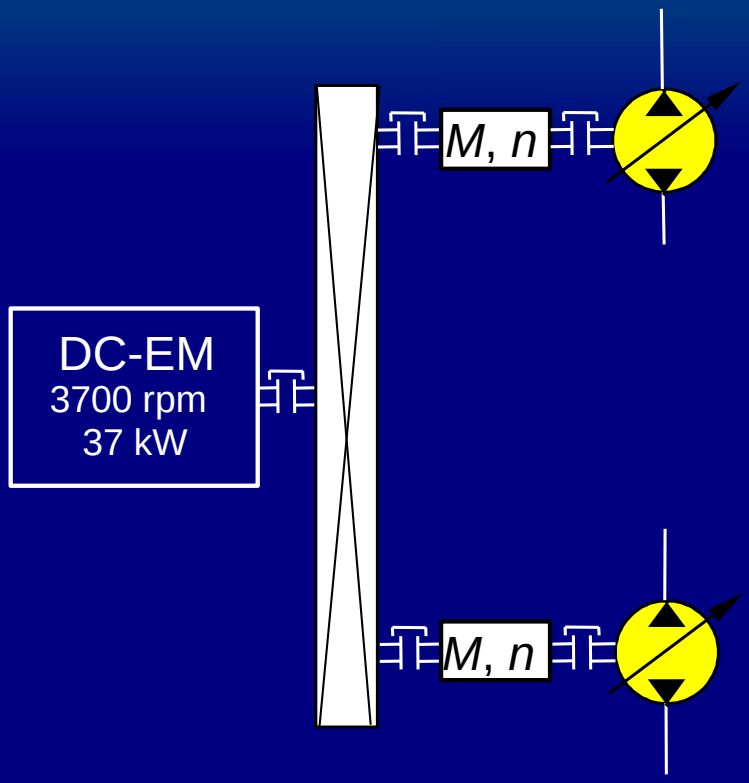
Monika Ivantysynova

Valveless Actuator - Advantages

- Simplification of System
  - Costs
  - Maintenance
- Better Use of Primary Energy
  - No Throttling Losses
  - Energy Recovery
- Powerful Dynamic System and Easy to Control



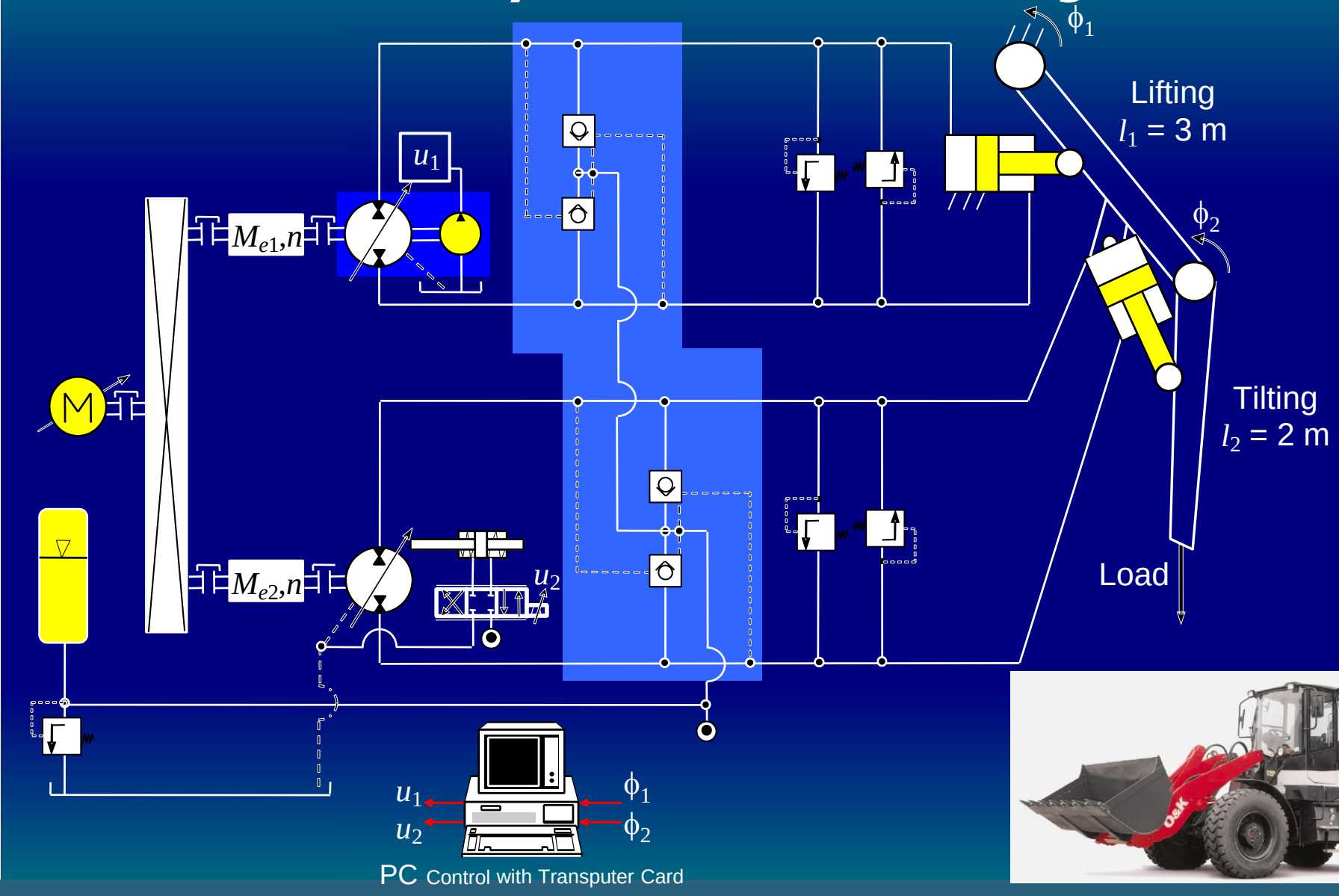
Stationary Wheel Loader Test Rig L5



Wheel loader with 0.5 m³ bucket capacity

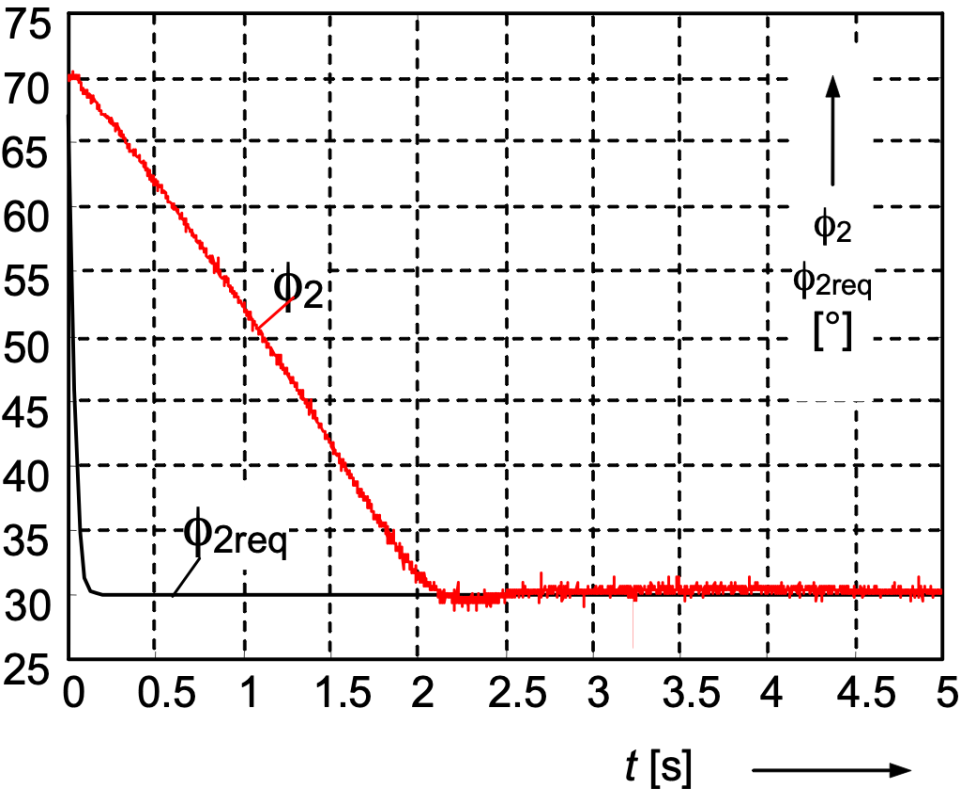
- Control via PC
- Electric driven pumps (Oilgear 10.8 ccm and Hydromatik A10VSG 10 ccm)
- Analogue and CAN-Bus position sensors

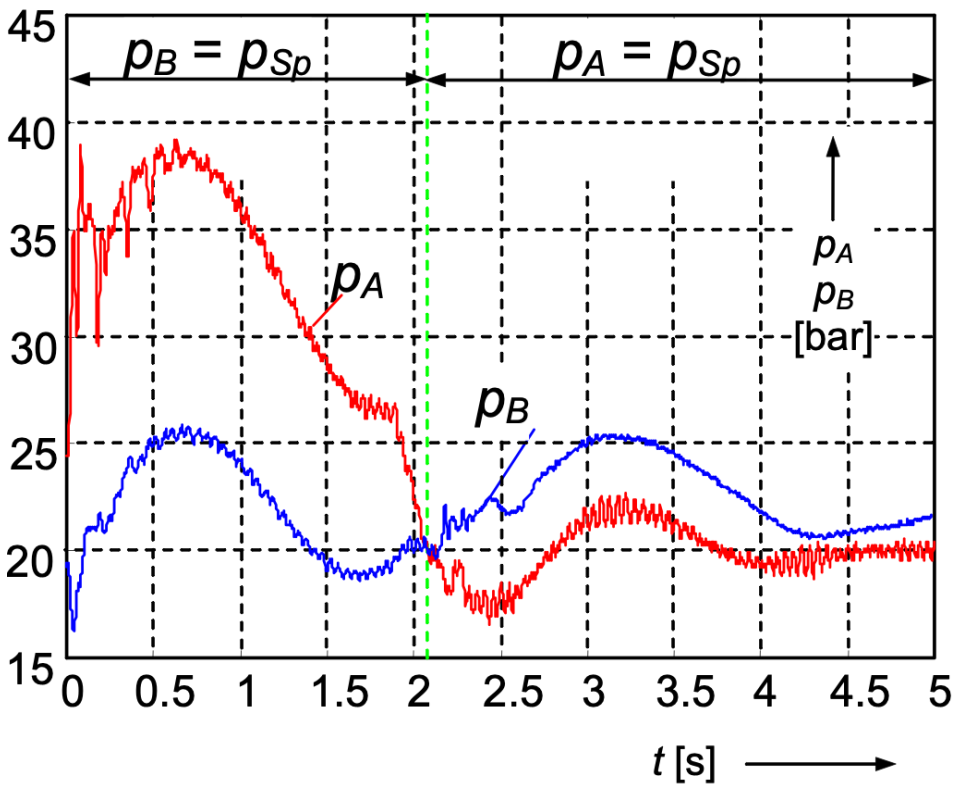
Stationary Wheel Loader Test Rig L5



System Step Response under Load Change

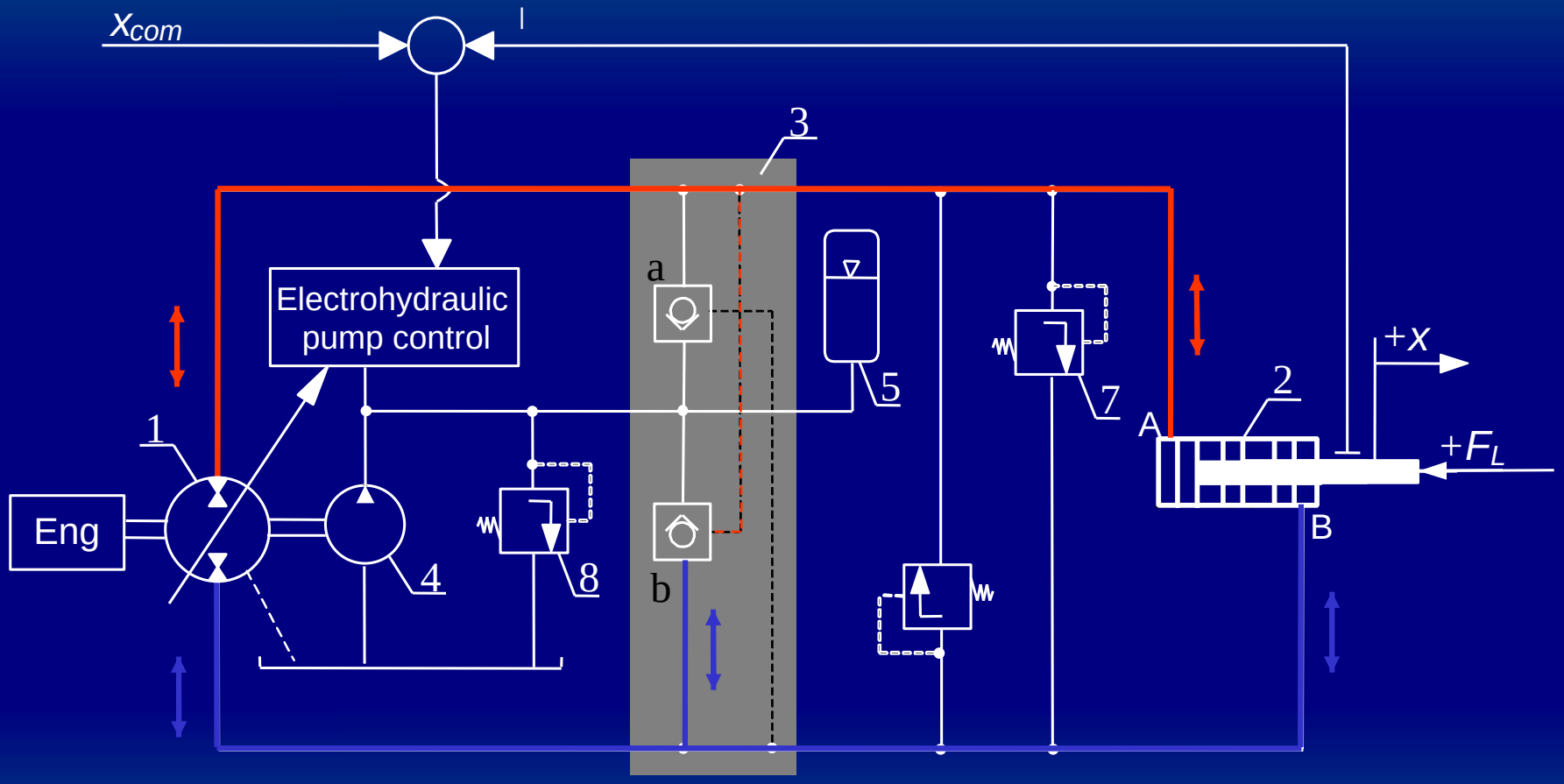
High Load Stiffness





Pilot Operated Check Valves work properly

Valveless Linear Actuator - Concept



Concept successfully tested !

IBIS
Advanced Multi-Functional Machinery for Outdoor Applications

Final Assessment
31th of May 2005

Project start: 1st of April 2002
Project duration: 36 month
Programme: FP5 “Competitive and Sustainable GROWTH”

IBIS – Main Aims of the Project

I. Innovative Design and Interfaces for multi-functional Mobile Machinery with Flexible Boom Structures

II. Alternative Energy-efficient Hydraulic Actuator Technologies
- CV: Cartridge Valve Technology
- DC: Displacement Control
- HT: Hydraulic Transformer

III. Control Concepts for
- Advanced Intelligent Hydraulic Actuators
- Automatic Motion Control for Flexible Boom Structures

IV. Condition Monitoring – on-board Diagnostics & Prognostic Methods

Technology Platform - Wheel Loader

O&K
- Provision of machine structure
- Machine field tests

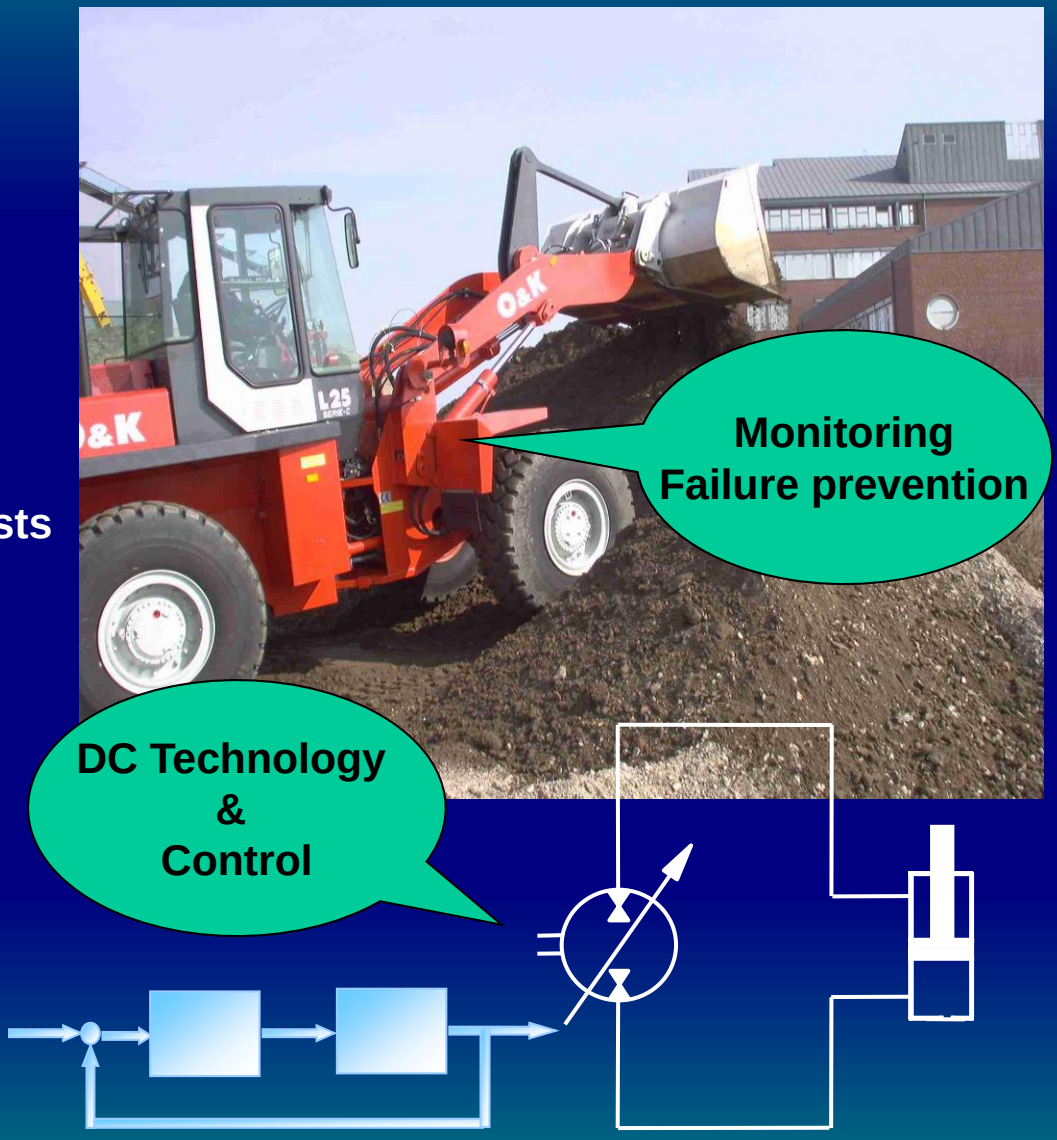
TuTech
- Actuator integration
- Actuator control
- Actuator steady-state and dynamic tests

CRF
- Sensor implementation

ACTIA
- Diagnostic hardware implementation

APS
- Diagnostic software implementation
- Test of diagnostic system

Responsible: Prof. M. Ivantysynova



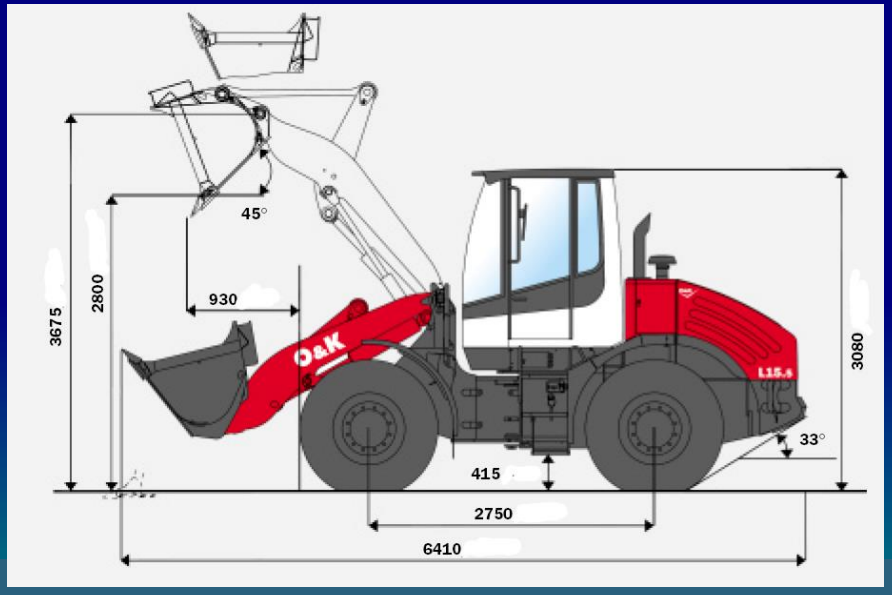
Technology Platform – Wheel Loader

- Wheel loader 9 tons
- Engine max. 82 kW at max. 2200 rpm
- Normal bucket capacity 1.5 m

- Working hydraulics / Functions:
  Lifting & Tilting, Parallel Fork Lift, Floating,
  Return to Dig, Lift Limitation, 3rd Function

- Hydraulic steering system

- Hydrostatic cooling and
  brake system



Overall functionality needs to be realized by the new system

Displacement Controlled DC Circuit Diagram

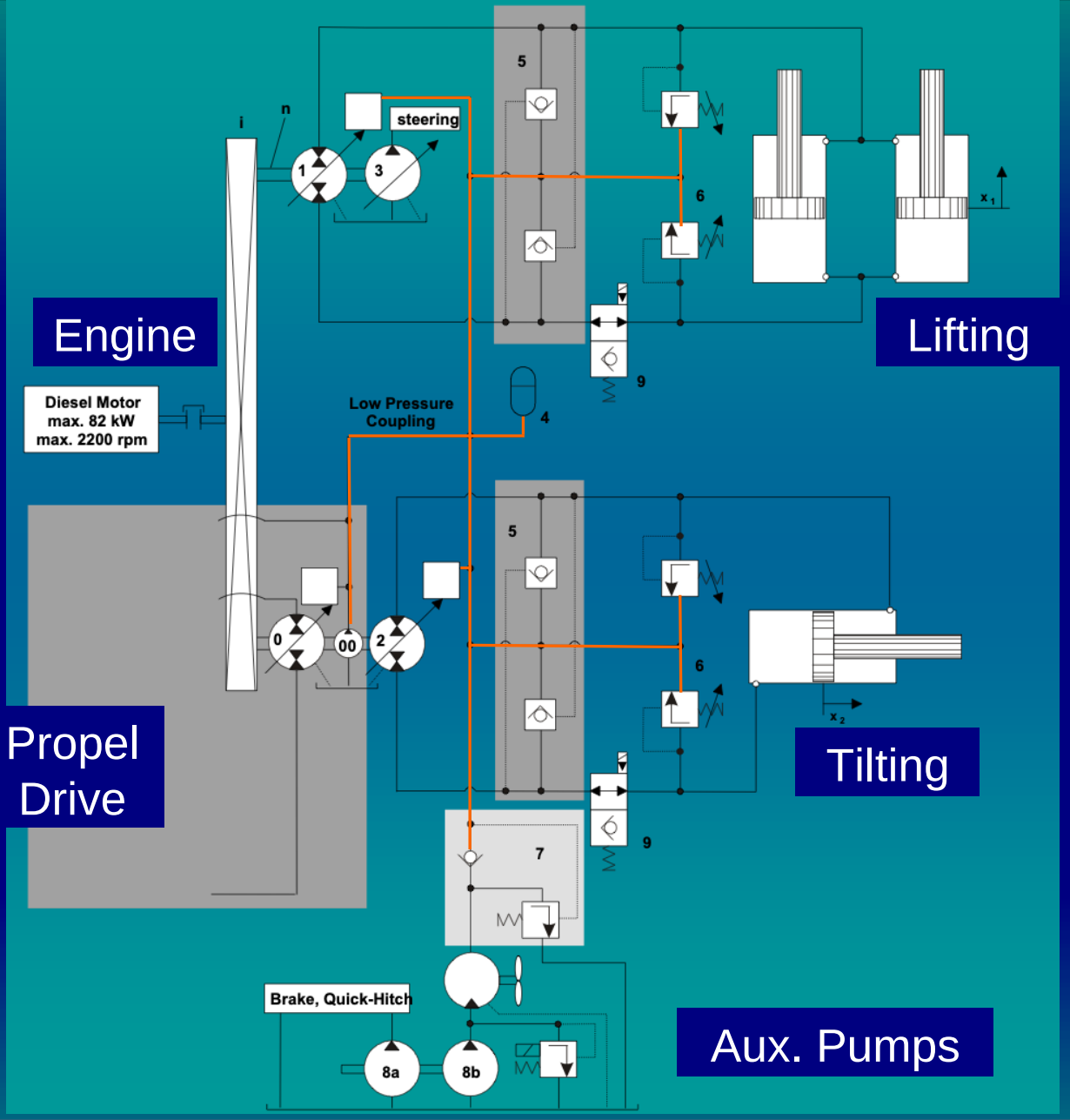
Working functions:

Pump 1,2: 75 ccm

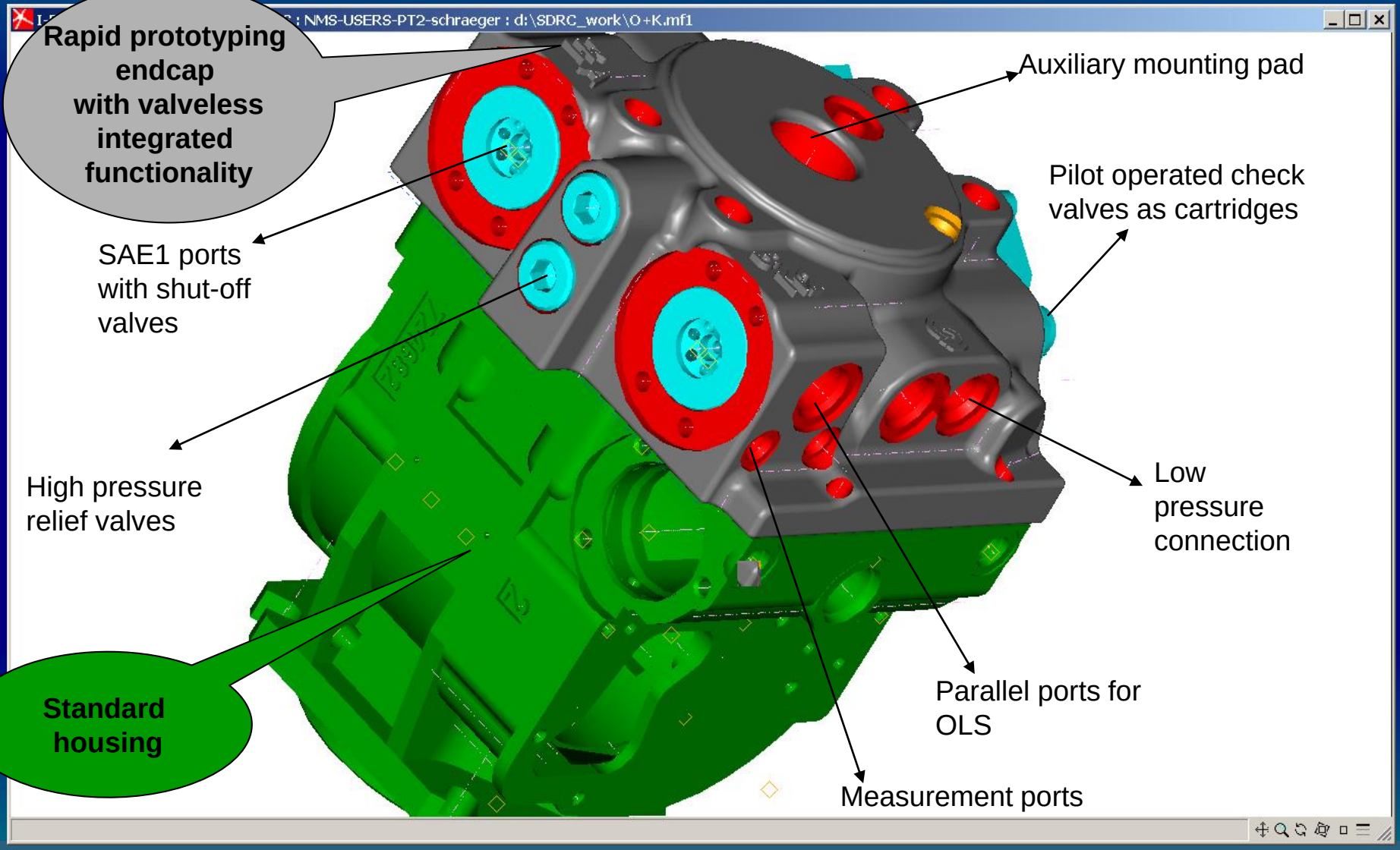
Steering:

Pump 3: 28 ccm

with hydrostatic transmission

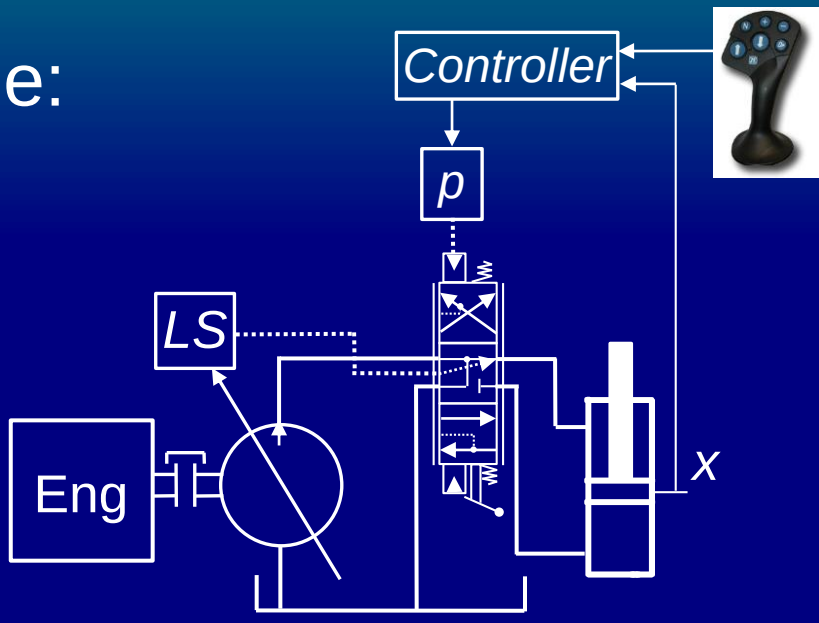


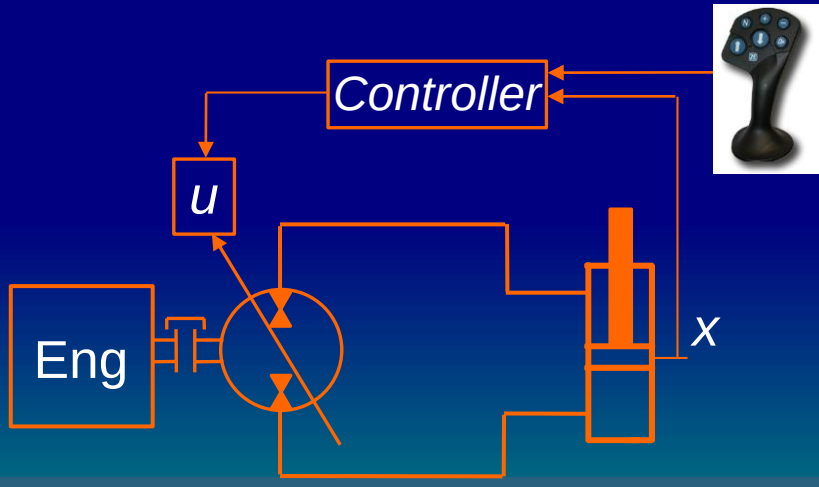
Valveless Pump Configuration



Machine Comparison Test

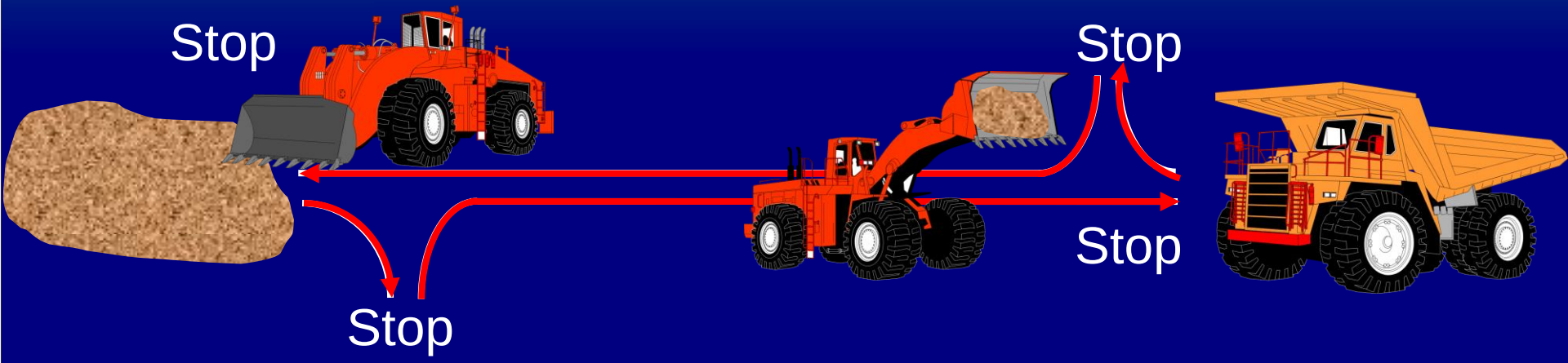
Field test programme side by side:
standard and valveless system





Machine Comparison Test

Truck loading – short & long cycle



valveless:
15 % less
fuel consumption

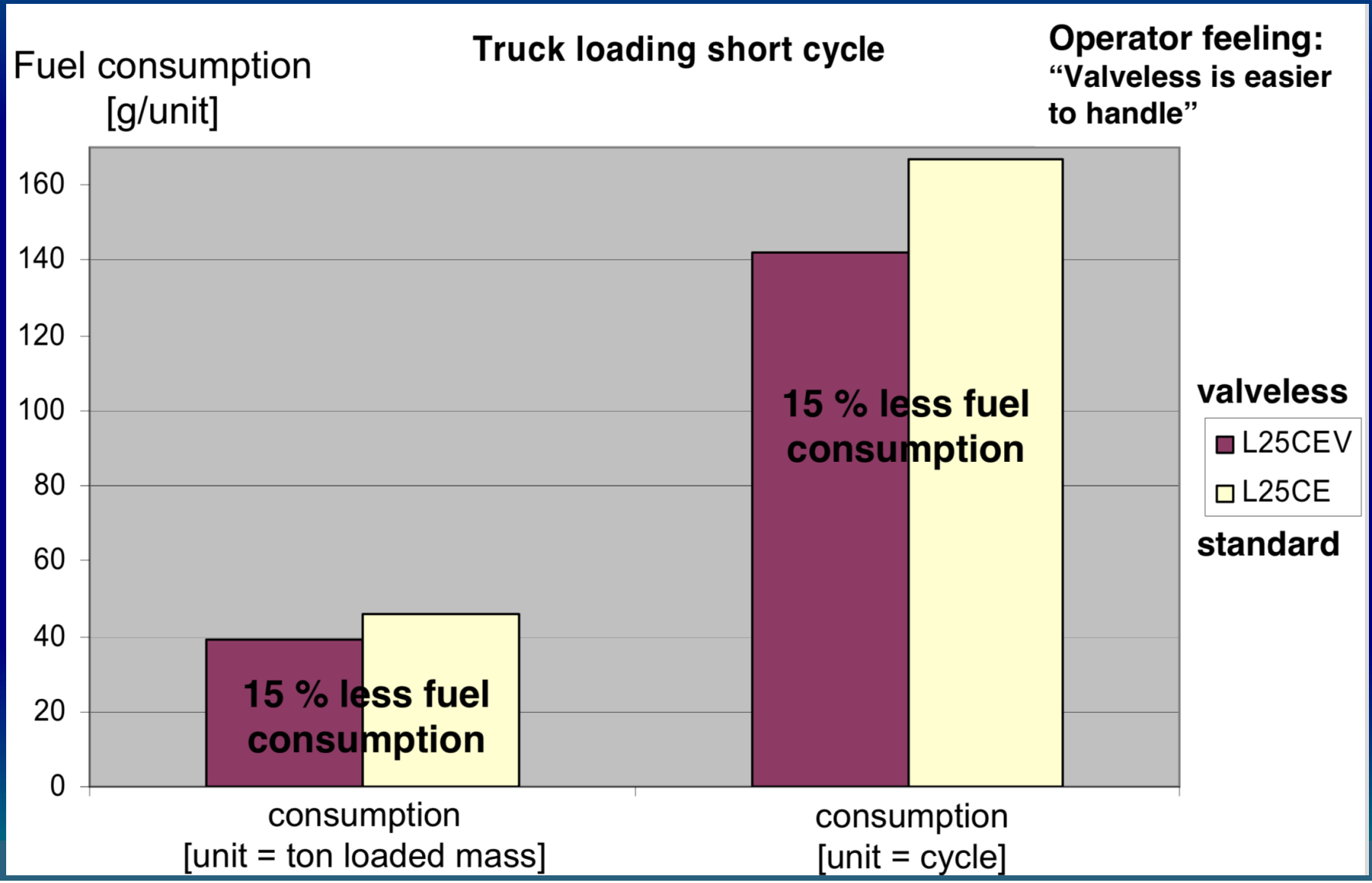
Machine Comparison Test

Parallel fork lifting

Easier to Operate

Excellent Controllability

Machine Comparison Test
Final Results



Technology Platform - Mobile Excavator

O&K

- Provision of machine structure
- Machine software frame and controller
- Assembly of multi-functional boom structure
- CV actuator integration
- Machine steady-state and field tests

CRF

- Motion control implementation

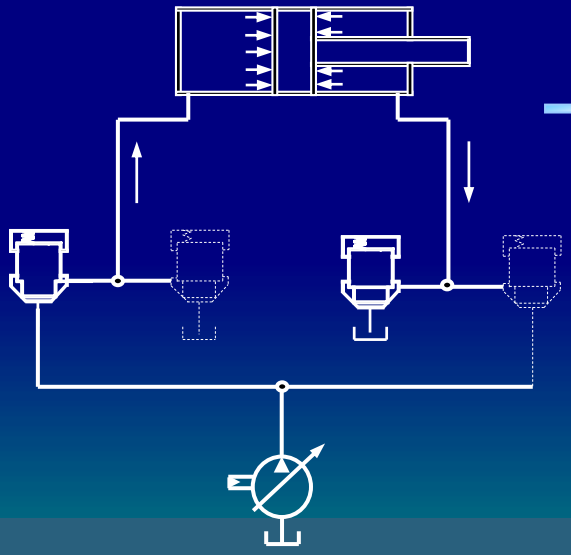
TuTech

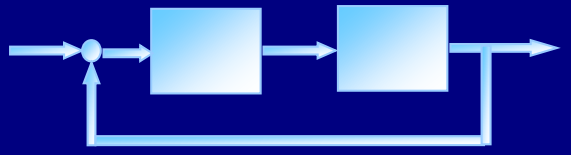
- Actuator control implementation
- Test of actuator dynamics

ACTIA

- Actuator control hardware

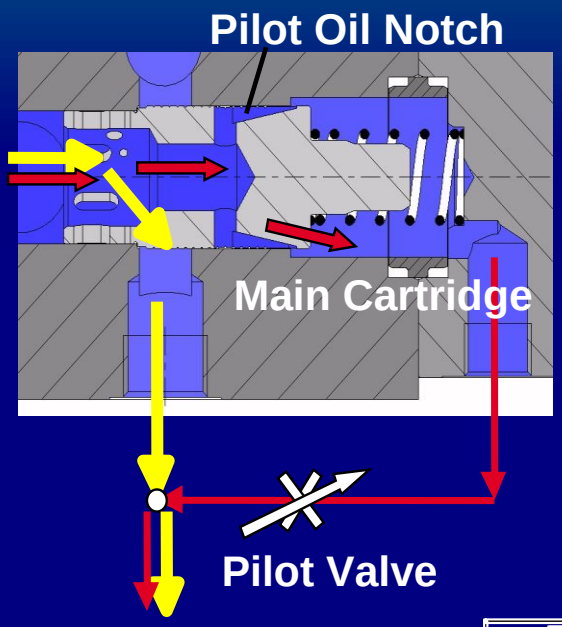
Responsible: Dr. J. Weber



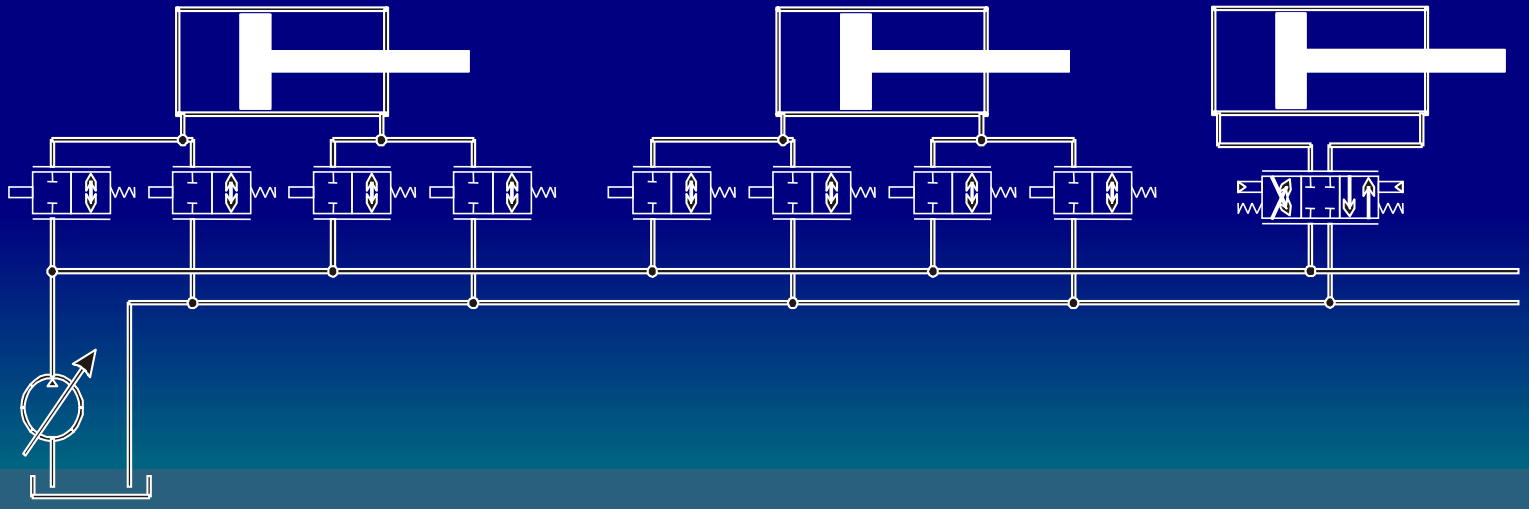


CV Technology & Control

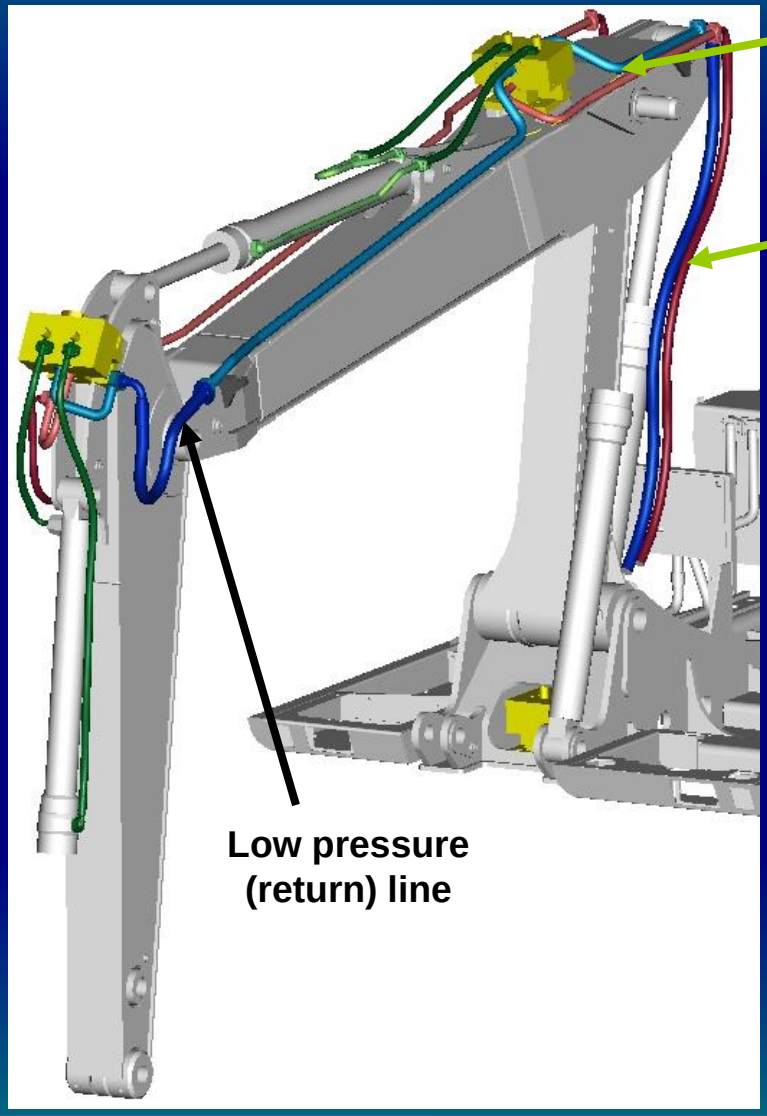
Cartridge Valve Technology

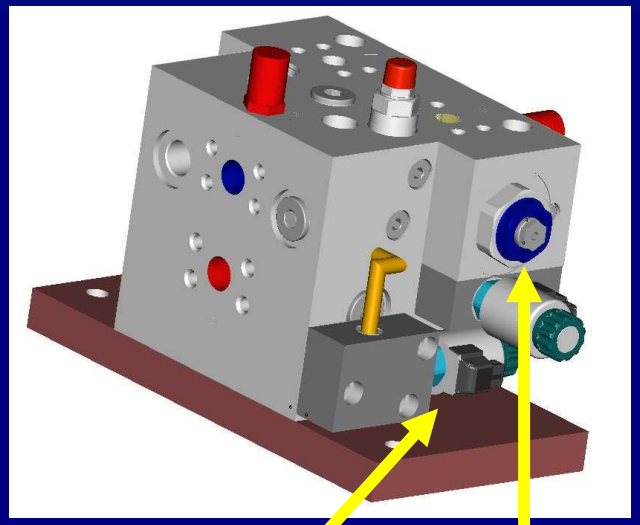


- High dynamic response
- Zero leakage
- Usable for different applications as
  - safety valve
  - pressure relief valve
  - flow control valve
  - pressure control valve



Attachment Routing and Piping

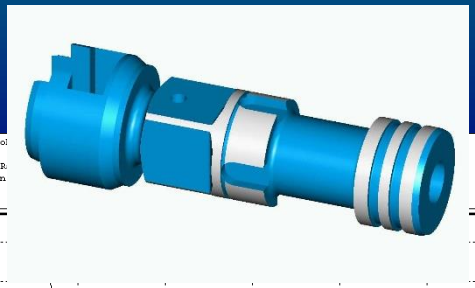


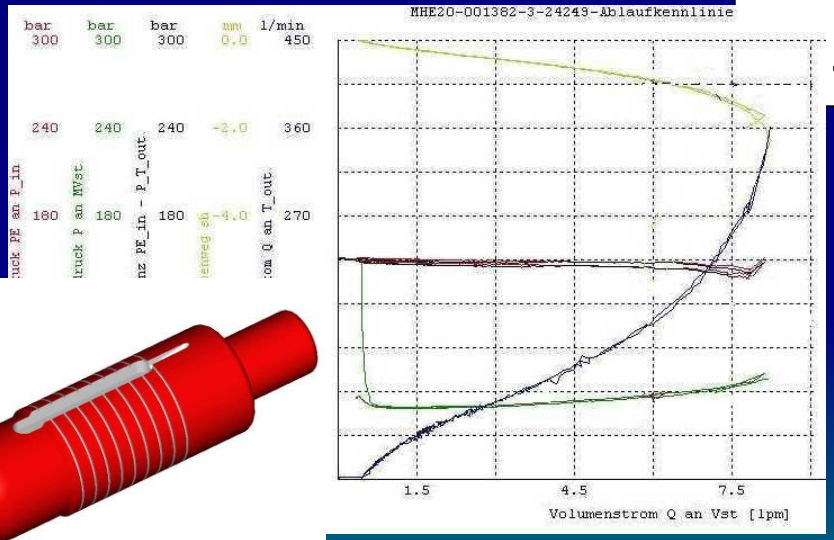


Main Stage and Pilot Stage - Measurements

Pilot Flow increased (about 15 l/min)

Hysteresis has been reduced





Main spool version III

p = 220 bar, Q = 0 - 360 l/min stability achieved

Improvements of Main Stage

Goals / Results:

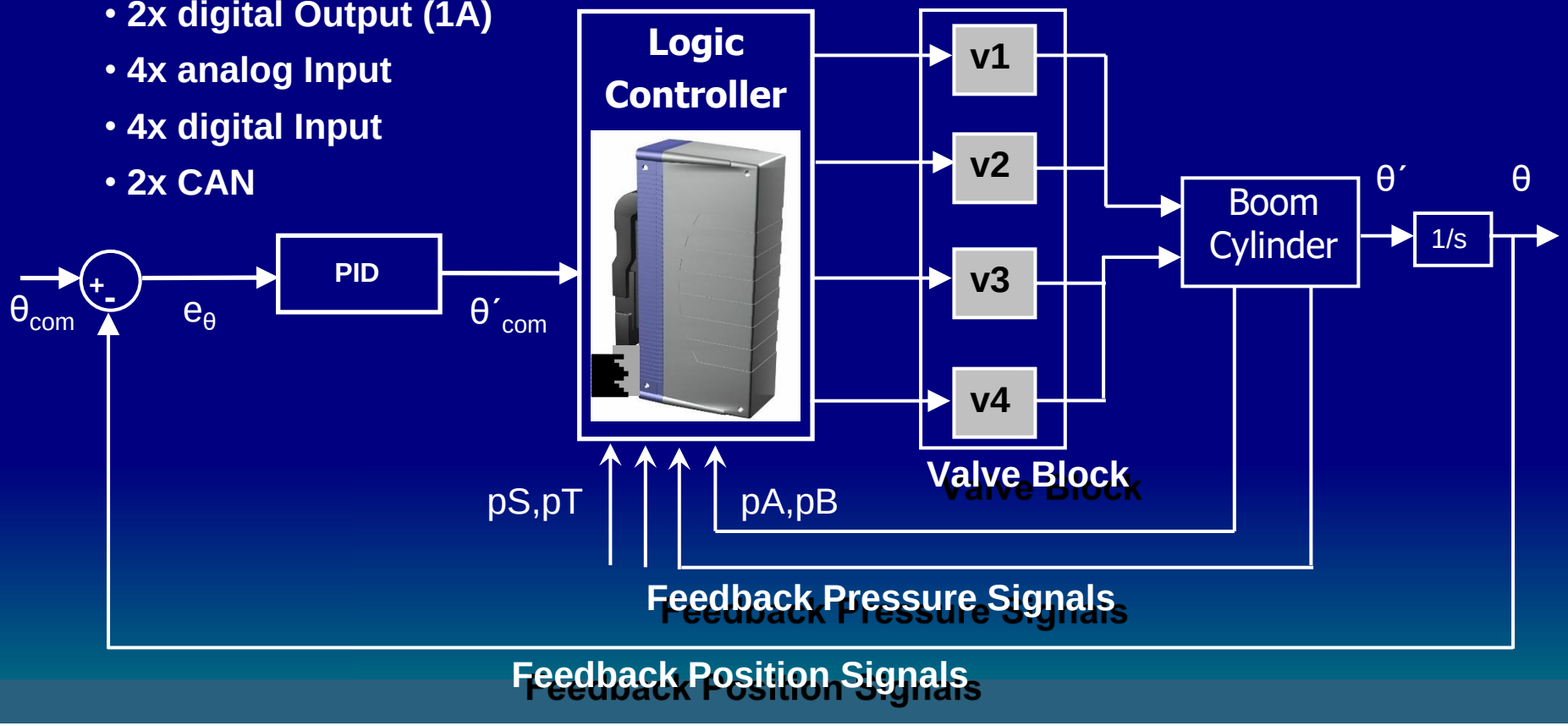
- Improvement of Stability
- Less sensitive on vibration
- Improvement of resolution in different pressure ranges
- Increase of stroke to 12 mm does not lead to improvements

Control Logic

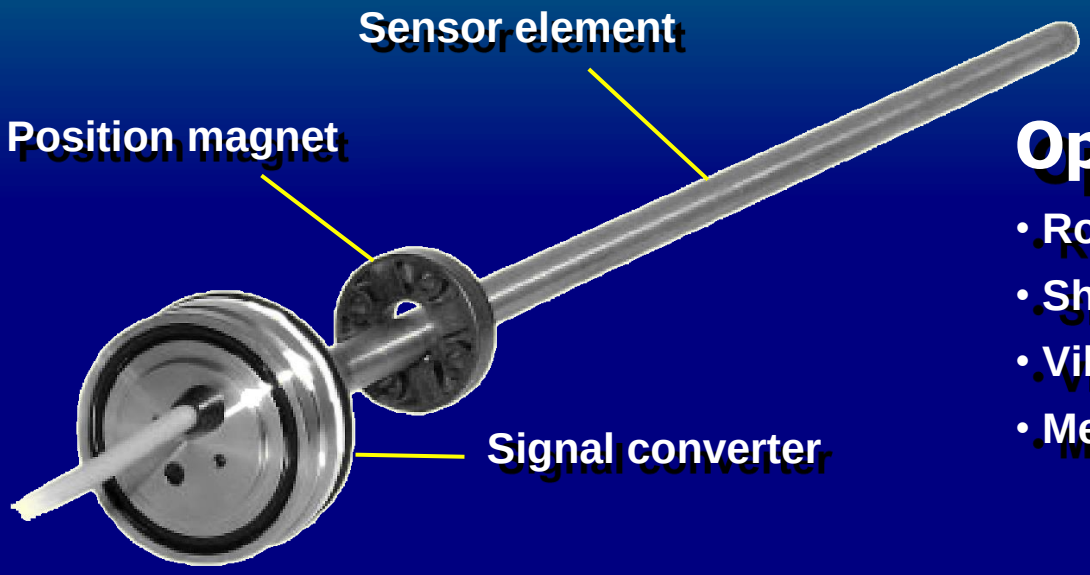
Actuator Requirements

- SIL2 / AK4
- IP 67
- 5x PWM Output (1A) with current feedback
- 2x digital Output (1A)
- 4x analog Input
- 4x digital Input
- 2x CAN

PID Control with Non-linear Compensation for each valve



Cylinders with integrated Sensors

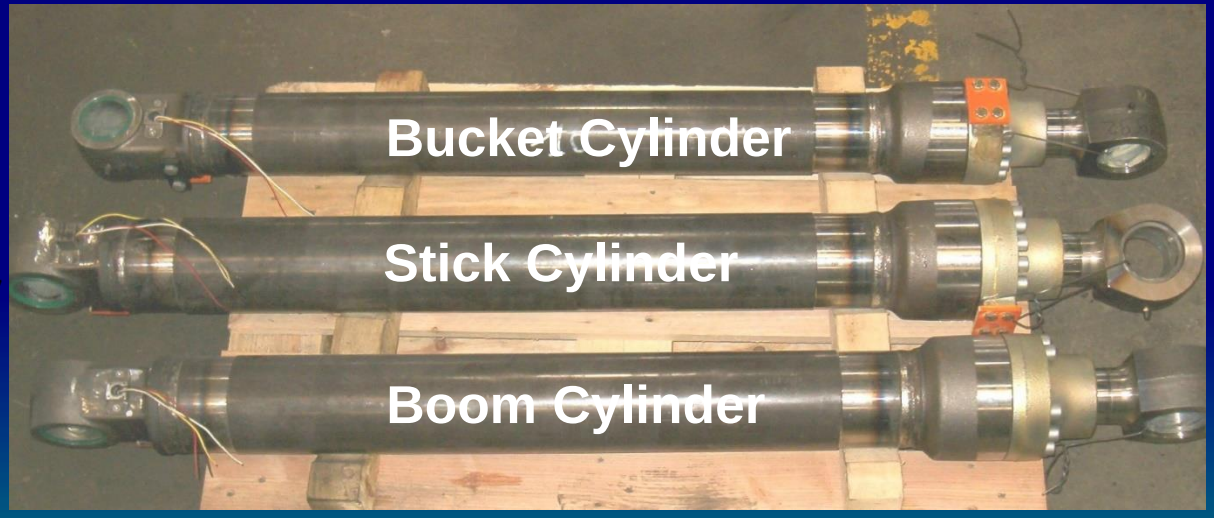


Operating Conditions

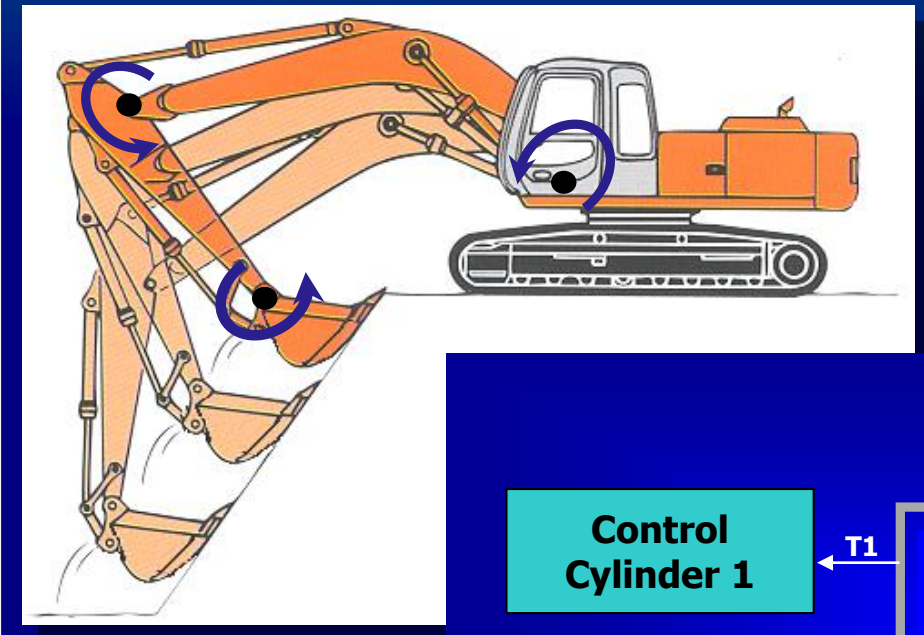
- Rod Pressure Rating: up to 530 bar
- Shock Rating: 50 g
- Vibration Rating: 5 g
- Measuring Range higher 1000 mm

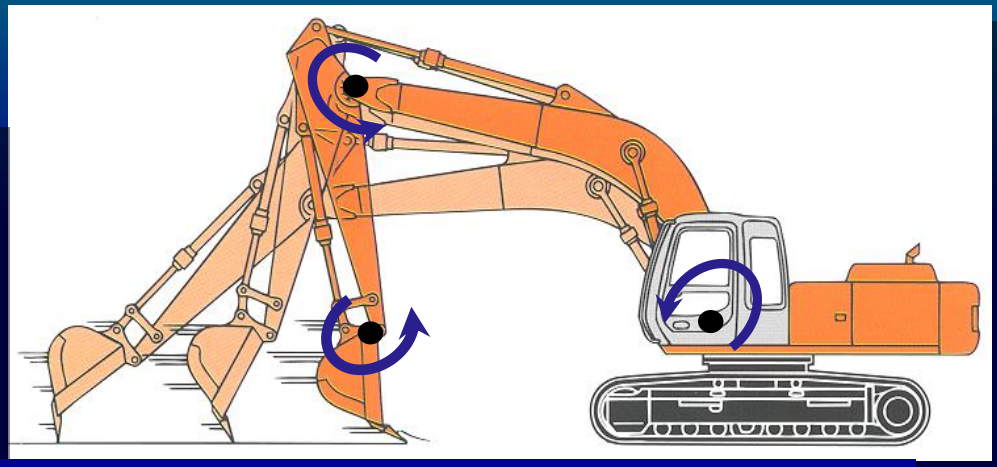
Sensor Data

- magnetostrictive principle
- No-contact Sensor
- No mechanical wear and tear
- resolution < 10 µm
- Linearity up to 0,01%
- Repeatability 0,001%

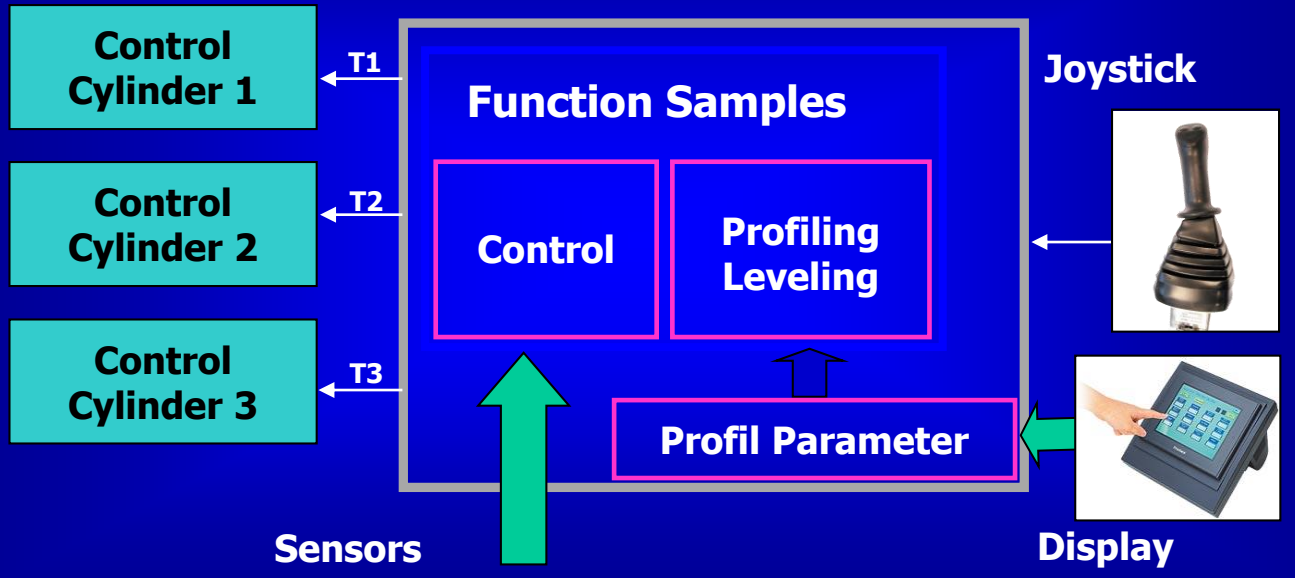


Motion Control – Semiautomatic Operation





Semiautomatic Control Operation



„The Green Wheelloader„

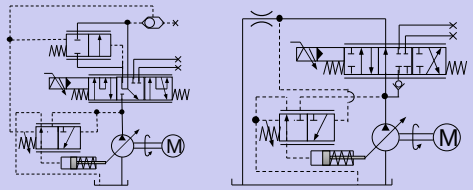
Research Project 2012 - 2015

State of the Art and Project Goal

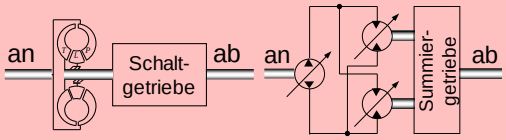
FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

State of the Art | Available Concepts | TEAM Project Goal

Working hydraulics

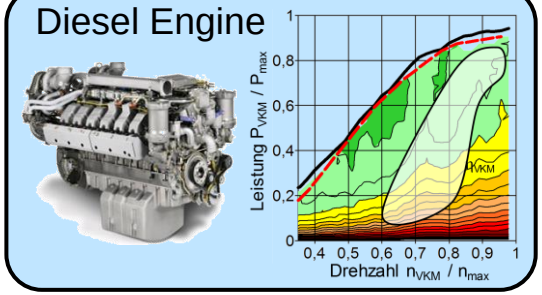


Transmission



hydrodynamic hydrostatic

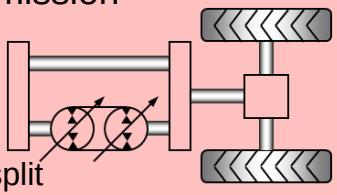
Diesel Engine



Working hydraulics

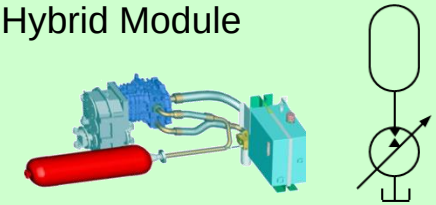
Displacement control

Transmission

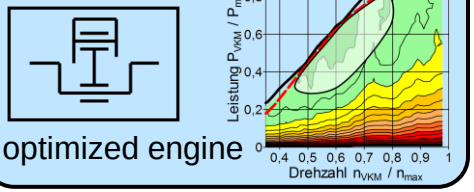


Power split

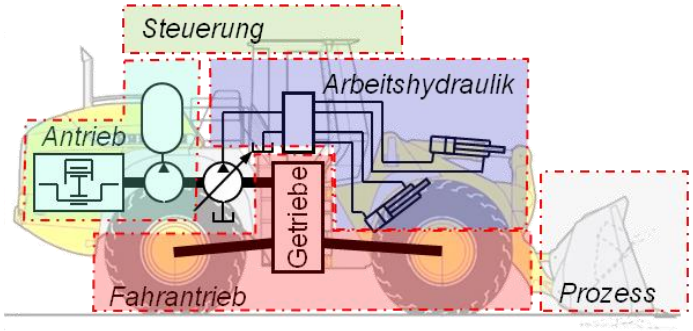
Hybrid Module

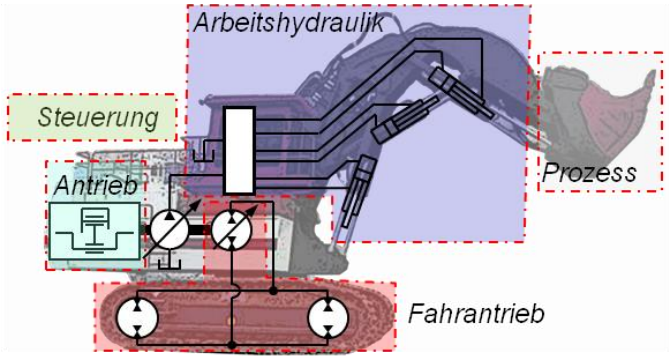


Diesel Engine



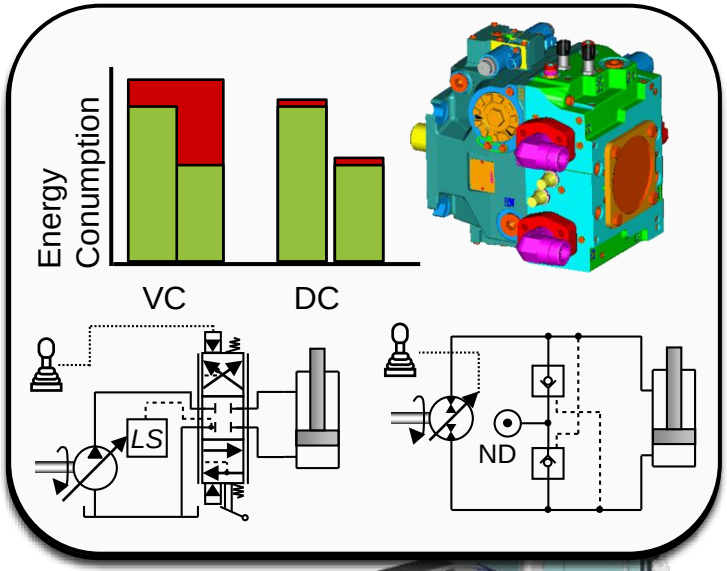
optimized engine

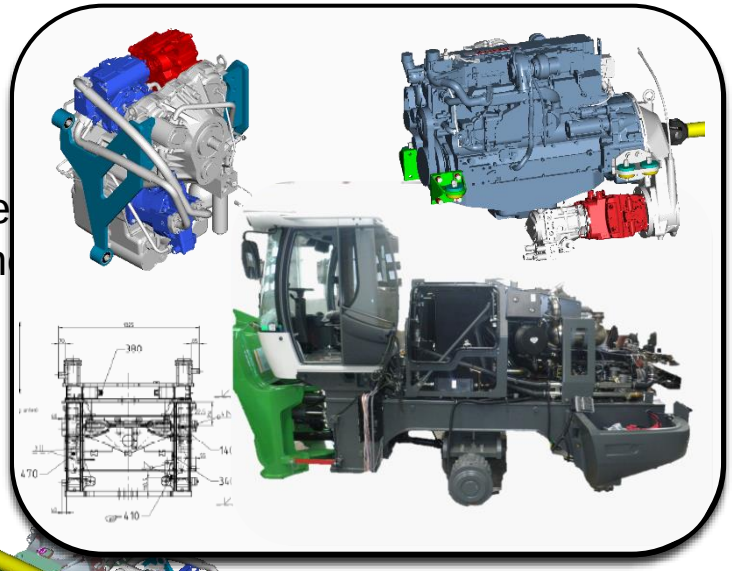




Systemstructure

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN





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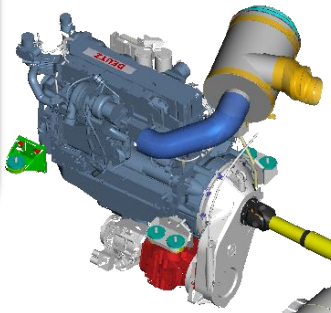
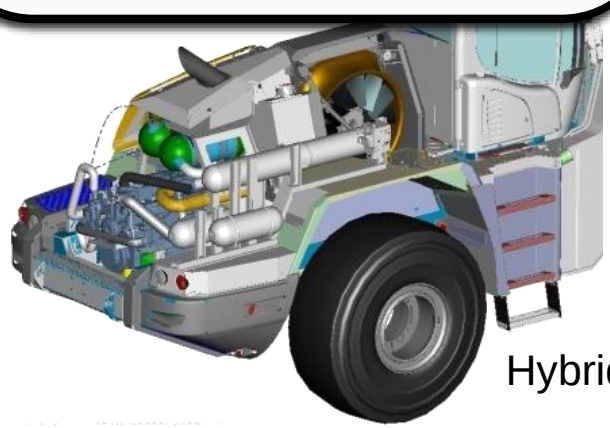
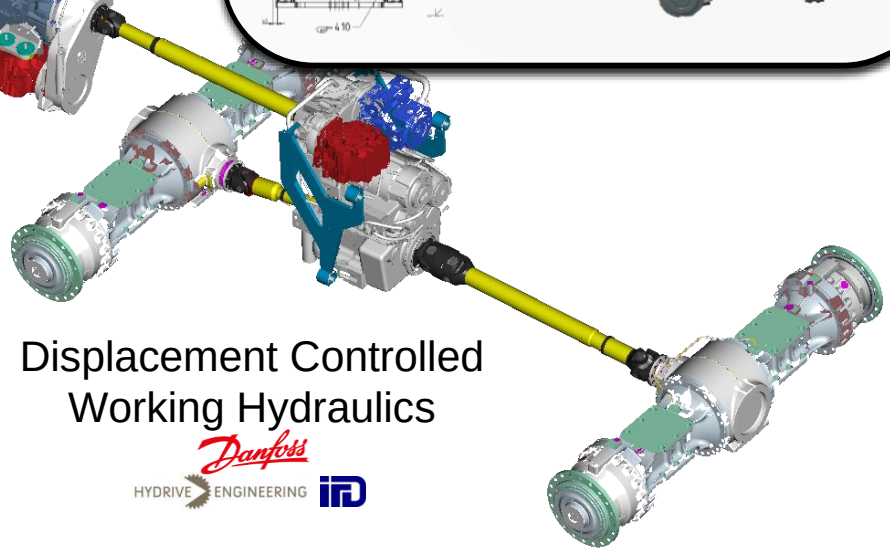




Hybrid Module

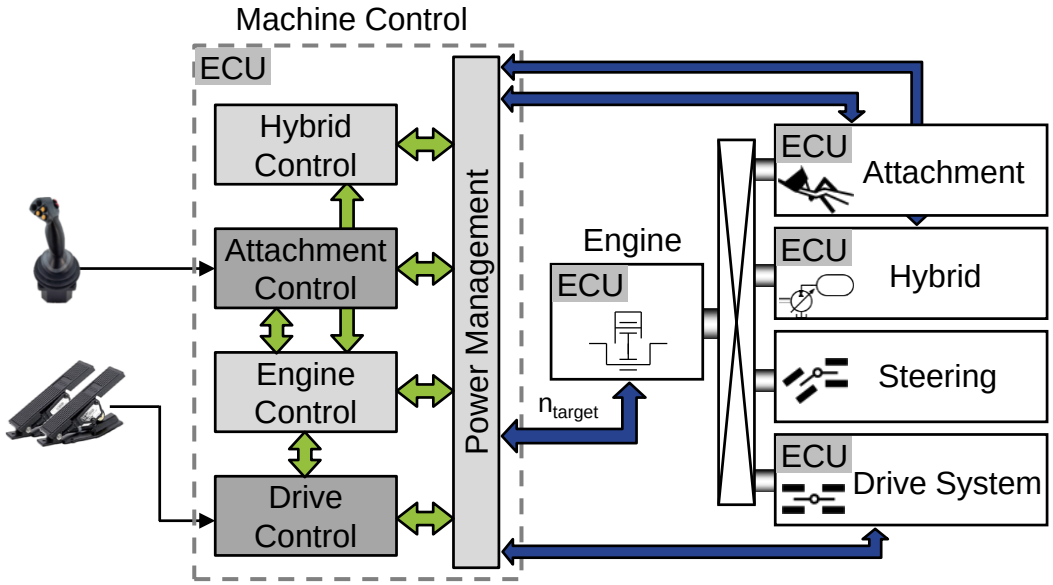


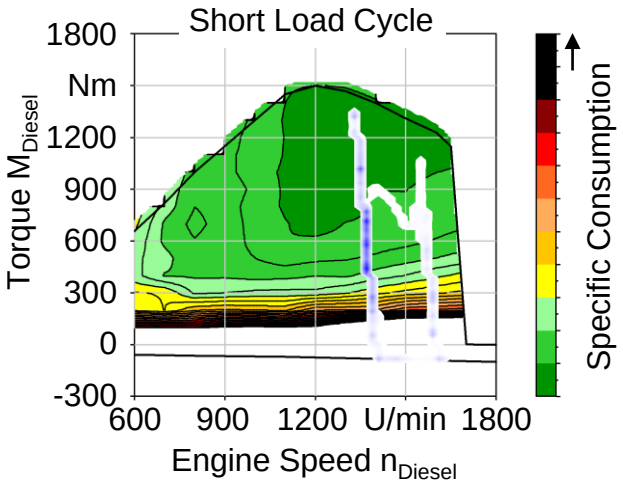
Displacement Controlled
Working Hydraulics

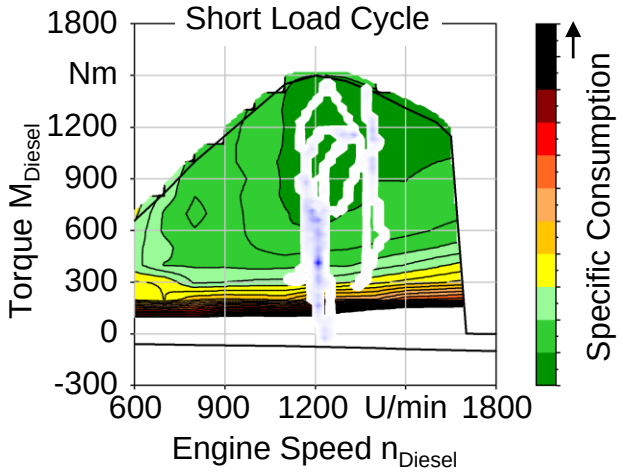
Danfoss HYDRIVE ENGINEERING

HYDAC LIEBHERR

Operating strategy







- Decoupling of the diesel engine from the user input
  - Dependent on the demand of the subsystems
- Engine speed control strategies:
  - Quasi-constant, low speed
  - Optimum speed in terms of load and efficiency map

→ Higher engine power capacity, lower losses

Simulation of the Process interaction

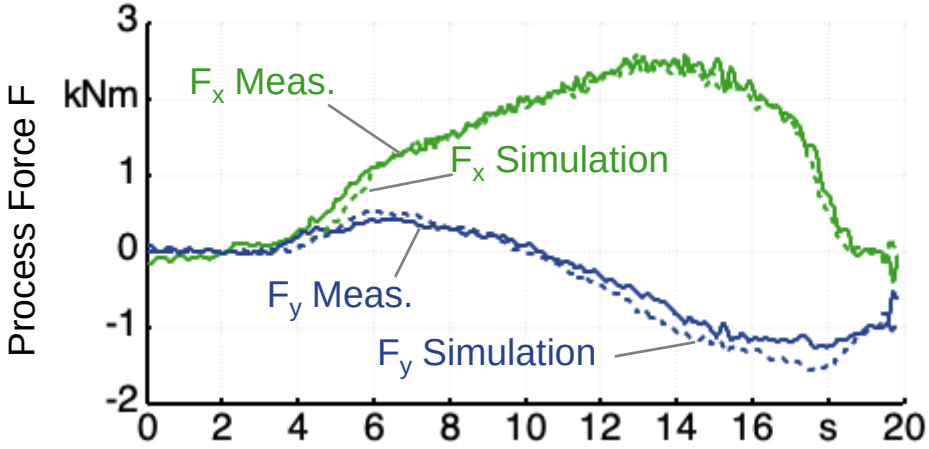
Model Creation

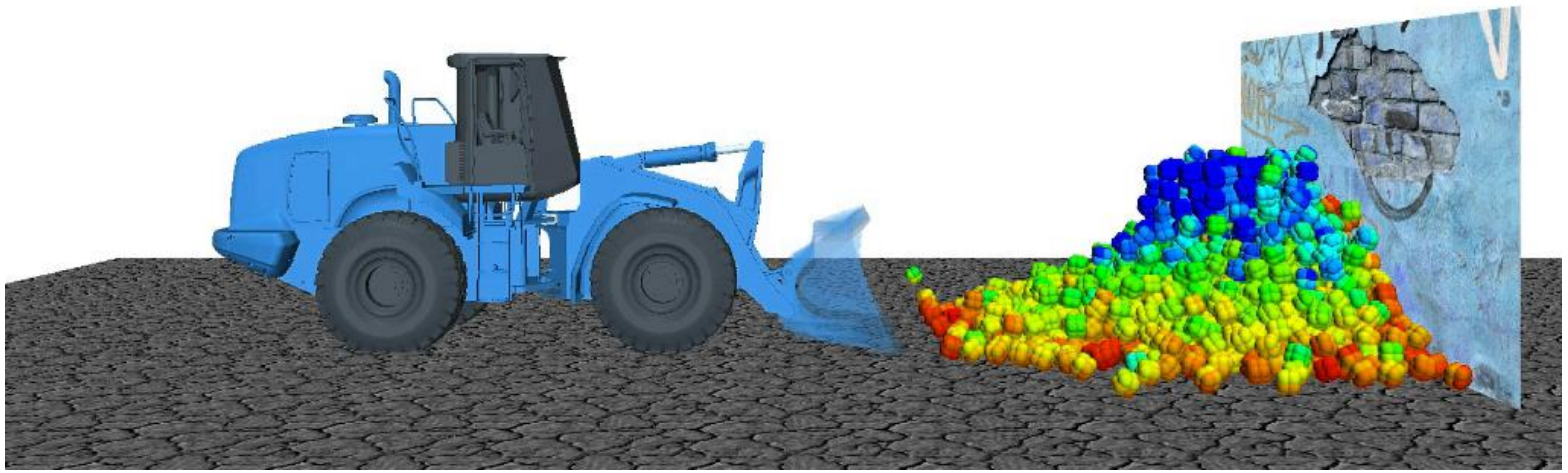
Test Rig

Validation

Parameterization

Comparison of the Process Forces

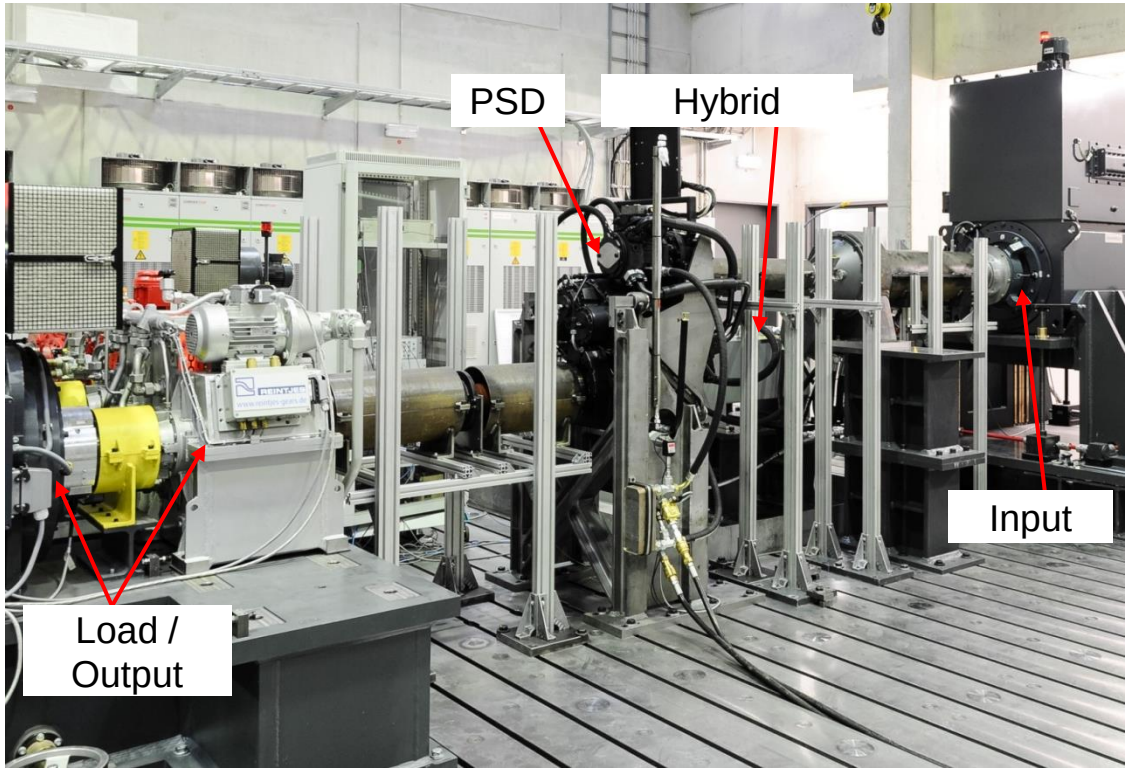


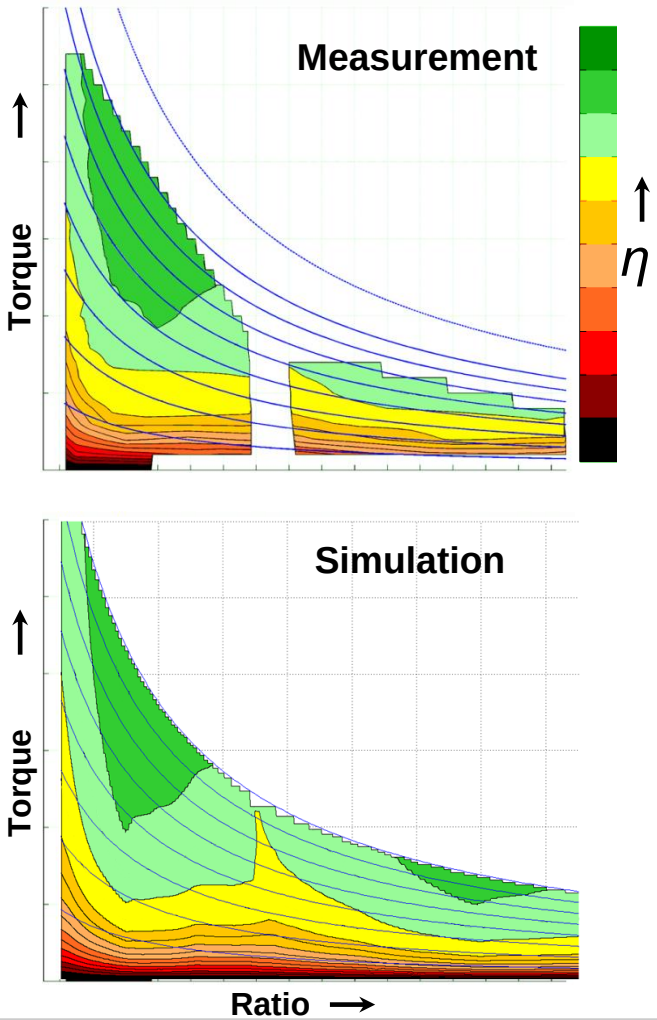


Experiments

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

Test Rig for the power split drives





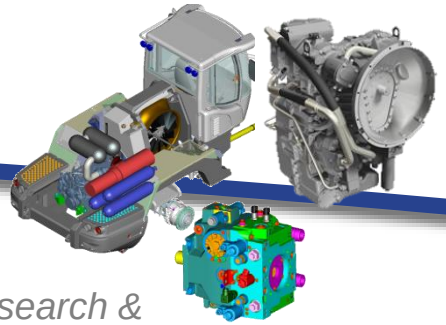
- Effiencieny measurements to validate the simulation
- Analysis of the gear transmission dynamics

Development Stations

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

January 2012

Project Start



Research & Development

October 2013

Integration and assembly at Liebherr, Bischofshofen

April 2014

Transport to Dresden

Start up, Dresden

August 2014

Rollout & and first test

November 2014

Machine adjustement and testing, gravel quarry near Dresden

Source: http://www.qomet.de

Testing

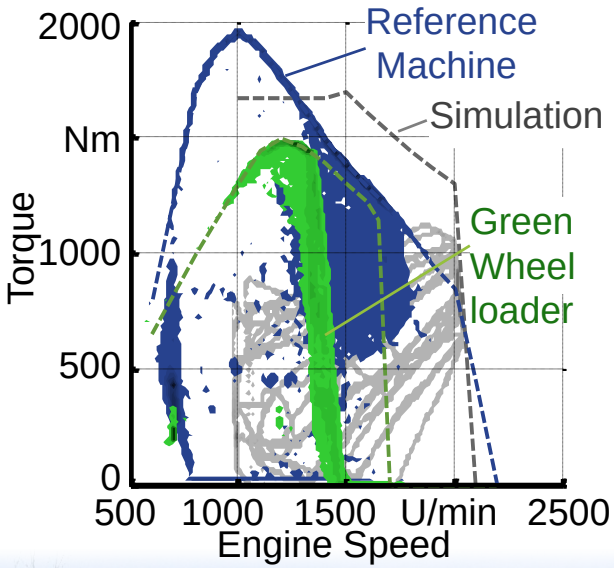
FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

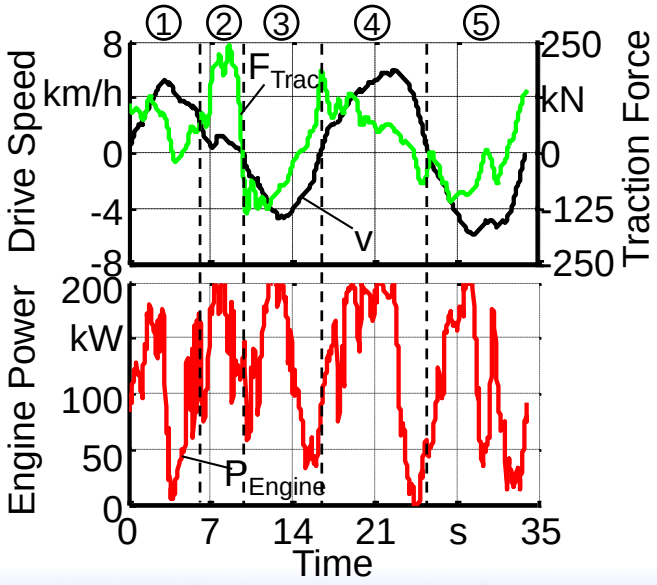
In real operating conditions with trained drivers

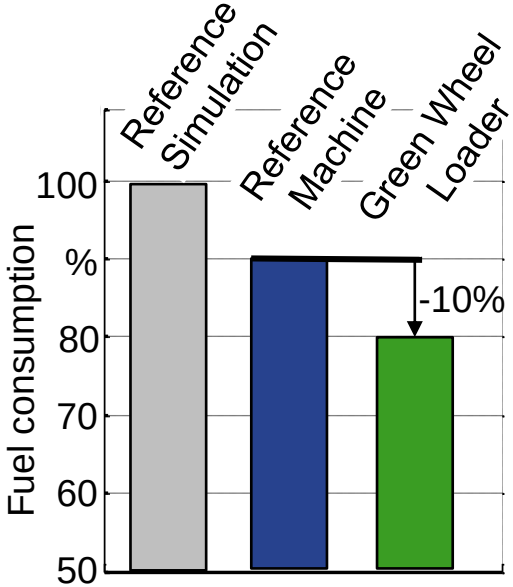
Testing

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

Results in comparison to the reference machine







DC Mining Excavator Machine

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

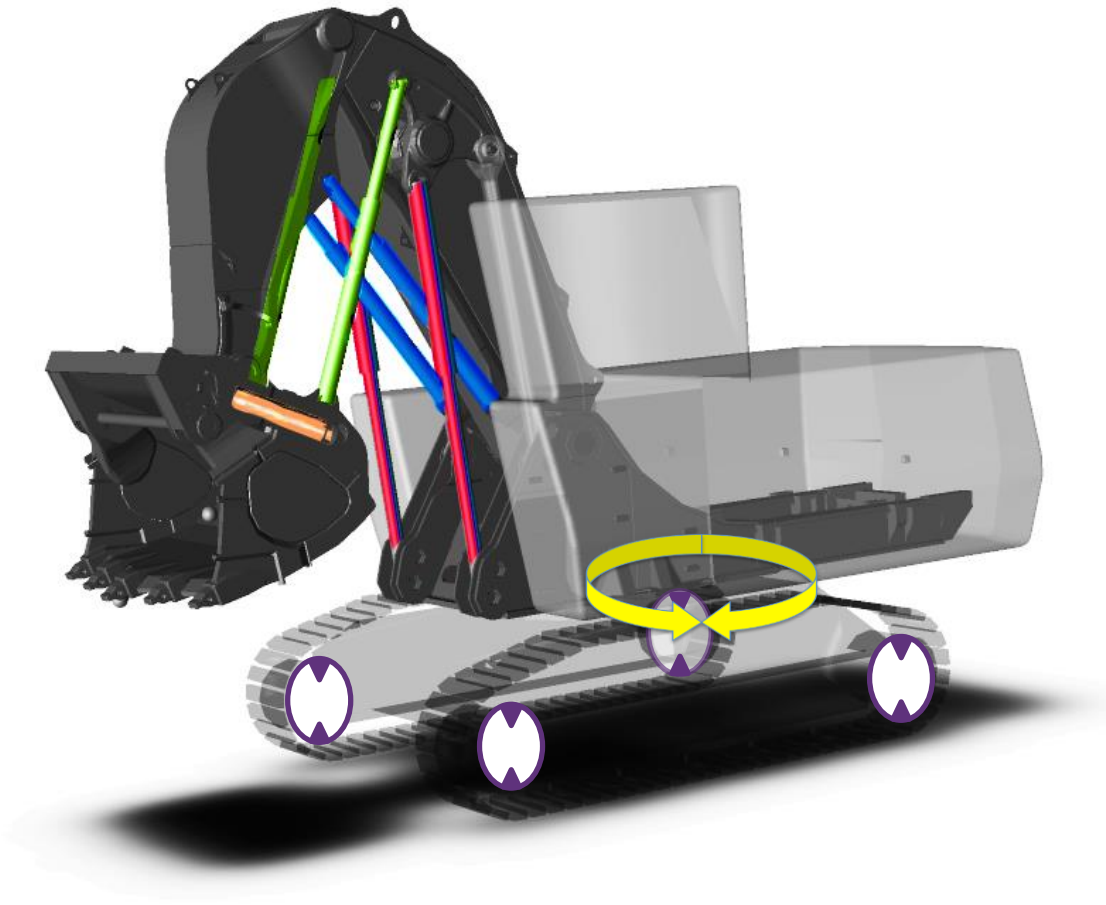
Working Hydraulics

CAT 6030 (Bucyrus RH-120E)

- Motor power: 1140 kW
- Weight: 287 t
- Max. Lifting force: 1370 kN
- Max. Break force: 920 kN
- Working Area: Mining

Actuators

- 2 Boom Cylinders (Red)
- 2 Stick Cylinders (Blue)
- 2 Bucket Cylinders (Green)
- 2 Clam Cylinders (Orange)
- 2 Swing Motors (Yellow)
- 4 Travel Motors (Purple)

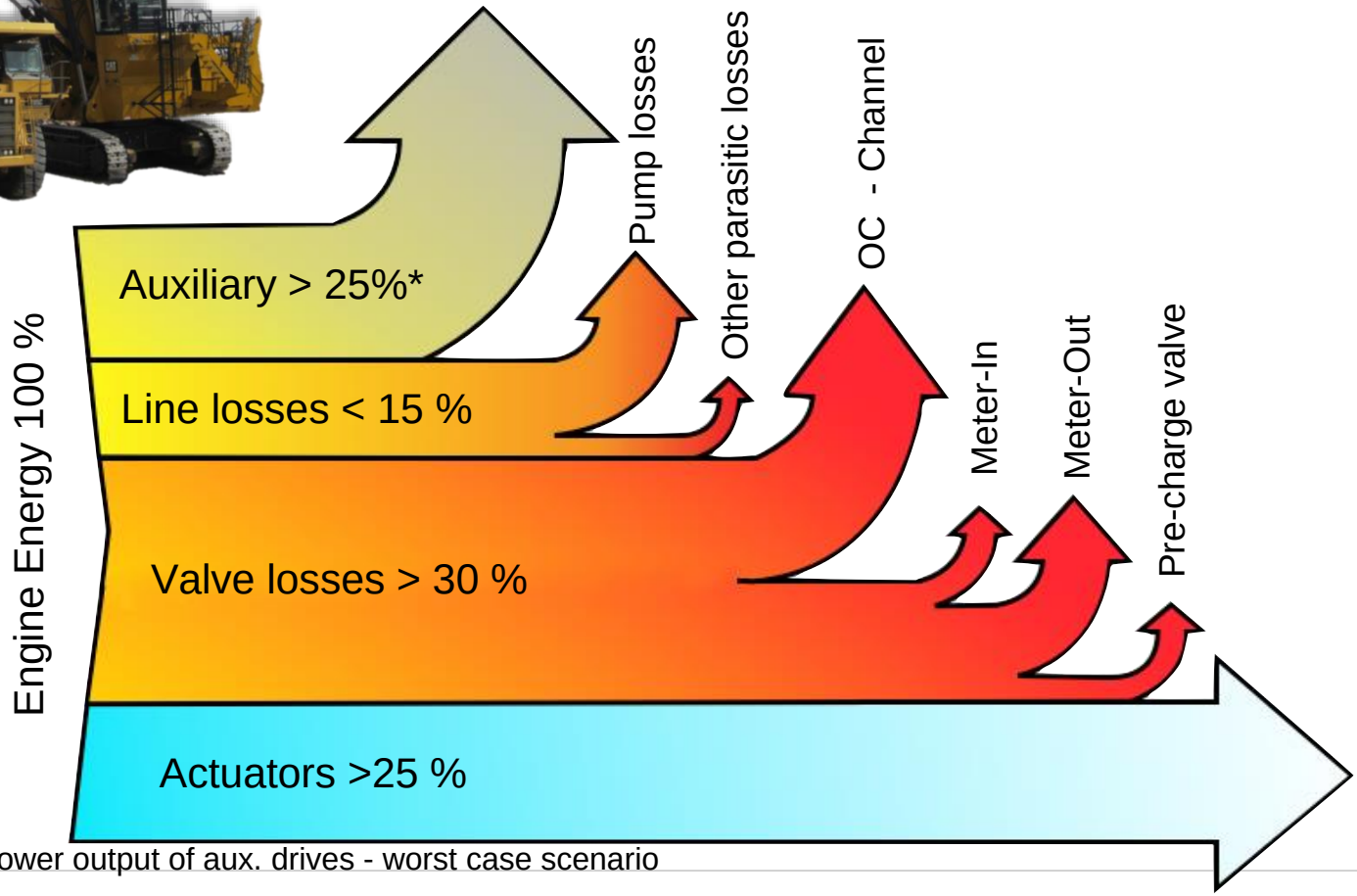


Energetic Overview Standard Machine

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

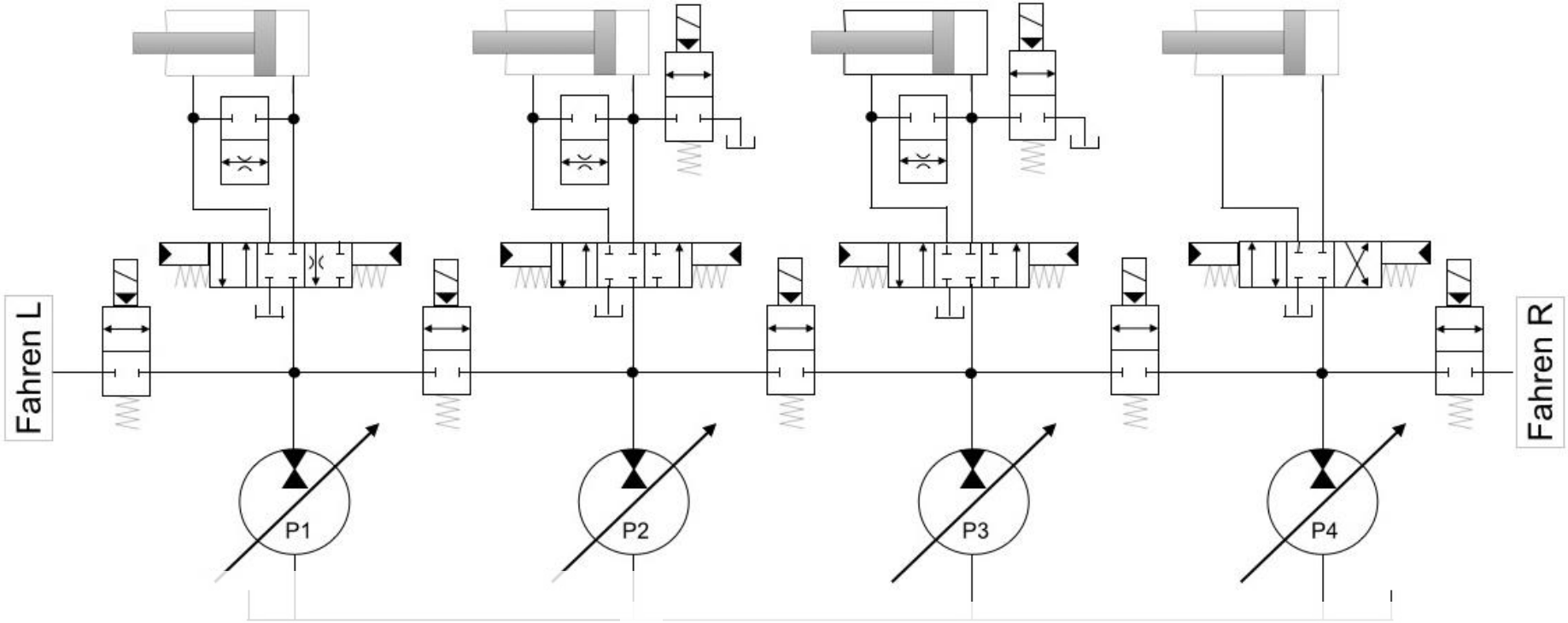
Energy Flow over one Cycle

$$E_M = \int n \cdot \tau$$

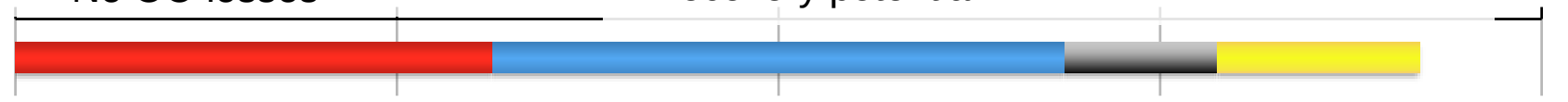


* Based on maximal power output of aux. drives - worst case scenario

New Open Circuit DC System

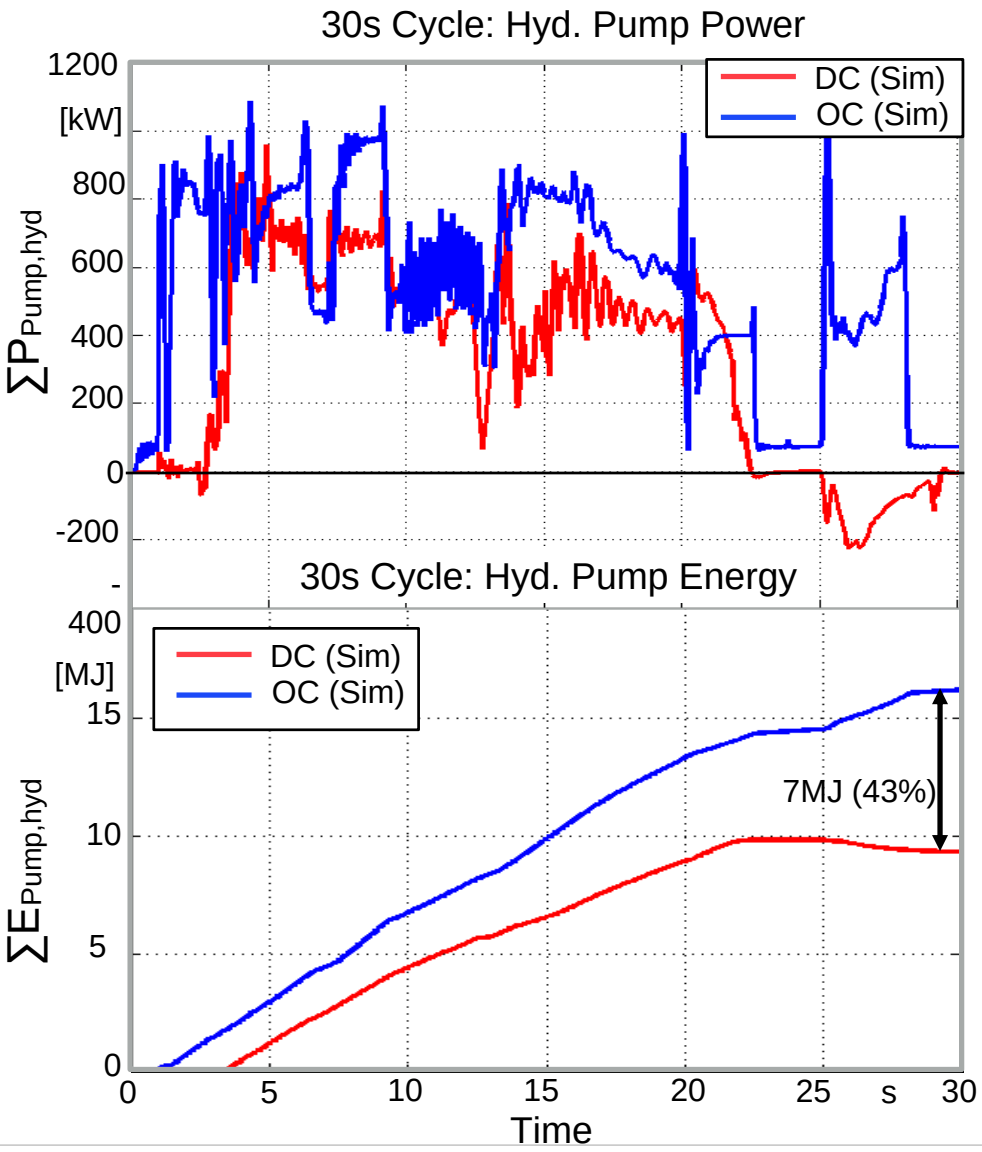


- No throttle losses
- No OC-losses
- Less line losses
- Recovery potential



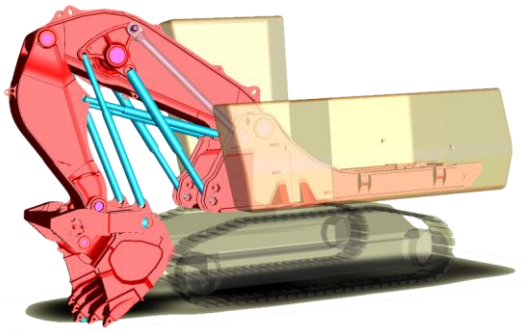
Savings potential per Cycle ($E_{VKM,\ mech}$ =100 %)

30s Cycle - (Sim vs. Sim)

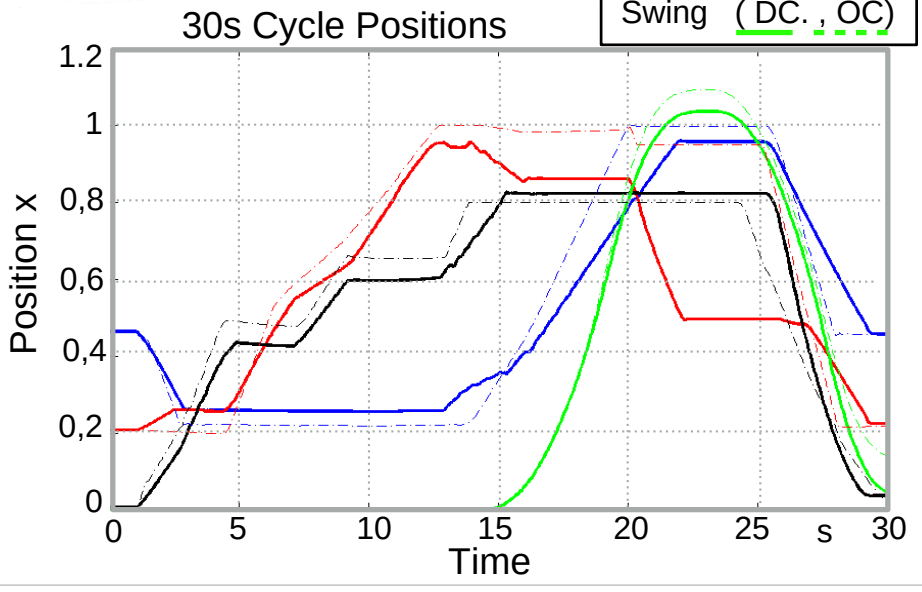


30 s Ideal Cycle

- Energy recovery: 3.2 %
- Energy savings: 43 % (hydraulic only)



Boom (DC , OC)
Stick (DC , OC)
Bucket (DC. , OC)
Swing (DC. , OC)

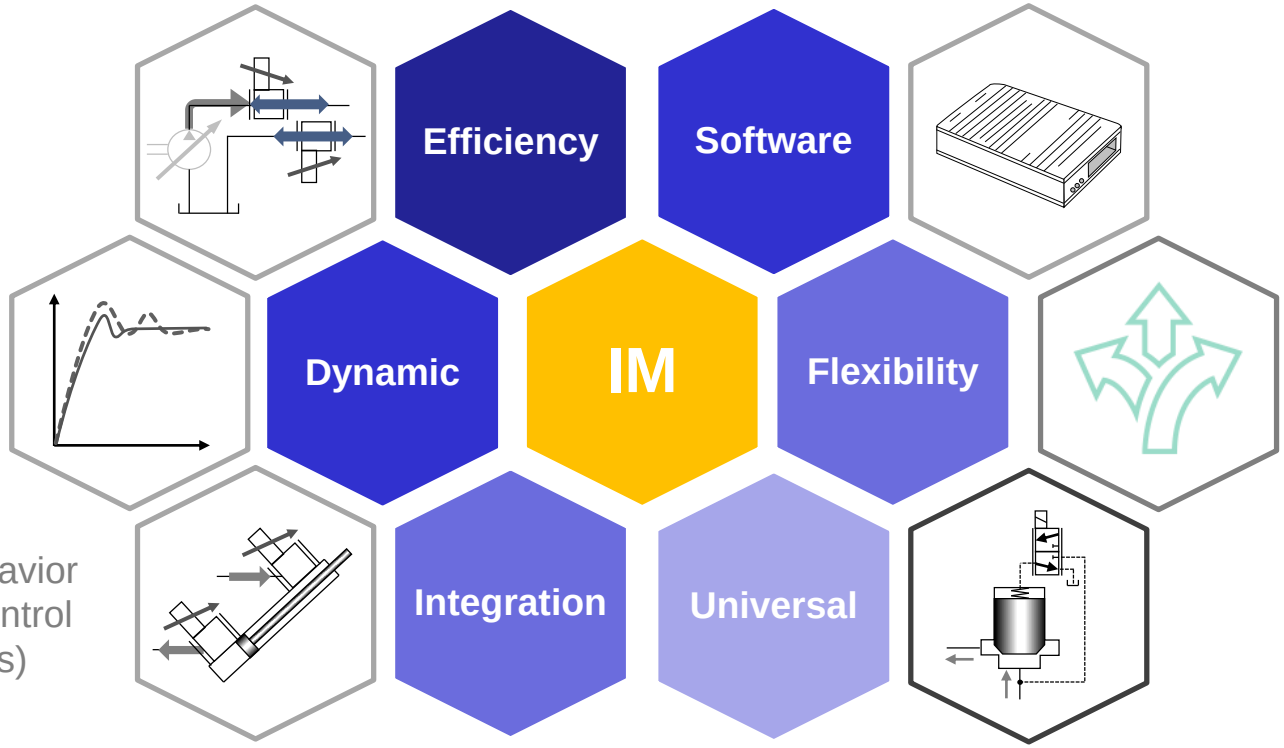


Technology Overview
Independent Metering Systems

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

Freely configurable flow paths
(flow regeneration)

Adaptable operating
characteristic



Dynamic behavior
(extended control
capabilities)

Decentral installation

Universal Valve Elements
Functional integration
(Load holding)

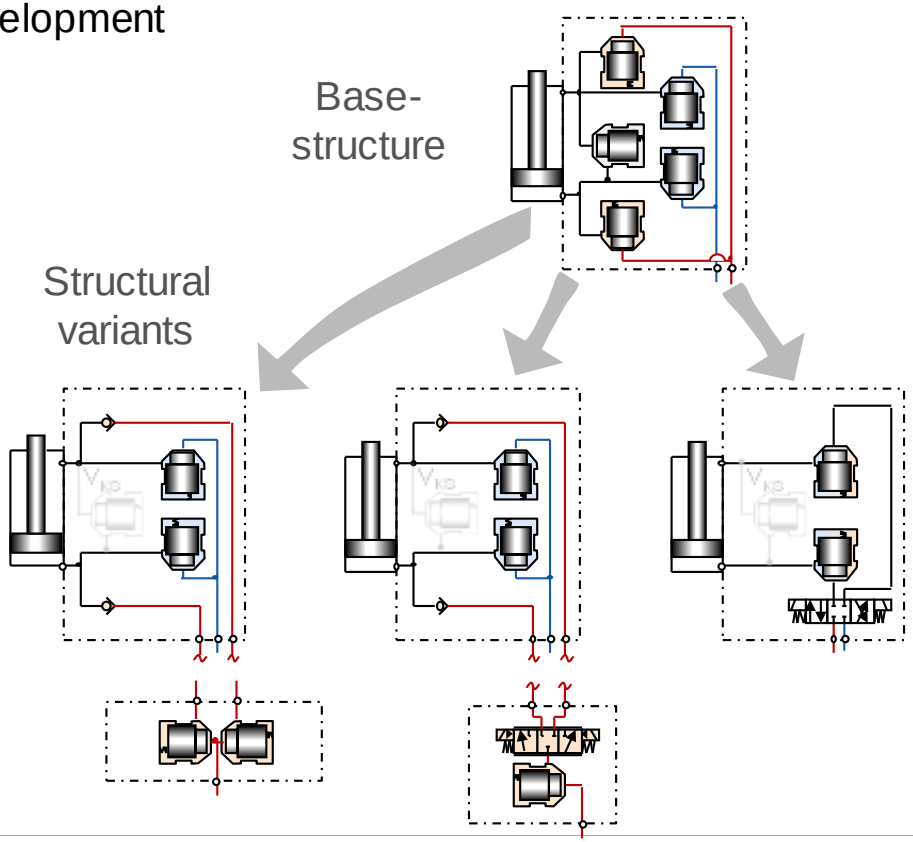
Machine Integration

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

Various Machine-types & requirements




System development

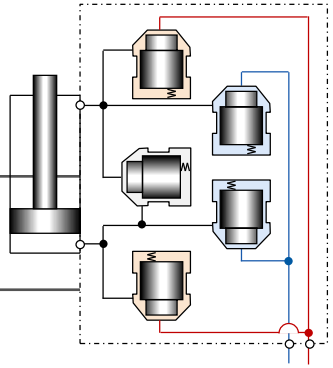


Valve structure concepts

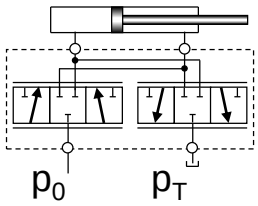
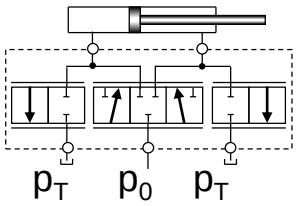
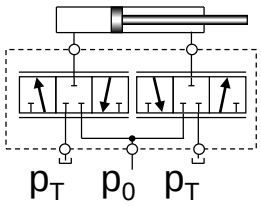
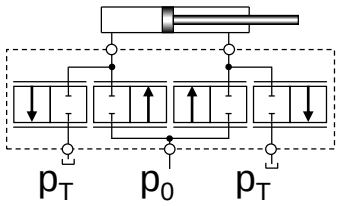
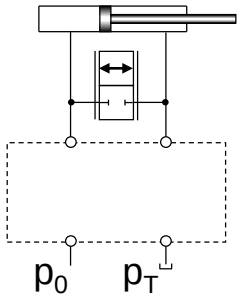
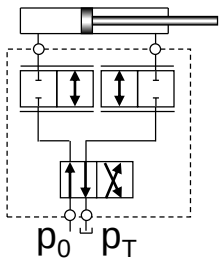
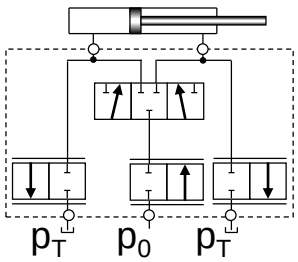
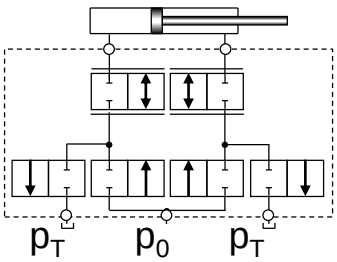
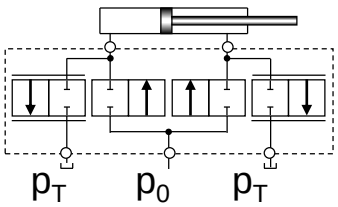
Aspects of integration
- Installation space
- Valve technology
- System Control
- Costs
- …

Valve Structures

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN



Circuit Variants

	normal meter in / out	+ low pressure regeneration		+ high / low pressure regeneration	
Prop.					Short circuit valve 
Prop. / Switch					

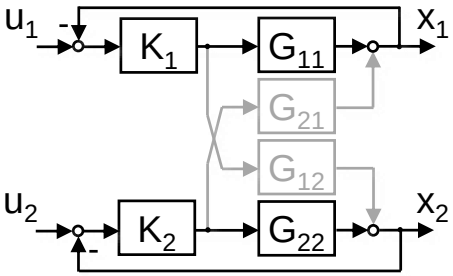
Control architecture

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

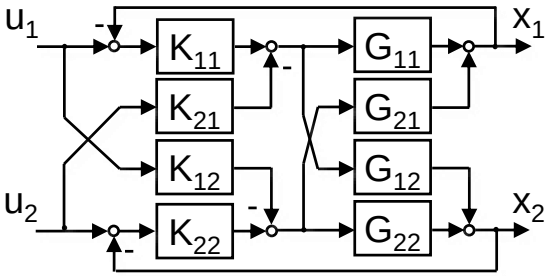
- MIMO Multiple Input / Multiple Output System
- Strength of cross coupling defines control system requirements

$$\begin{pmatrix} \dot{x} \\ p \end{pmatrix} = \begin{pmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix}$$

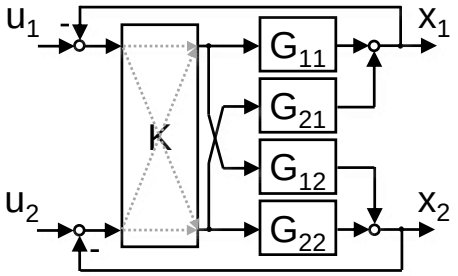
low — cross coupling behavior — high



Decentralized Control
2 separate SISO Systems

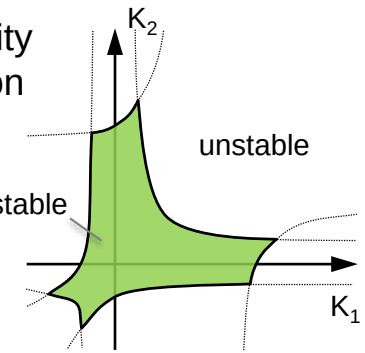


Linear / Nonlinear decoupling
Feedforward Control

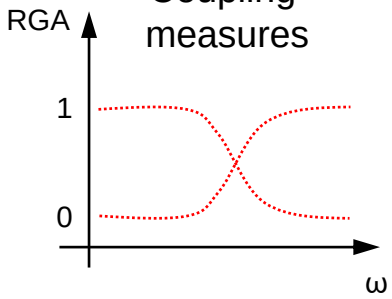


Multivariable Control
e.g. flatness based Control

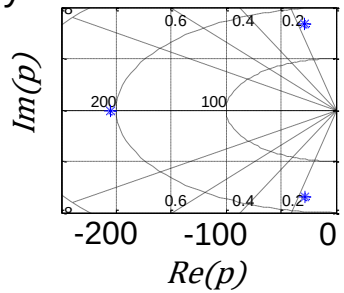
Stability region



Coupling measures

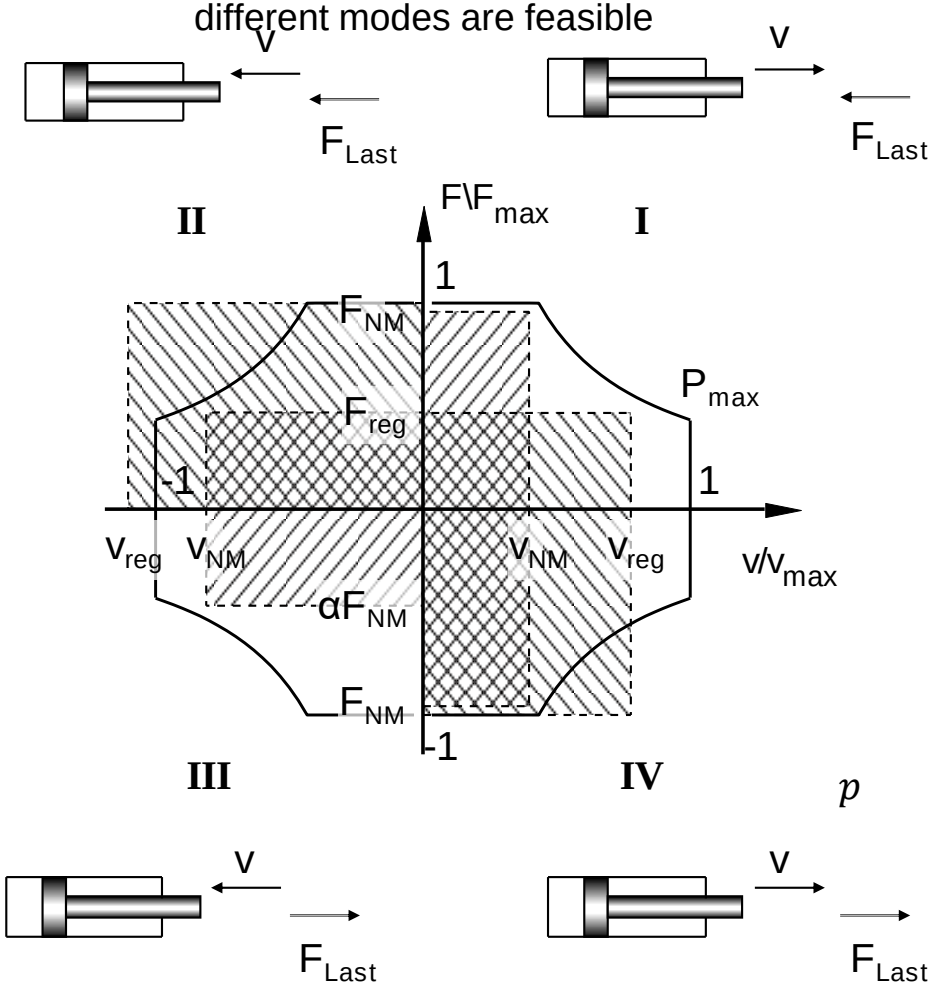


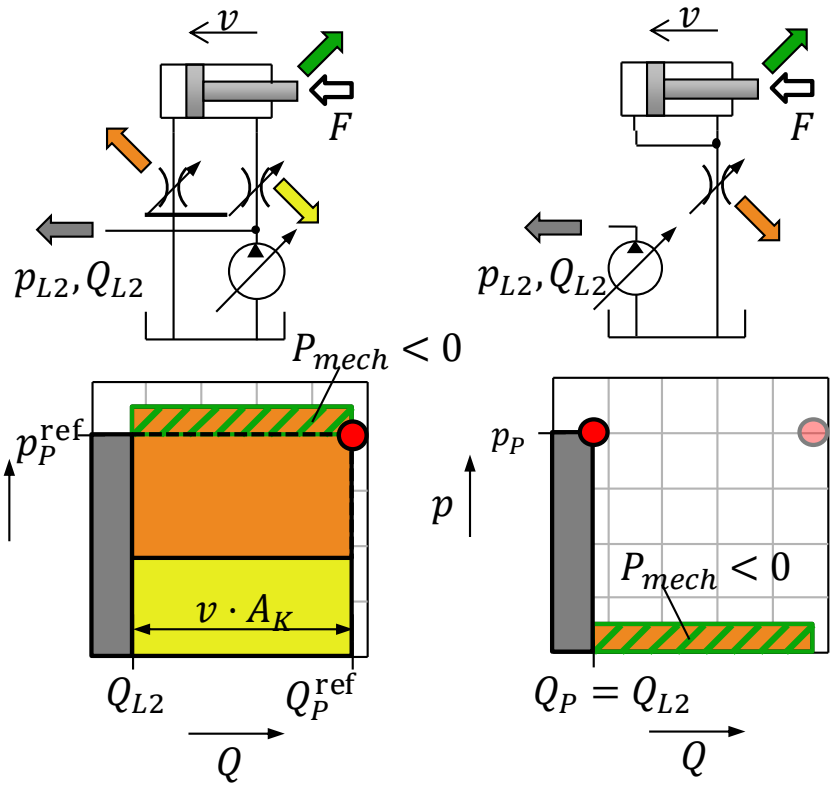
Frequency domain



Energy efficient operation

depending on load direction
different modes are feasible





Power loss intlet

Power loss outlet

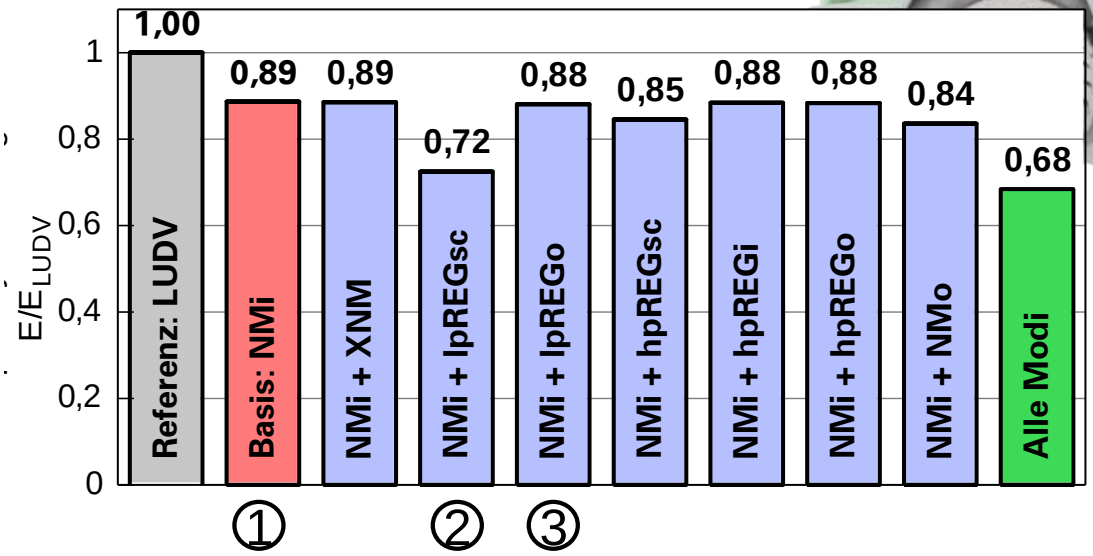
Mechanical work

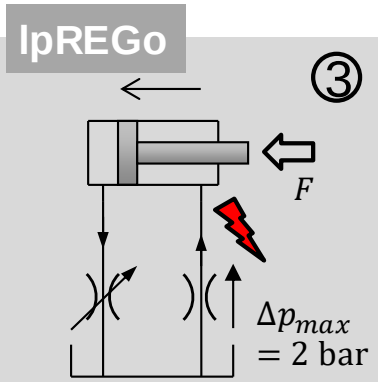
Energy efficient operation

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

Study Wheel loader working hydraulics

- Possible energy savings





Normal meter in / meter out ①

\+ Low pressure regen. incl. short circuit valve ②

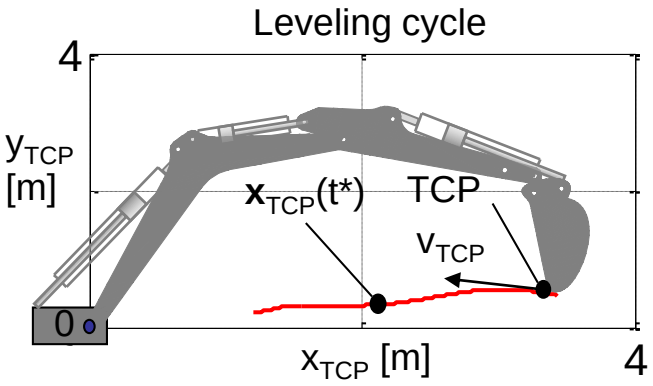
\+ Low pressure regen. excl. short circuit valve ③

Danger of cavitation

Energy efficient operation

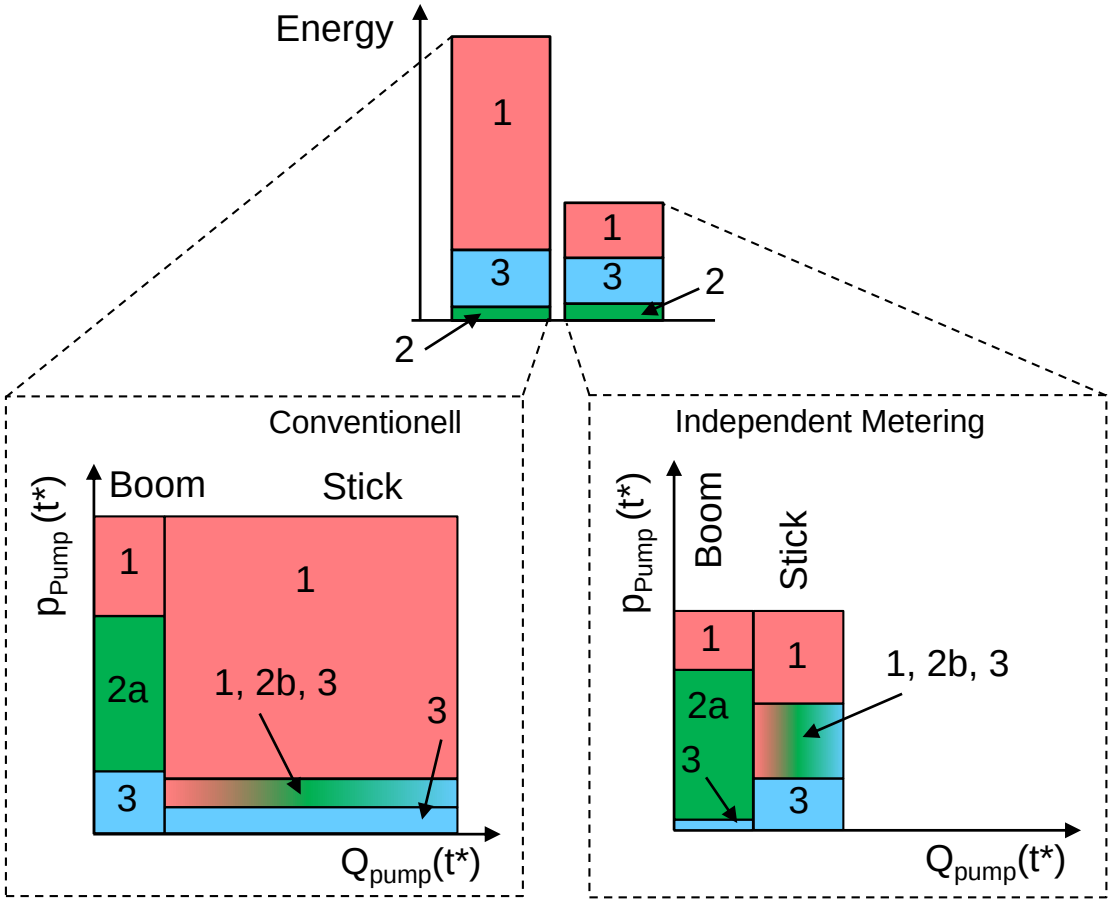
FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

Study and measured Excavator working hydraulics



1: throttle losses inlet
2a: effective power
2b: moving load
3: throttle losses outlet

Introduced mech. Power – throttled at inlet and outlet valve edges

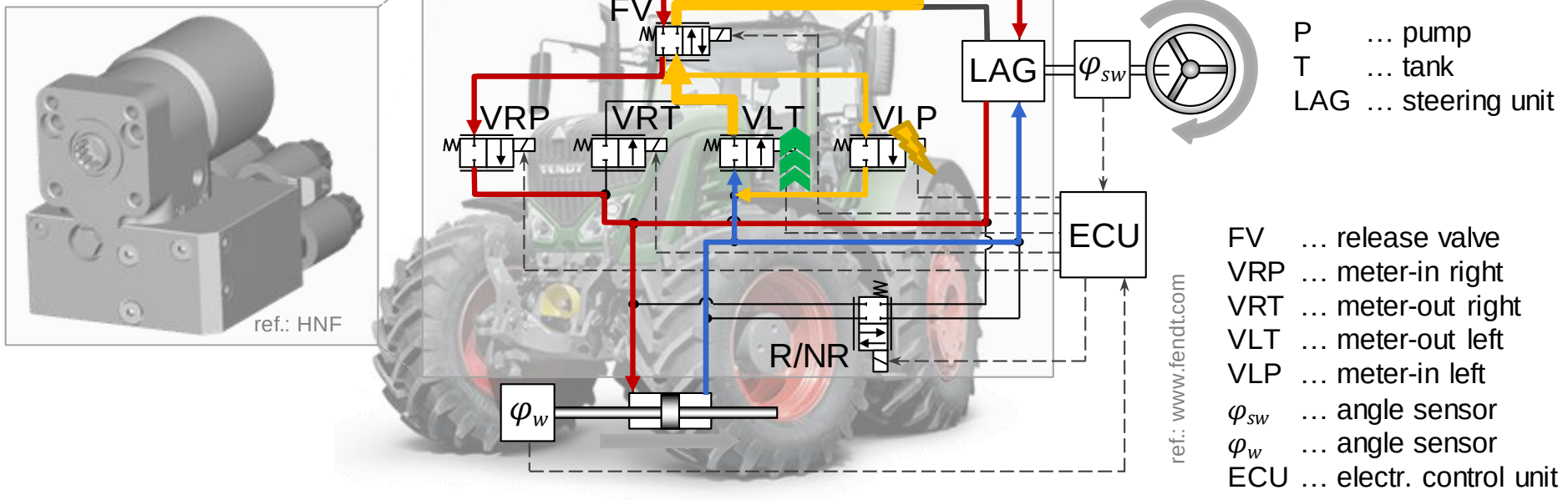


Functional Safety

FLUID-MECHATRONISCHE SYSTEMTECHNIK DRESDEN

Independent metering for power assisted steering systems

- electrical drives offer very often integrated safety functions
- leads to an easy system integration for OEM
- benefits of IM structures in steering systems:
  - driver assisted steering
  - high safety level due to extended control intervention



P … pump
T … tank
LAG … steering unit

FV … release valve
VRP … meter-in right
VRT … meter-out right
VLT … meter-out left
VLP … meter-in left
φ_{sw} … angle sensor
φ_w … angle sensor
ECU … electr. control unit

….Back to the future

TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

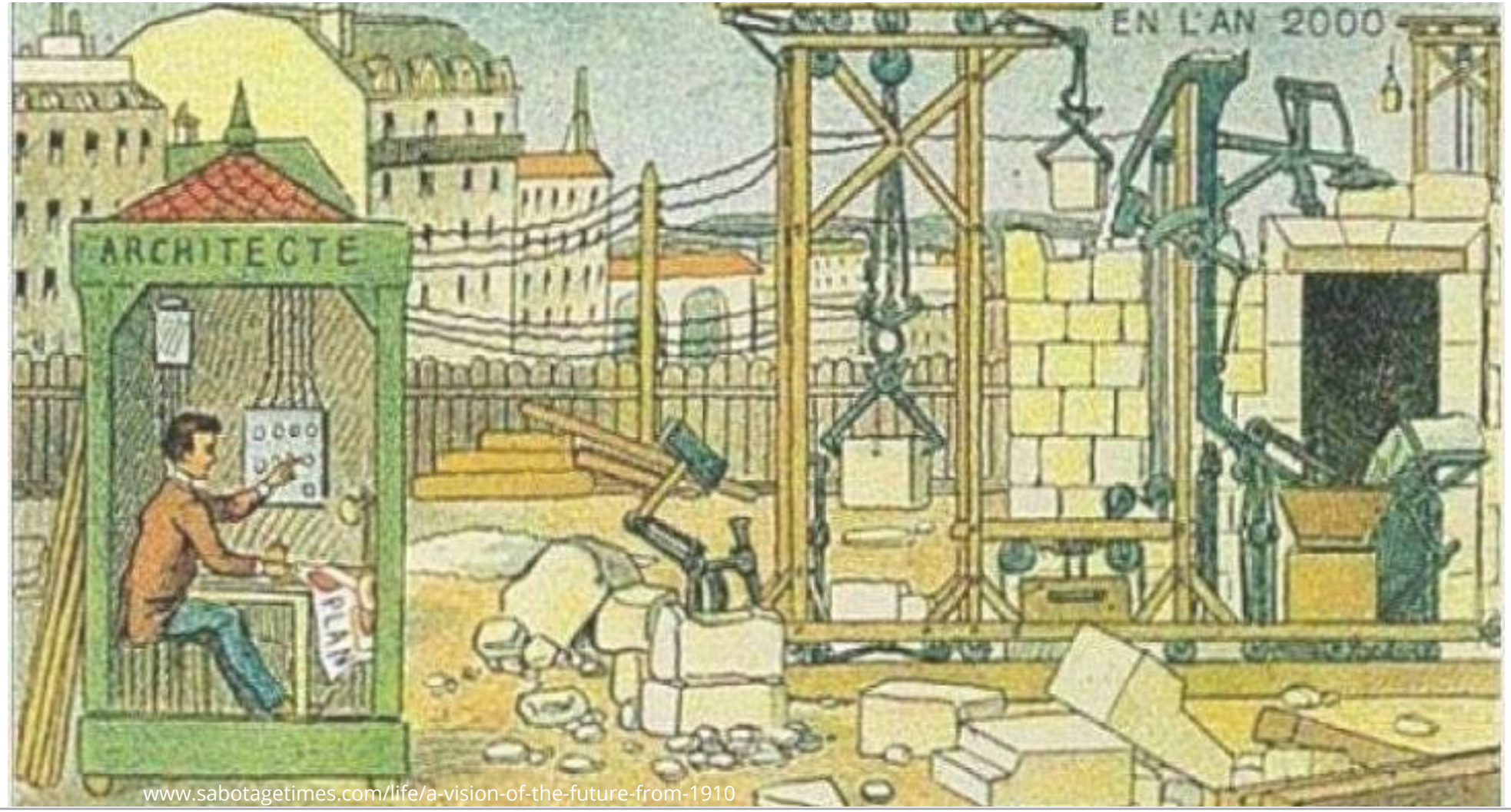
Joint Research Project BAUEN 4.0

Prof. Dr.-Ing. Jürgen Weber, Chair of Fluid Mechatronic Systems (Fluidtronics)

West Lafayette, June 5, 2019

1910 – Vision of a construction site in the year 2000

shown in the world exposition in Paris 1910



www.sabotagetimes.com/life/a-vision-of-the-future-from-1910

Joint Research Project „BAUEN 4.0“

… fully digitized, highly automated, highly customizable construction site

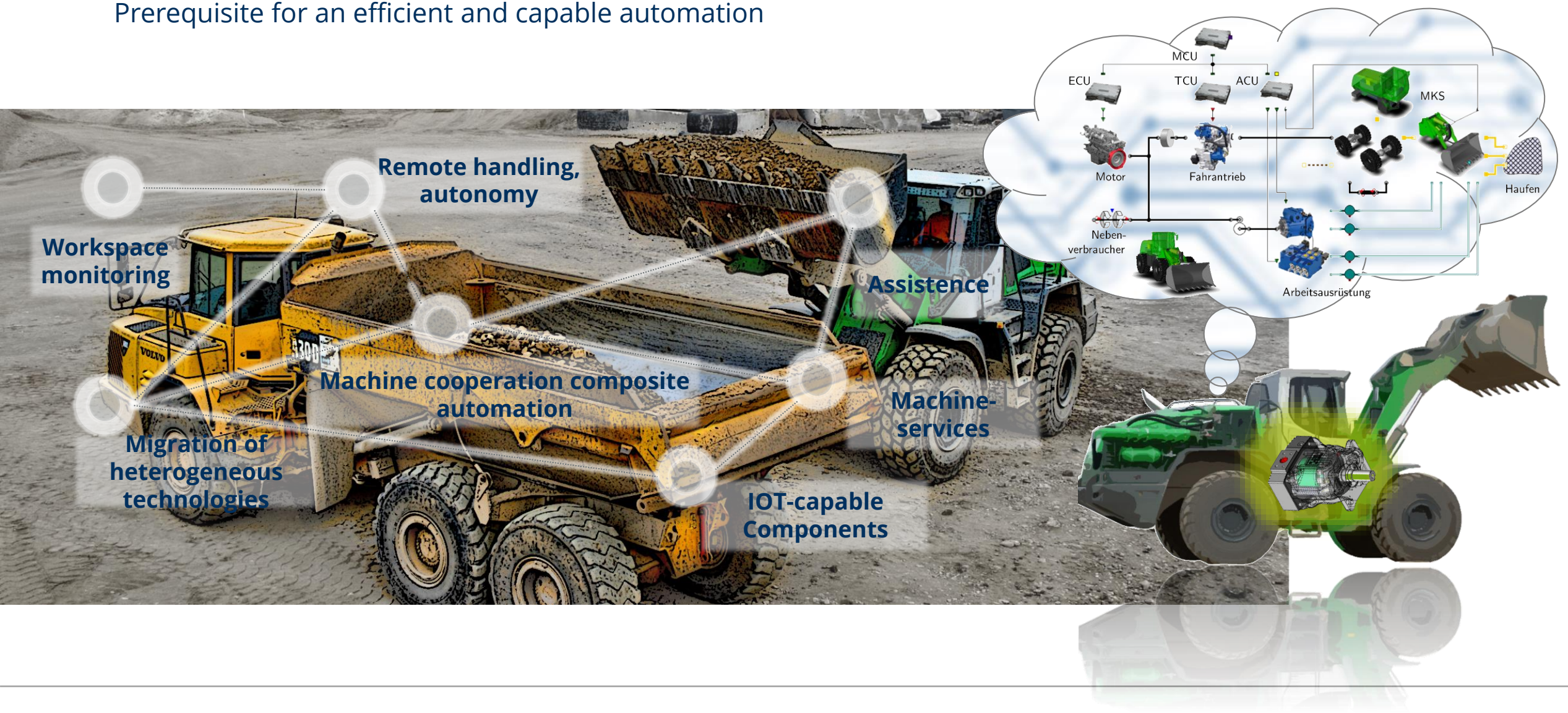
… holistic simulation & optimization of today's and future construction machinery and construction processes through massive networking and communication

… efficiency and productivity gains through assistance, automation and data collection
- operator as machine coordinator

… new business and value chains technological leadership

5G Communication of the Machines and the digital construction site

Prerequisite for an efficient and capable automation



Holistic approach to establish Industry 4.0 technologies

Connected and automated machines

wireless communication

5G Machine and Construction Site Networks

wireless communication

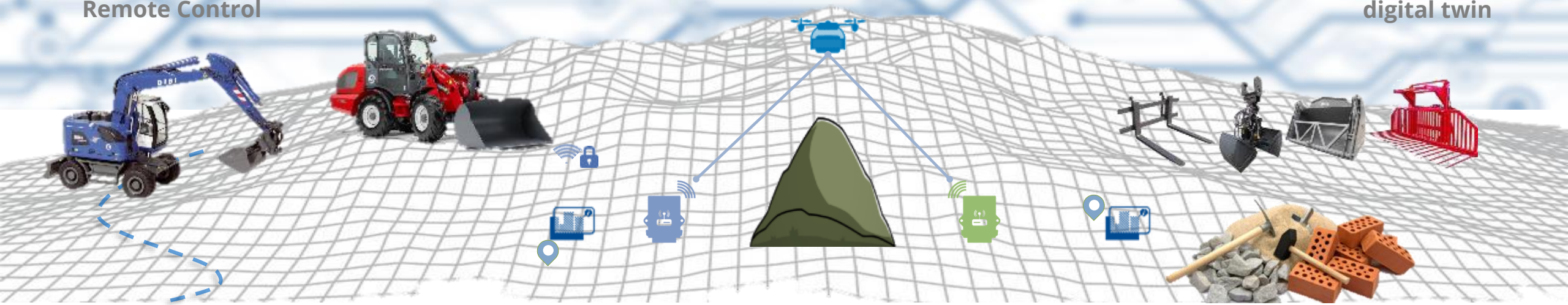
Processes of the digital construction site

Sensor technology
Operator assistance
Automation
Remote Control

Cloud integration
Distributed intelligence

Reliable & secure Data transfer

Logistic-, Construction Data
remote management
environment recognition
digital twin



Automation/ autonomous Machines

Sensor data fusion

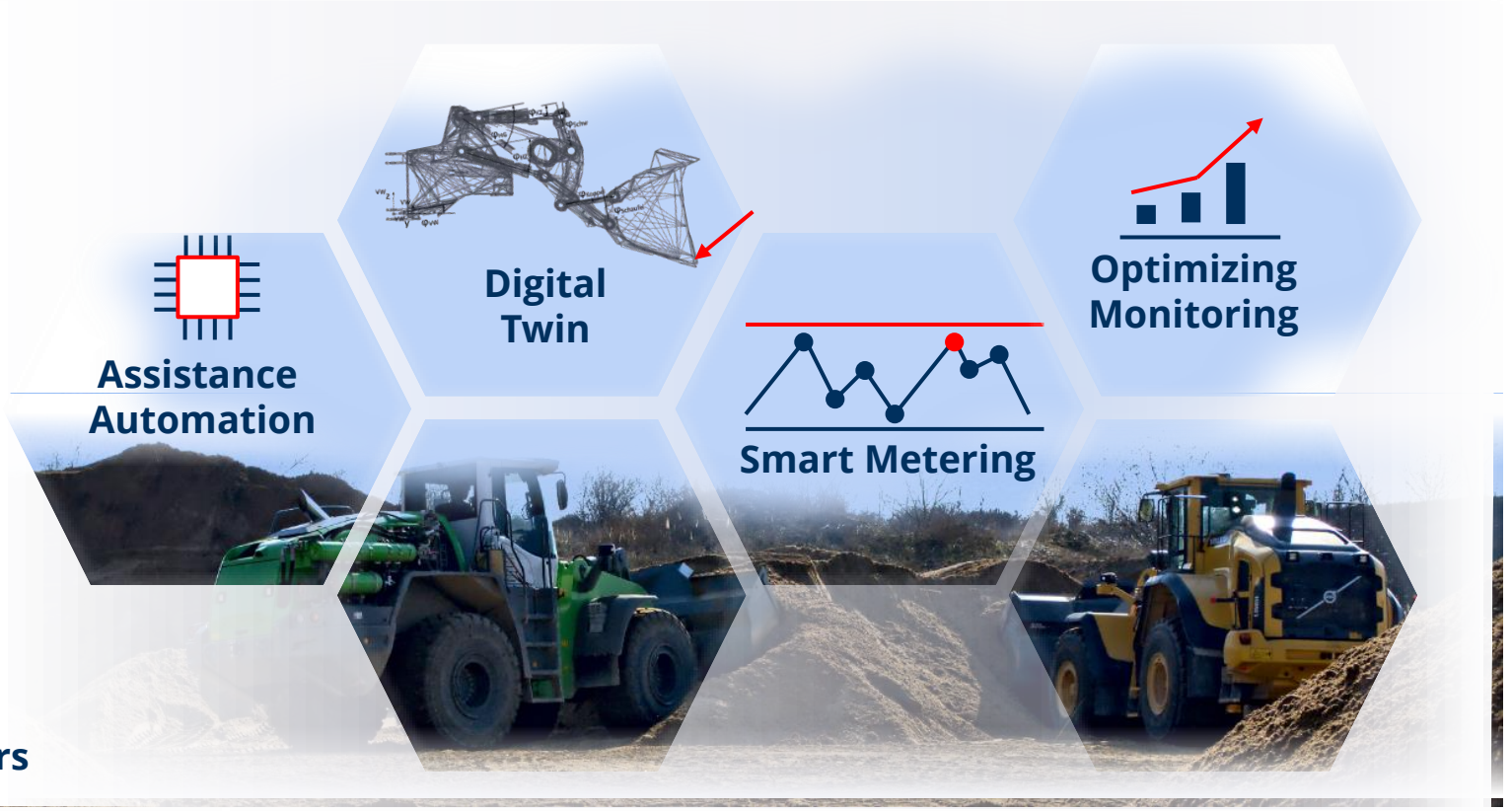
Networking and Communication

Condition Monitoring

Integration of data planning and processing

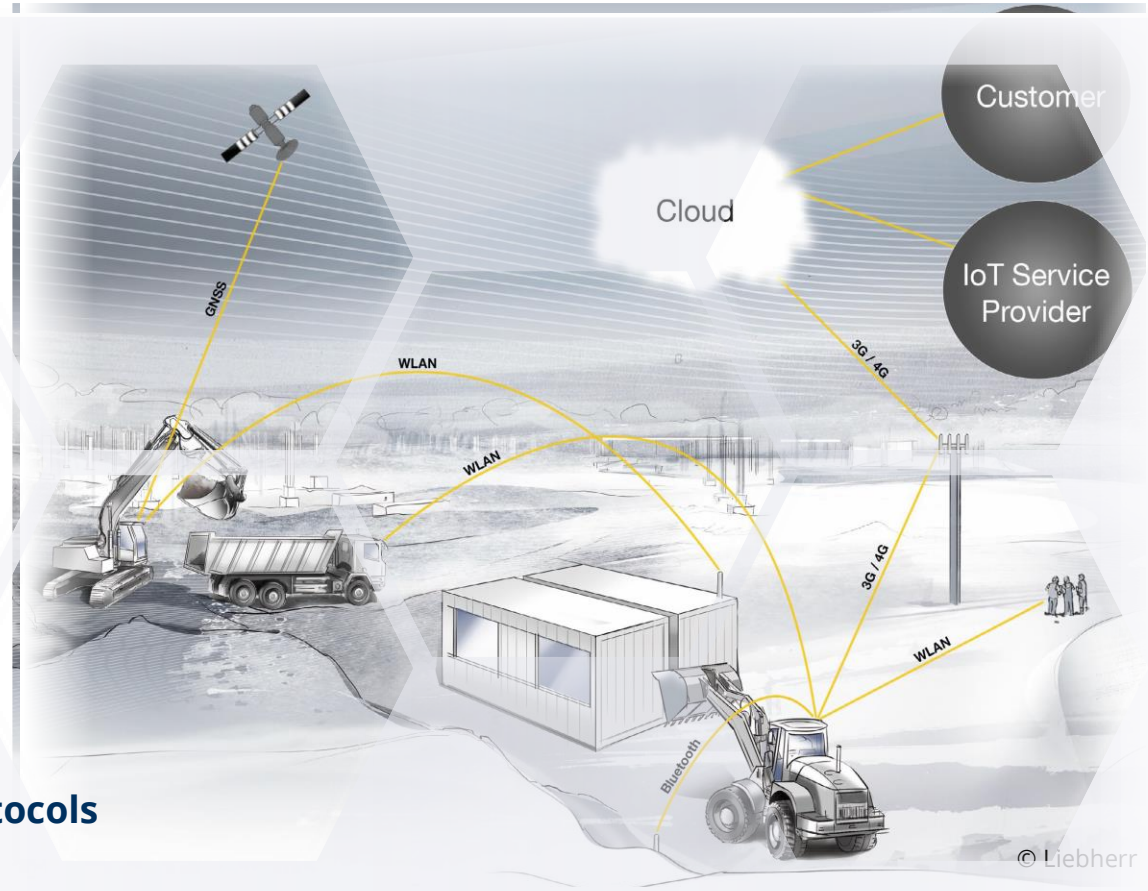
Major Project Topics
Connected and automated machines

- **Machine capability to communicate, automation**
  Software-based networking controllers, appropriate architecture for electronics and control, automation-oriented system design,
- **Assistance & virtual usability/operation**
  Integration of sensors, digital model and environmental information
- **Digital Machine Model / Twin**
  Optimizing, real-time analysis
- **Machine services**
  Condition monitoring, failure prediction, diagnosis, maintenance & repair
- **Implementation & testing on demonstrators**



Major Project Topics
5G Machine and Construction Site Networks

- **Machine and construction site dependent 5G communication infrastructure**
  Inclusion of external / ambient sensor units temporary on-site or available cellular networks
- **Communication units & systems**
  compatible to communication standards used today in the machines (CAN / Ethernet)
- **Machine and construction site optimized cloud concepts and solutions**
  Mobile Edge Cloud, Regional-Cloud, Global-Cloud
- **Integration of solutions in demonstration scenarios for civil engineering**
- **Standards for message formats and communication protocols**
  Inclusion of RAMI 4.0



Major Project Topics
Processes of the Digital Construction Site

- **Construction site process model - production synchronous**
  digital twin,
  5D-BIM construction site,
  formalized workflow descriptions

- **Digital construction planning for civil engineering**
  Real-time status information of actuators and entities,
  information and task coordination of the machines

- **Quality and efficiency management,**
  optimization of processes via holistic simulations
  Algorithms to analyze and evaluate the building process
  efficiency based on the real-time state information

5G Machine and Construction Site Networking
Demand-specific networking solutions

Global Cloud
(via Internet)

External Server

External Services

On Site Cloud
(local on construction site)

On site server

Digital construction planning

Tracking & Tracing

Embedded Machine Cloud
(local on the radio module)

5G Connectivity-Module
uniform interface

Monitoring, automation

Device interfaces
And services

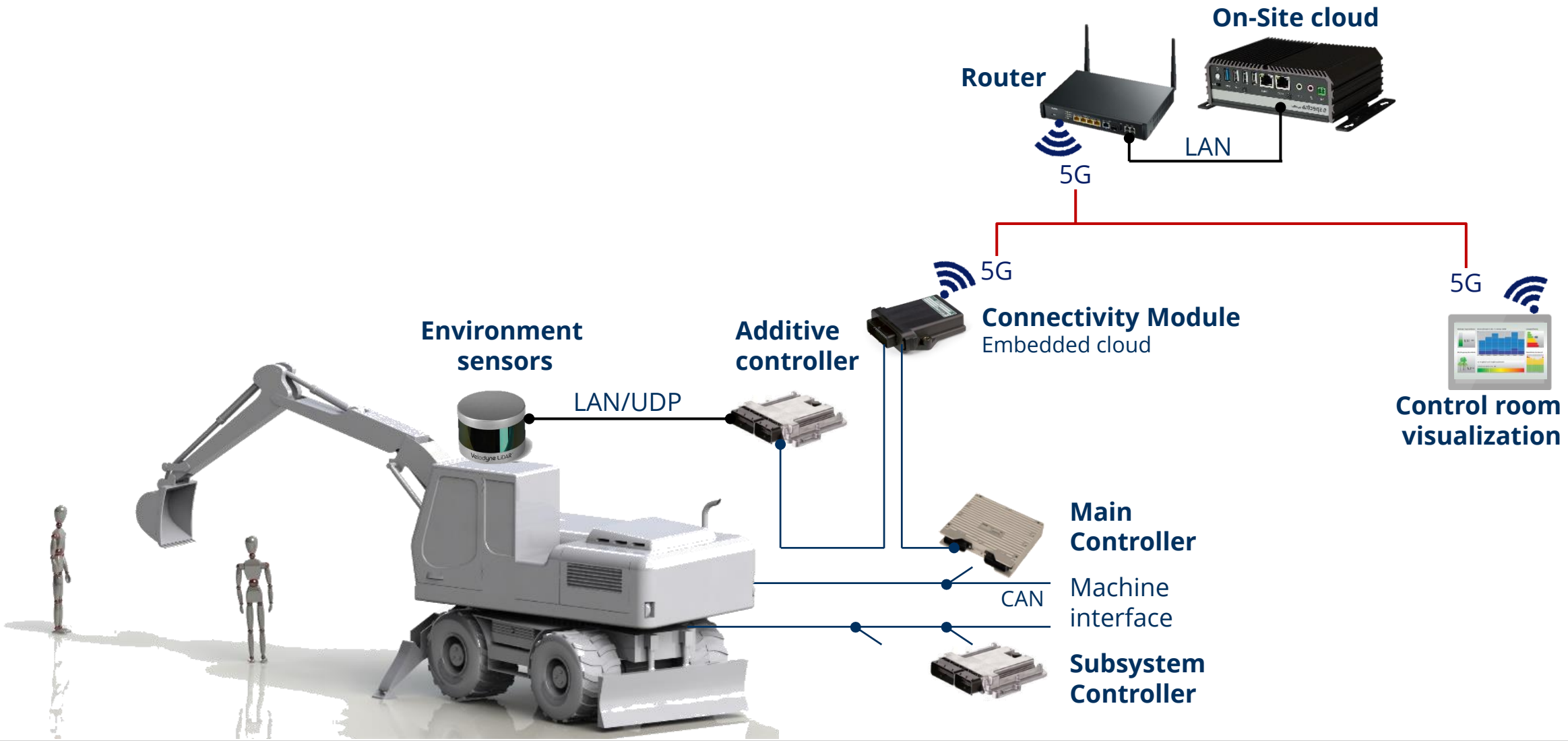
Machine / Device level

Interface to the
main controller / subsystem
(CAN, Ethernet application specific)

Main controller
with subsystem architecture
(as unchanged as possible)

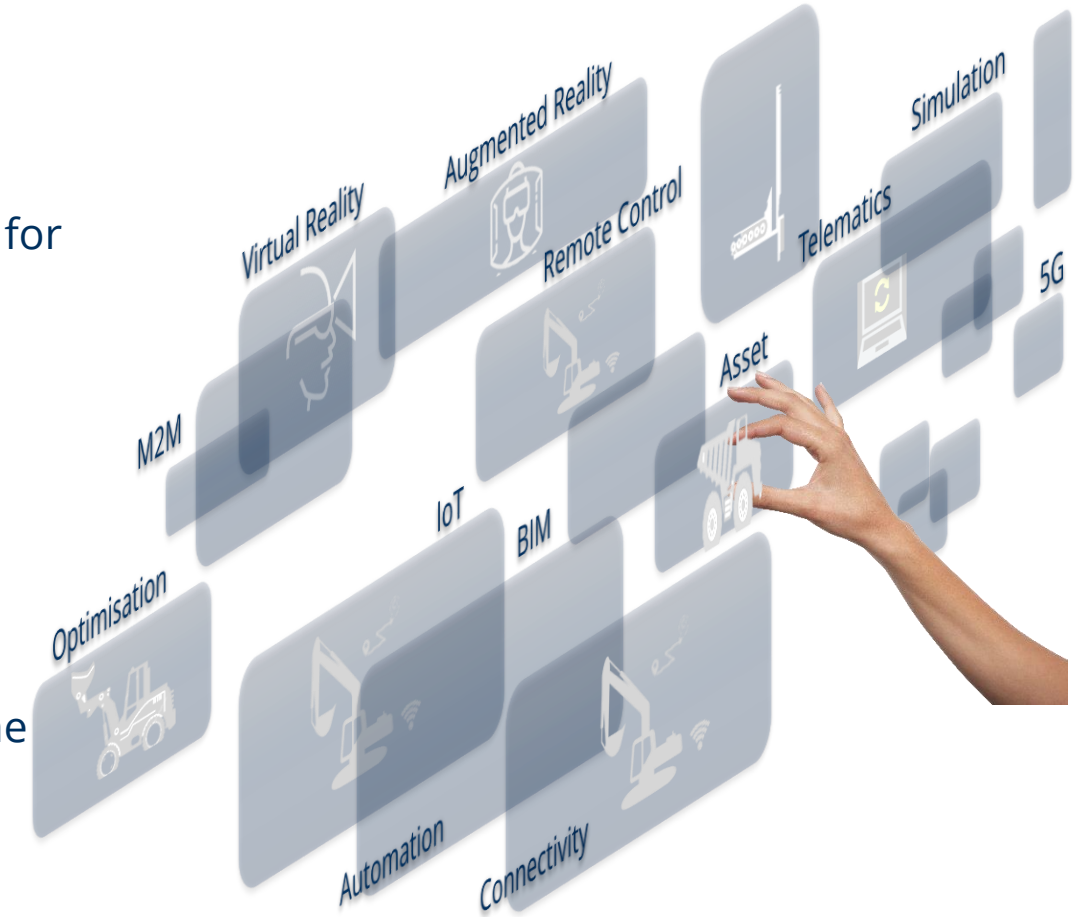
Attachments, Sensors,
Displays, Material,
Machines, Subsystems

Communication and Control Architecture on Machine level



Results and Benefit

- **Automation, assistance, digitization and optimization** of machines and construction processes, technologically proven solutions
- Testing / establishment of **5G communication technologies** for the construction site, for the construction machine - future innovative business and value creation models
- **Experimental construction site for research and development** activities related to the digitization and automation of the construction site environment
- Development / publication of an information platform with the findings, solution principles and application examples



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12th International Fluid Power Conference

March 9-11, 2020 in Dresden

12.IFK

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