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
  Green Wheel Loader, Mining Excavator
• 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

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

Wheel loader with 0.5 m³ bucket capacity

DC-EM
3700 rpm
37 kW
System Step Response under Load Change

High Load Stiffness

Pilot Operated Check Valves work properly

Prof. Dr.-Ing. J. Weber
Electrohydraulic pump control

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

Monitoring
Failure prevention

DC Technology & Control
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

Engine

Lifting

Propel Drive

Tilting

Aux. Pumps

Diesel Motor
max. 82 kW
max. 2200 rpm

Low Pressure Coupling

Brake, Quick-Hitch

8a

8b
Valveless Pump Configuration

- **Rapid prototyping endcap with valveless integrated functionality**
- **SAE1 ports with shut-off valves**
- **High pressure relief valves**
- **Standard housing**
- **Auxiliary mounting pad**
- **Pilot operated check valves as cartridges**
- **Low pressure connection**
- **Parallel ports for OLS**
- **Measurement ports**
Machine Comparison Test

Field test programme side by side: standard and valveless system

standard

valveless
Machine Comparison Test
Truck loading – short & long cycle

valveless: 15 % less fuel consumption
Parallel fork lifting

- Valveless
- Standard

Easier to Operate

Excellent Controllability
Machine Comparison Test
Final Results

Fuel consumption [g/unit]

Truck loading short cycle

Operator feeling: “Valveless is easier to handle”

15% less fuel consumption

valveless
L25CEV

standard
L25CE

15% less fuel consumption

consumption [unit = ton loaded mass]

consumption [unit = cycle]
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
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

- Cartridge Valve
- High pressure line
- Low pressure (return) line
- Pilot Valves
- Main Stage
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

PID Control Logic

Valve Block

Feedback Pressure Signals

Feedback Position Signals

θ \text{com} 

PID

\theta' \text{com} 

\pm

e_\theta

pS,pT

pA,pB

v1

v2

v3

v4

Boom Cylinder

\theta' 

1/s

\theta
Cylinders with integrated Sensors

Sensor element

Position magnet

Signal converter

Operating Conditions
- Rod Pressure Rating: up to 530 bar
- Shock Rating: 50 g
- Vibration Rating: 5 g
- Measuring Range higher than 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

Control Cylinder 1

Control Cylinder 2

Control Cylinder 3

Function Samples

Control

Profiling Leveling

Profil Parameter

Sensors

Joystick

Display

Prof. Dr.-Ing. J. Weber
„The Green Wheelloader„

Research Project 2012 - 2015
State of the Art and Project Goal

**State of the Art**

- **Working hydraulics**
  - LS
  - NFC

- **Transmission**
  - an Schaltgetriebe
  - ab

- **Hydrostatic**

- **Hydrodynamic**

**Available Concepts**

- **Working hydraulics**
  - Displacement control

- **Transmission**
  - Power split

- **Hybrid Module**

**Project Goal**

- **Diesel Engine**
  - Optimized engine

- **Diesel Engine**
  - Displacement control

- **Transmission**
  - Power split

- **Hybrid Module**

- **Steuerung**

- **Arbeitshydraulik**

- **Fahrantrieb**

- **Prozess**
Systemstructure

Energy Consumption

VC | DC

Hybrid Module

Diesel engine

Displacement Controlled Working Hydraulics

Standard Engine

Optimized Engine

Hydro Dynamic Power Split

ND | LS | VC | DC

Energy Consumption

Torque

Engine Speed

$0 \rightarrow 400 \rightarrow 800 \rightarrow 1200 \rightarrow 1600 \rightarrow 2200 \rightarrow 2800 \rightarrow 0$

$0 \rightarrow 600 \rightarrow 1000 \rightarrow 1400 \rightarrow 2200 \rightarrow 0$

Total Efficiency

Hydraulic Efficiency

Productivity

Maintain Machine Functionality
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
Parameterization

Comparison of the Process Forces

Process Force $F$

$F_x$ Meas.
$F_x$ Simulation

$F_y$ Meas.
$F_y$ Simulation

Validation
Experiments

Test Rig for the power split drives

- Efficiency measurements to validate the simulation
- Analysis of the gear transmission dynamics
Development Stations

January 2012

Project Start

Research & Development

October 2013

Integration and assembly at Liebherr, Bischofshofen

April 2014

Transport to Dresden

November 2014

Machine adjustment and testing, gravel quarry near Dresden

August 2014

Rollout & first test

Source: http://www.qomet.de
Testing

In real operating conditions with trained drivers
Testing

Results in comparison to the reference machine

- Engine Power (kW)
- Torque (Nm)
- Drive Speed (km/h)
- Traction Force (kN)
- Fuel consumption (%)

Reference Machine
Simulation
Green Wheel Loader

Engine Speed (U/min)

Time (s)

Fuel consumption comparison:
- Reference Simulation
- Reference Machine
- Green Wheel Loader

- Reduced fuel consumption by 10%
DC Mining Excavator Machine

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

Energy Flow over one Cycle

\[ E_M = \int n \cdot \tau \]

- Engine Energy 100%
- Actuators > 25%*
- Valve losses > 30%
- Line losses < 15%
- Auxiliary > 25%* (Based on maximal power output of aux. drives - worst case scenario)

- Pump losses
- Other parasitic losses
- Meter-In
- Meter-Out
- Pre-charge valve

Line losses < 15%
New Open Circuit DC System

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

Savings potential per Cycle ($E_{VKM,\text{mech}} = 100\%$)
30s Cycle - (Sim vs. Sim)

30s Cycle: Hyd. Pump Power

- DC (Sim)
- OC (Sim)

30s Cycle: Hyd. Pump Energy

- DC (Sim)
- OC (Sim)

30s Cycle Positions

30 s Ideal Cycle

- Energy recovery: 3.2%
- Energy savings: 43% (hydraulic only)
Technology Overview
Independent Metering Systems

Freely configurable flow paths (flow regeneration)

Efficiency

Dynamic

Integration

Universal

Adaptable operating characteristic

Software

IM

Flexibility

Decentral installation

Universal Valve Elements
Functional integration (Load holding)

Dynamic behavior (extended control capabilities)
Machine Integration

Various Machine-types & requirements

System development

Valve structure concepts

Base-structure

Structural variants

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

Circuit Variants

<table>
<thead>
<tr>
<th></th>
<th>normal meter in / out</th>
<th>+ low pressure regeneration</th>
<th>+ high / low pressure regeneration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prop.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>p₀ pₜ</td>
<td>pₜ p₀ pₜ</td>
<td>pₜ p₀ pₜ</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prop. / Switch</td>
<td>p₀ pₜ</td>
<td>pₜ p₀ pₜ</td>
<td>pₜ p₀ pₜ</td>
</tr>
</tbody>
</table>

Short circuit valve
Control architecture

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

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

- Decentralized Control
  2 separate SISO Systems

- Linear / Nonlinear decoupling
  Feedforward Control

- Multivariable Control
  e.g. flatness based Control

Stability region

- Stable
- Unstable

Frequency domain

- RGA
- Coupling measures

Frequency domain

- \( \text{Re}(p) \)
- \( \text{Im}(p) \)
Energy efficient operation

depending on load direction
different modes are feasible

\[ v \]

\[ F_{\text{Last}} \]

\[ F_{\text{NM}} \]

\[ F_{\text{reg}} \]

\[ F_{\text{max}} \]

\[ v_{\text{reg}} \]

\[ v_{\text{NM}} \]

\[ P_{\text{max}} \]

\[ P_{\text{mech}} < 0 \]

\[ p_{L2}, Q_{L2} \]

\[ P_{\text{mech}} < 0 \]

\[ Q_{L2} \]

\[ Q_{P} = Q_{L2} \]

\[ Q_{\text{ref}} \]

\[ v \cdot A_{K} \]

\[ p_{P} \]

\[ p_{P}^{\text{ref}} \]

\[ p_{P} \]

\[ Q \]

\[ Q_{P} \]

\[ v \]

\[ F_{\text{Last}} \]

\[ F_{\text{Last}} \]

Power loss inlet

Power loss outlet

Mechanical work
Energy efficient operation

Study Wheel loader working hydraulics

- Possible energy savings

Normal meter in / meter out

+ Low pressure regen. incl. short circuit valve
+ Low pressure regen. excl. short circuit valve

Danger of cavitation

Referenz: LUDV
Basis: NMi
NMi + XNM
NMi + lpREGsc
NMi + IpREGGo
NMi + hpREGsc
NMi + hpREGi
NMi + hpREGo
NMi + NMo
Alle Modi

\[ \Delta p_{max} = 2 \text{ bar} \]
Energy efficient operation

Study and measured Excavator working hydraulics

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

1, 2a, 3: Energy

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

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
....Back to the future
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/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**
  - Sensor technology
  - Operator assistance
  - Automation
  - Remote Control

- **5G Machine and Construction Site Networks**
  - Wireless communication
  - Cloud integration
  - Distributed intelligence
  - Reliable & secure Data transfer

- **Processes of the digital construction site**
  - 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)

On Site Cloud
(local on construction site)

Embedded Machine Cloud
(local on the radio module)

Machine / Device level

5G Connectivity-Module
uniform interface

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

Main controller
with subsystem architecture
(as unchanged as possible)

External Server

On site server

5G Connectivity-Module

Monitoring, automation

Device interfaces
And services

Attachments, Sensors,
Displays, Material,
Machines, Subsystems

External Services

Digital construction planning

Tracking & Tracing

External Services

Digital construction planning

Tracking & Tracing

External Services

Digital construction planning

Tracking & Tracing
Communication and Control Architecture on Machine level

![Diagram of communication and control architecture on machine level. The diagram shows a machine connected to various components including Environment sensors, Additive controller, Connectivity Module, Main Controller, Subsystem controller, Control room visualization, and Router. Connections are made through interfaces such as CAN, LAN/UDP, and 5G.](Image)
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
Contakt:

Prof. Dr.-Ing. Jürgen Weber
fluidtronik@mailbox.tu-dresden.de
+49 351 463 33559

André Sitte
andre.sitte@tu-dresden.de
+49 351 463 33707

Oliver Koch
oliver.koch@tu-dresden.de
+49 351 463 33706
12th International Fluid Power Conference
March 9-11, 2020 in Dresden

Technische Universität Dresden | Institut für Mechatronischen Maschinenbau
Professur für Fluid-Mechatronische Systemtechnik
Prof. Dr.-Ing. J. Weber | Tel. 0351-463 33559 | fluidtronik@mailbox.tu-dresden.de

www.ifk2020.com