CompactRIO Real-Time Control for Hydraulic Turbomachinery Model Testing

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Overview

- New HES-SO Valais//Wallis universal hydraulic test rig [1]
  - Designed, executed and assembled at the HES-SO VS

Main characteristics:
- Maximum head: 160 mWC
- Maximum discharge: 45 m³/h
- Generating power: 10 kW
- Pumping power: 3 x 5.5 kW
- Maximum pump speed: 3'000 rpm
- Total circuit volume: 4.5 m³
Strategy of regular performance tests

Verification checklist
Instruments, sensors, actuators

Drive the test
Data-logging, processing and managing
Preliminary results → 2D and 3D plots

- Regulation of hydraulic energy
  Recirculating pumps: configurations and speed

- Regulation of implantation level
  Pressure tank

- Control of the testing model
  Rotating speed for every stage

Monitoring of safety indicators
Reaction to events

Reaction to events
Technical challenges

• Security of the user and of the infrastructure

• Robust automatic control

• Integration of several sensors of different types

• Multiple synchronized acquisition/control systems

• High-precision measurements in respect to the IEC 60193 standard recommendations [2]
Hydraulic circuit
## Hydraulic circuit

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Component</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R</strong>₁</td>
<td>Main reservoir</td>
<td>Supplies the test rig with water</td>
</tr>
<tr>
<td><strong>F</strong>₁</td>
<td>Filter</td>
<td>Water filter</td>
</tr>
<tr>
<td><strong>EV</strong>₁</td>
<td>Solenoid valve</td>
<td>Controls the water supply from the drinking water system</td>
</tr>
<tr>
<td><strong>P</strong>₄</td>
<td>Centrifugal pump</td>
<td>Drains the main reservoir</td>
</tr>
<tr>
<td><strong>CV</strong>₄</td>
<td>Check valve</td>
<td>Ensures unidirectional flow toward drain</td>
</tr>
<tr>
<td><strong>P</strong>₁,₂,₃</td>
<td>Centrifugal pumps</td>
<td>Supply the circuit with hydraulic power</td>
</tr>
<tr>
<td><strong>CV</strong>₁,₂,₃</td>
<td>Check valves</td>
<td>Ensure unidirectional flow in turbine mode operation</td>
</tr>
<tr>
<td><strong>T/P</strong></td>
<td>Turbine/Pump</td>
<td>Variable speed reduced-scale testing model</td>
</tr>
<tr>
<td><strong>EV</strong>₂,₃...₉</td>
<td>Solenoid valves</td>
<td>Control the hydraulic circuit configuration</td>
</tr>
<tr>
<td><strong>EV</strong>₁₄</td>
<td>Solenoid valve</td>
<td>Controls the fresh water supply for cooling</td>
</tr>
<tr>
<td><strong>CV</strong>₅</td>
<td>Check valve</td>
<td>Ensures unidirectional flow during cooling</td>
</tr>
<tr>
<td><strong>EC</strong>₁</td>
<td>Expansion compensator</td>
<td>Ensures axial direction flexibility for the testing model assembly</td>
</tr>
<tr>
<td><strong>HC</strong>₁,₂</td>
<td>Honeycomb sections</td>
<td>Ensure uniform flow upstream the flowmeter and the testing model</td>
</tr>
<tr>
<td><strong>R</strong>₂</td>
<td>Pressurised reservoir</td>
<td>Allows simulating different positive or negative implantation levels</td>
</tr>
<tr>
<td><strong>EV</strong>₁₀,₁₁,₁₂</td>
<td>Solenoid valves</td>
<td>Control the air pressure into the pressurised reservoir</td>
</tr>
<tr>
<td><strong>VP</strong>₁</td>
<td>Vacuum pump</td>
<td>Supplies the pressurised reservoir with vacuum</td>
</tr>
<tr>
<td><strong>SV</strong>₁</td>
<td>Safety valve</td>
<td>Protects the pressurised reservoir from excessive pressure</td>
</tr>
<tr>
<td><strong>S</strong>₁,₂</td>
<td>Silencers</td>
<td>Silencers for pressurised air drain</td>
</tr>
<tr>
<td><strong>R</strong>₃</td>
<td>Level reservoir</td>
<td>Water reservoir for the zero implantation level of the testing model</td>
</tr>
<tr>
<td><strong>V</strong>₁,₂...</td>
<td>Manual valves</td>
<td>Security and control for filling, spillway and operation of the test rig</td>
</tr>
</tbody>
</table>
Electrical circuit
Instrumentation

Electromagnetic flowmeter

Temperature transducer

Absolute pressure transducers

Optical tachymeters

Differential pressure transducers
## Instrumentation

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Measured/displayed quantity</th>
<th>Output signal</th>
<th>Range</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>Discharge</td>
<td>4..20 [mA]</td>
<td>0..50 [m³/h]</td>
<td>± 0.5 [%]</td>
</tr>
<tr>
<td>H</td>
<td>Head</td>
<td>4..20 [mA]</td>
<td>0..16 [bar]</td>
<td>± 0.1 [%]</td>
</tr>
<tr>
<td>H_s</td>
<td>Implantation level</td>
<td>4..20 [mA]</td>
<td>0..5 [bar]</td>
<td>± 0.2 [%]</td>
</tr>
<tr>
<td>M_1, 2, 3</td>
<td>Absolute static pressure</td>
<td>4..20 [mA]</td>
<td>0..10/20 [bar]</td>
<td>± 0.05 [%]</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>4..20 [mA]</td>
<td>0..100 [°C]</td>
<td>± 0.1 [%]</td>
</tr>
<tr>
<td>n_pump 1, 2, 3</td>
<td>Rotational speed</td>
<td>24 [V] pulse</td>
<td>0..1000 [Hz]</td>
<td>-</td>
</tr>
<tr>
<td>L_min, max, s</td>
<td>Min, max &amp; security levels</td>
<td>24 [V]</td>
<td>on/off</td>
<td>-</td>
</tr>
<tr>
<td>Man_1</td>
<td>Relative static pressure</td>
<td>-</td>
<td>0..16 [bar]</td>
<td>± 1 [%]</td>
</tr>
<tr>
<td>MV_1, 2, 3</td>
<td>Absolute static pressure</td>
<td>-</td>
<td>-1..9/15 [bar]</td>
<td>± 1 [%]</td>
</tr>
</tbody>
</table>

### Graphs

- **H** – differential pressure transducer
- **H_s** – differential pressure transducer
- **T** – temperature transducer
Security and control

Vacuum pump

Solenoid valves

Water level detectors
Multi-user control system architecture
Controller

NI CompactRIO 9074

- FPGA
  - Scan Engine

- CPU
  - Drivers, Controllers and communication.

NI Modules

<table>
<thead>
<tr>
<th>Module</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NI 9425</td>
<td>32 DI</td>
</tr>
<tr>
<td>NI 9477</td>
<td>32 DO</td>
</tr>
<tr>
<td>NI 9203</td>
<td>8 AI (current)</td>
</tr>
<tr>
<td>NI 9265</td>
<td>4 AO (current)</td>
</tr>
<tr>
<td>NI 9411</td>
<td>6 DI (CTR)</td>
</tr>
</tbody>
</table>

- Shared Variable Engine (SVE)
- Timed Loop (Scan Interface Synchronized)
- Low priority loop: Finite State Machines, communication and Network-Published-Shared-Variables hosting (database)
Controller

- Managed test rig I/O variables
Real-Time software structure

- Control and monitoring software: created with Labview®
- Real-time application: main sequences

1. Initialize
   - Initialize variables and arrays
   - Load default hardware setup values from the configuration file

2. Main Processing
   - High Priority Loop
     - Scan engine synchronized
     - Sample/updates channels at the scan engine rate
     - Single process shared variables with single-element RT FIFO enabled
   - Low Priority Loop
     - Communication (NPSV)
     - PIDs
     - Finite State Machines

3. Shutdown
   - Output channels to default values
   - Set variables to default values
Shared Variable Engine

- The networking implementation is handled entirely by the *network-published variables*:
  - cRIO-R : Monitoring (Read)
  - cRIO-W : Control (Write)

- Based on the NI Publish and Subscribe Protocol (NI-PSP)
  - a networking protocol optimized to be the transport for Network Shared Variables

- Running in the cRIO 9074
Shared Variable Engine and value changes

CLIENT

SERVER (Publisher)
- SVE running on cRIO controller
- NPSV cRIO-R is updated every 100ms aprox.
- Interpret NPSV cRIO-W

MAIN PROCESSING
READ: cRIO-R & cRIO-W
- Time out
- cRIO-W == cRIO-W-aux?
  - No
  - Yes
- Quit ?

SHUT DOWN
- cRIO-W.MasterClient = free
- End
1. *Variable 1* is deployed to the CPU where SVE service hosts it

2. Client writes a Value to *Variable 1*

3. Value change is sent to SVE where *Variable 1* is hosted using NI-PSP protocol.

4. SVE records the value change and publishes the new value to all subscribers

5. Value change is sent to all subscribers using NI-PSP

6. Value change is received and read

The SVE *client* is part of the internal implementation of the variable reference
Shared Variable Engine RT implementation

- Reduced Network traffic

Low priority loop used for local logging

Single-process variable since it is a more efficient transfer route to the low priority loop

High priority loop acquiring and writing data to physical channels
Finite-state machine

- Ensures secured regulation for:
  - Automatic filling of the main reservoir
  - Pressure level in the pressurized tank
  - Water temperature in the closed-loop hydraulic circuit
Finite-state machine

- Conditions and states

Pressure level

Reservoir filling

Water cooling
PID driver

- Parallel multi-loop / parameter control: pumps speed, discharge and head
- Manual mode
- Bump-less manual-to-automatic transitions
- Non-linear integral action
- Two degree-of-freedom control
- Error-squared control

PID algorithm
PID tuning: Ziegler-Nichols Method

- It tests the open-loop reaction of the process to a change in the control variable output.

- Open-loop step test:

\[ K_0 = \frac{X_0 \tau}{M_u \tau_d} \]

- Determine the dead time, \( \tau_d \), the time constant, \( \tau \), and the ultimate value that the response reaches at steady-state, \( M_u \), for \( X_0 \) step change.
PID tuning: Ziegler-Nichols Method

- **Advantages**
  - Widely accepted
  - Robust
  - Quick-to-implement and less disruptive method

- **Drawbacks**
  - $I$ and $D$ depends purely on proportional measurements
  - Approximations for $K_c$, $T_i$ and $T_d$ - must be validated experimentally
  - Not suitable for $I$, $D$ and PI controllers

<table>
<thead>
<tr>
<th>Fast</th>
<th>$K_c$</th>
<th>$T_i$</th>
<th>$T_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>$\frac{\tau}{\tau_d}$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$I$</td>
<td>$0.9 \frac{\tau}{\tau_d}$</td>
<td>$3.33 \tau_d$</td>
<td>–</td>
</tr>
<tr>
<td>$D$</td>
<td>$1.1 \frac{\tau}{\tau_d}$</td>
<td>$2 \tau_d$</td>
<td>$0.5 \tau_d$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normal</th>
<th>$K_c$</th>
<th>$T_i$</th>
<th>$T_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>$0.44 \frac{\tau}{\tau_d}$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$I$</td>
<td>$0.4 \frac{\tau}{\tau_d}$</td>
<td>$5.33 \tau_d$</td>
<td>–</td>
</tr>
<tr>
<td>$D$</td>
<td>$0.53 \frac{\tau}{\tau_d}$</td>
<td>$4 \tau_d$</td>
<td>$0.8 \tau_d$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Slow</th>
<th>$K_c$</th>
<th>$T_i$</th>
<th>$T_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>$0.26 \frac{\tau}{\tau_d}$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$I$</td>
<td>$0.24 \frac{\tau}{\tau_d}$</td>
<td>$5.33 \tau_d$</td>
<td>–</td>
</tr>
<tr>
<td>$D$</td>
<td>$0.32 \frac{\tau}{\tau_d}$</td>
<td>$4 \tau_d$</td>
<td>$0.8 \tau_d$</td>
</tr>
</tbody>
</table>
Testing model (μTurbomachine)

- **NI Modules**
  - **NI 9203**: 8-Ch ±20 mA, 200 kS/s, 16-Bit Analog Current Input Module
  - **NI 9205**: 32-Ch ±200 mV to ±10 V, 16-Bit, 250 kS/s Analog Input Module
  - **NI 9263**: 4-Channel, 100 kS/s, 16-bit, ±10 V Analog Output Module

**I/O MODULES** — **PC Control & Communication**
Human-Machine Interfaces: μPower

1. Initialize
- Connect to the Shared Variables Engine
- Initialize variables and arrays
- Load default software and hardware setup from the configuration file
- 2D and 3D graphs

2. Main Processing
- Event Structure
- Control and monitoring of the μTurbomachine

3. Shutdown
- Close connections to shared variables
- Set variables to default values
- Output channels to default values
- Save setup file
Human-Machine Interfaces: \( \mu \)Power
Example: counter-rotating microturbine

- Rotational speed of runners controlled independently
- Fully instrumented laboratory prototype
Example: counter-rotating microturbine

- Measured 2D and 3D hill-charts at constant test head

- Regulation: \[ \alpha = \frac{\omega_A}{\omega_B} \] [–]
Example: pump-as-turbine

- 5-stage centrifugal pump (11 kW)
Conclusions

• New universal hydraulic test rig for small-power turbomachines designed, executed and assembled at the HES-SO VS

• The instrumentation follows the IEC 60193 standard recommendations

• State-of-the-art approach of an automatic regulation for test rigs has been introduced

• Equipped with an autonomous regulation system based on real-time measurements

• Wireless communication architecture and dedicated cloud of variables allows for safe data sharing, centralization and storage on model testing
Ongoing work

• Measurement precision improvement – avoid undesirable noise

• Integration of an automatic measurement interface

• Integration of an additional dynamic acquisition system or either of a high-speed visualization system for advanced hydrodynamic analysis

• Implementation of a dynamic measurement method of the testing model characteristics – e.g. the sliding gate method
References

  Design and control of a new hydraulic test rig for small-power 
  turbomachines. 

  Hydraulic turbines, storage pumps and pump-turbines – Model 
  acceptance tests. 

  Numerical simulations of a counter rotating micro turbine. 
  Advances in Hydroinformatics, P. Gourbesville et al. (eds.), Springer 
  Hydrogeology.
Acknowledgments

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