Georgia Institute of Technology | Marquette University | Milwaukee School of Engineering | North Carolina A&T State University | Purdue University | University of California, Merced | University of Illinois, Urbana-Champaign | University of Minnesota | Vanderbilt University

Control and Diagnostic of Electro-Hydraulic Machines

Project PI & presenter

Dr. Andrea Vacca

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CCEFP Summit at the University of Kentucky
March 7-9, 2018

Outline

- Project rationale and goals
- Reference machine
- Past accomplishments within 16MO2 (diagnostics)
- Research approach for prognostics
- Conclusions and future works

possible applications

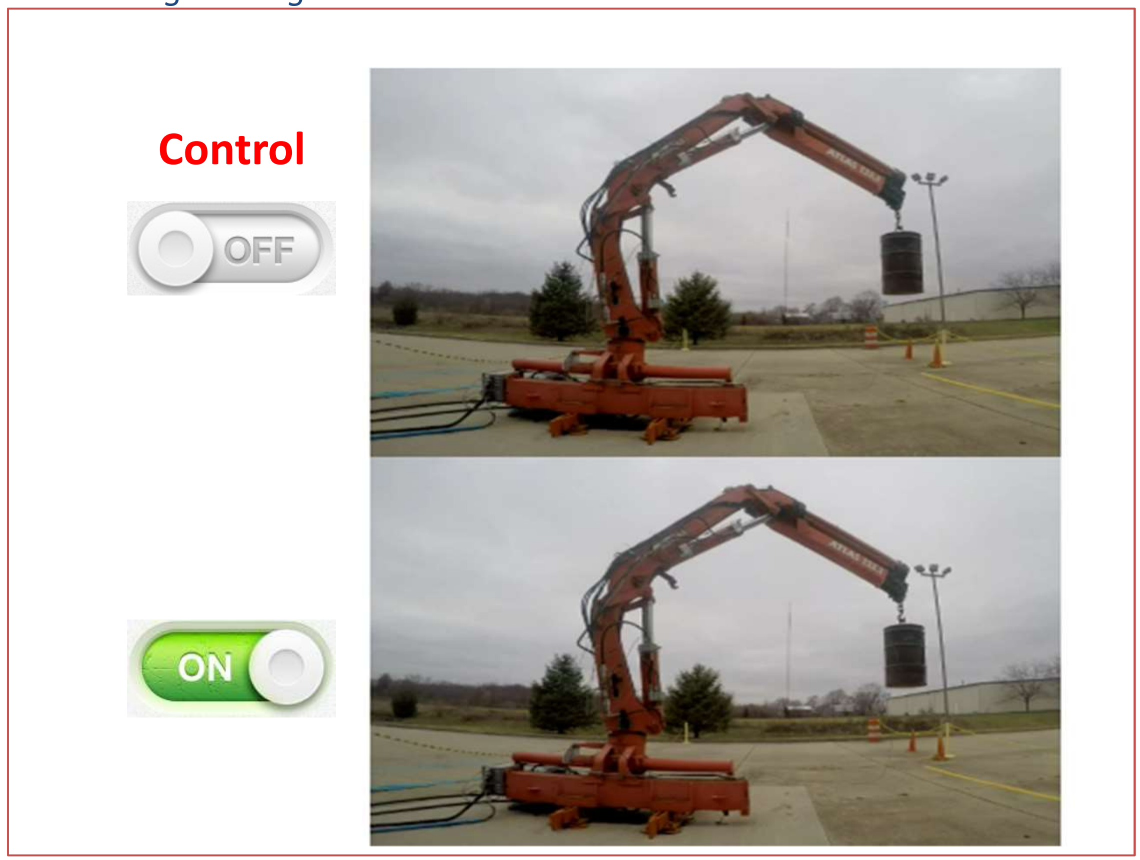





Project rationale

Electro-Hydraulics (EH)
a well established technology

2017 Bianchi R., Ritelli G. F., Vacca A. “**Payload oscillation reduction in load-handling machines: A frequency-based approach**” *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*

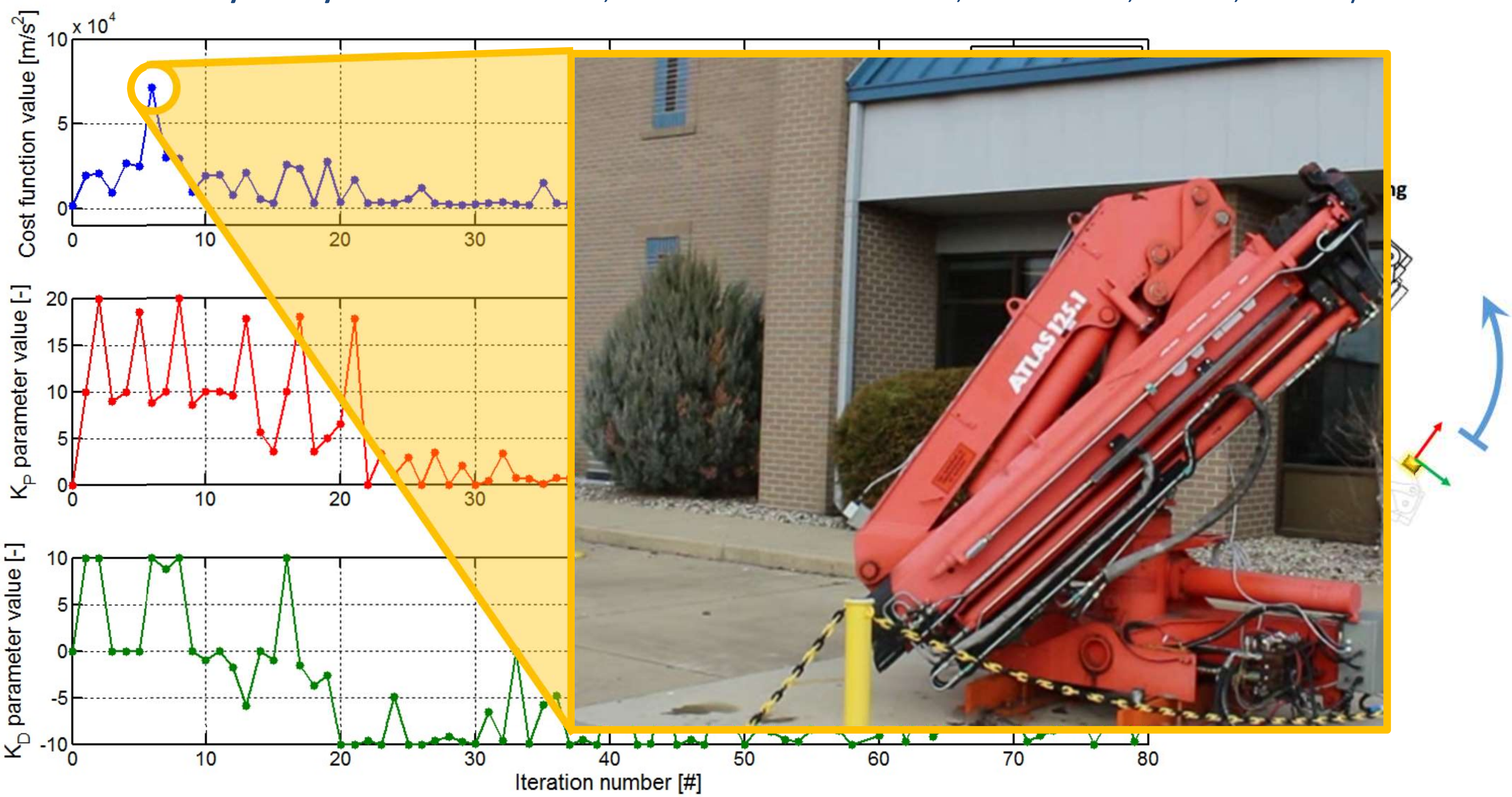


EH has enabled advanced control techniques

Limited research effort for combining EH control with Prognostics and Health Management (PHM)

Project rationale

Ritelli, G.F., Vacca, A. 2014, "**Experimental-Auto-Tuning Method for Active Vibration Damping Controller. The Case Study of a Hydraulic Crane**" 9th IFK, Int. Fluid Power Conference, March 24-26, Aachen, Germany



Project rationale

Electro-Hydraulics (EH)
a well established technology

EH has enabled advanced control techniques

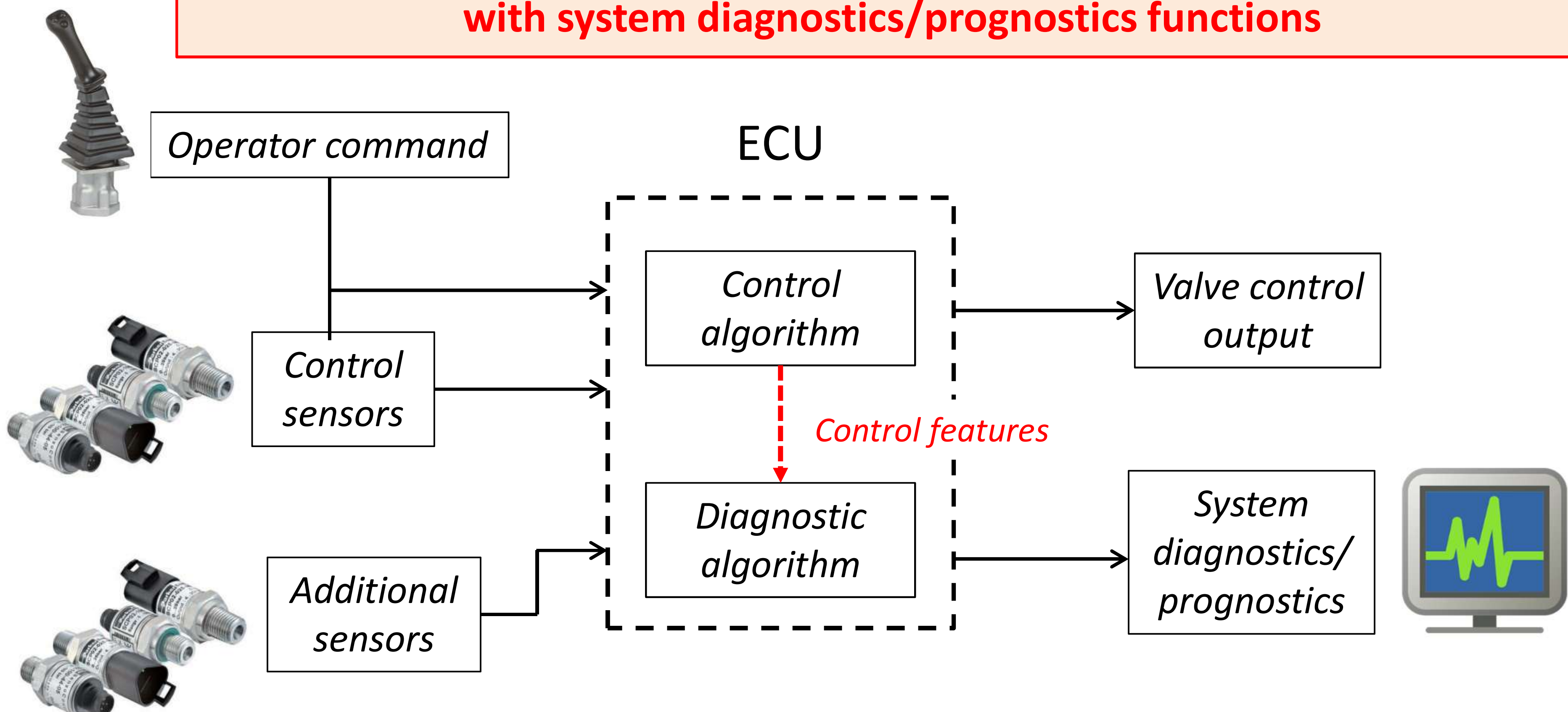
Limited research effort for combining EH control with Prognostics and Health Management (PHM)

Combine Control and PHM

→ machine maintenance downtime costs reduction

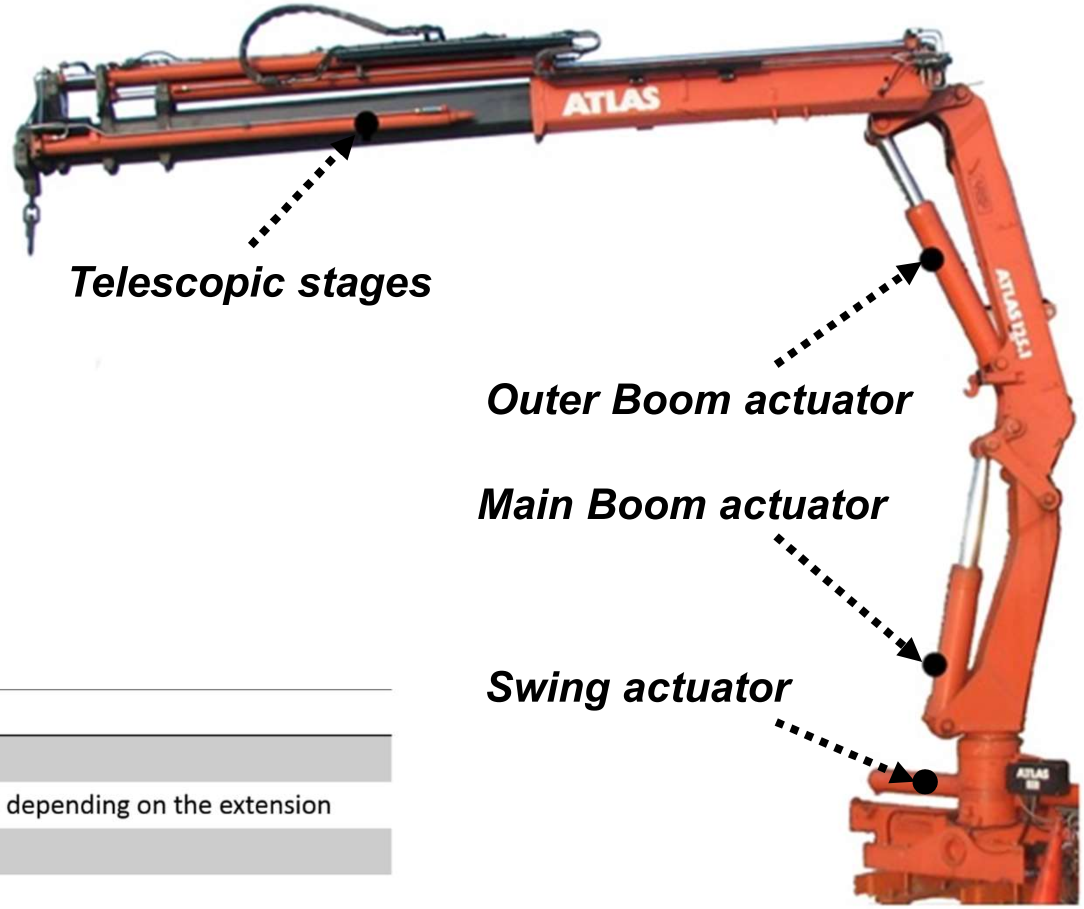
Project goal

..to formulate a control approach for load handling hydraulic machines that combines advanced control features (such as oscillation damping features) with system diagnostics/prognostics functions



PHM: Prognostics and Health Management

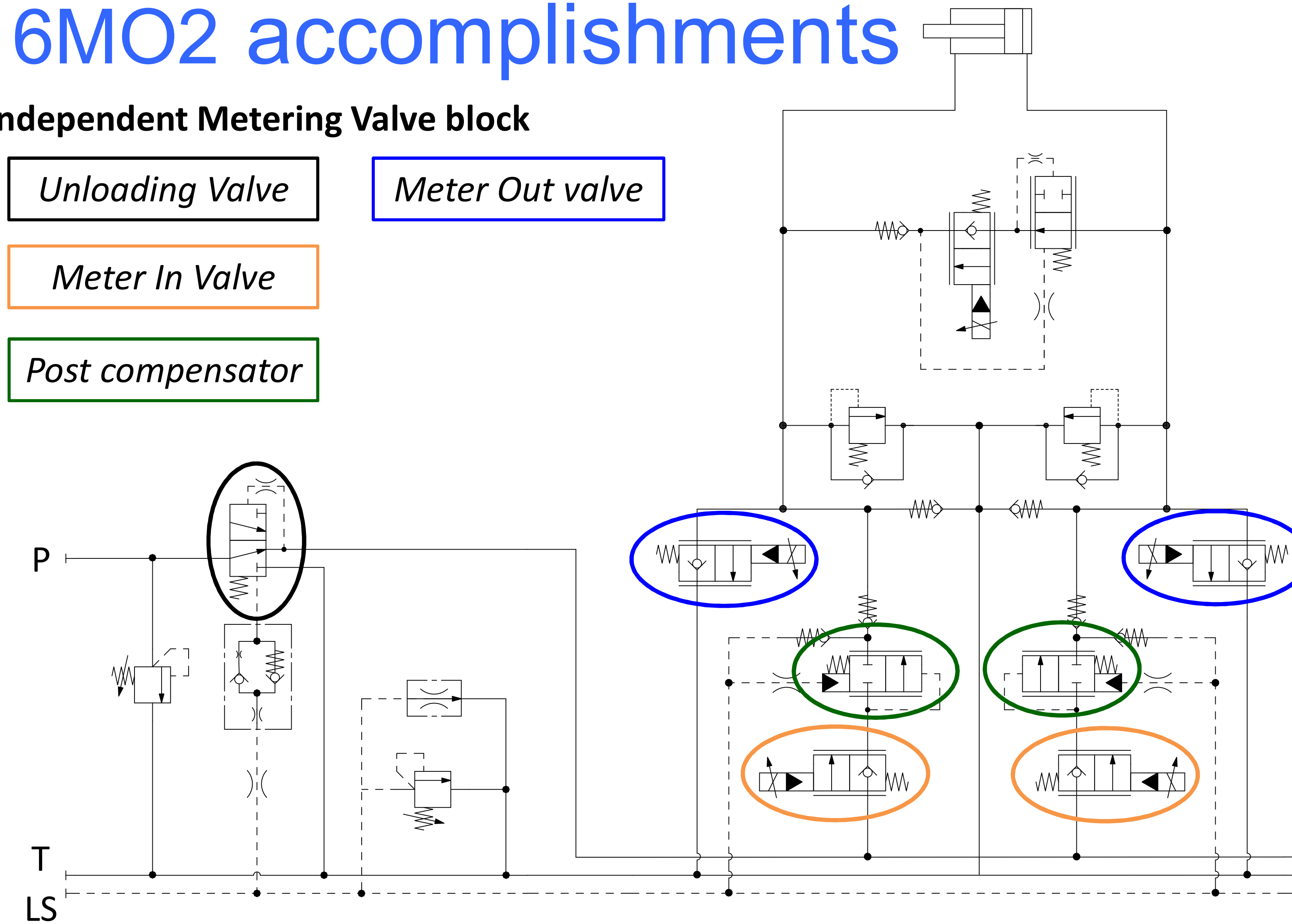
Reference Machine



Atlas 125.1 A4	
Weight	1740 [kg]
Load capability	5÷0.51 [t] depending on the extension
Slewing range	410°
Max operating pressure	270 [bar]
Number of extensions	4
Hydraulic Range	12.3 [m]
Mechanical Range	16.1 [m]

16MO2 accomplishments

Independent Metering Valve block

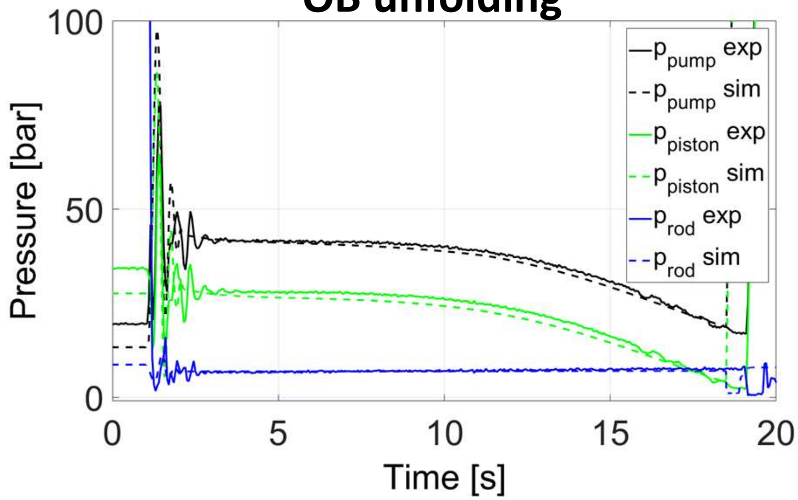


16MO2 accomplishments

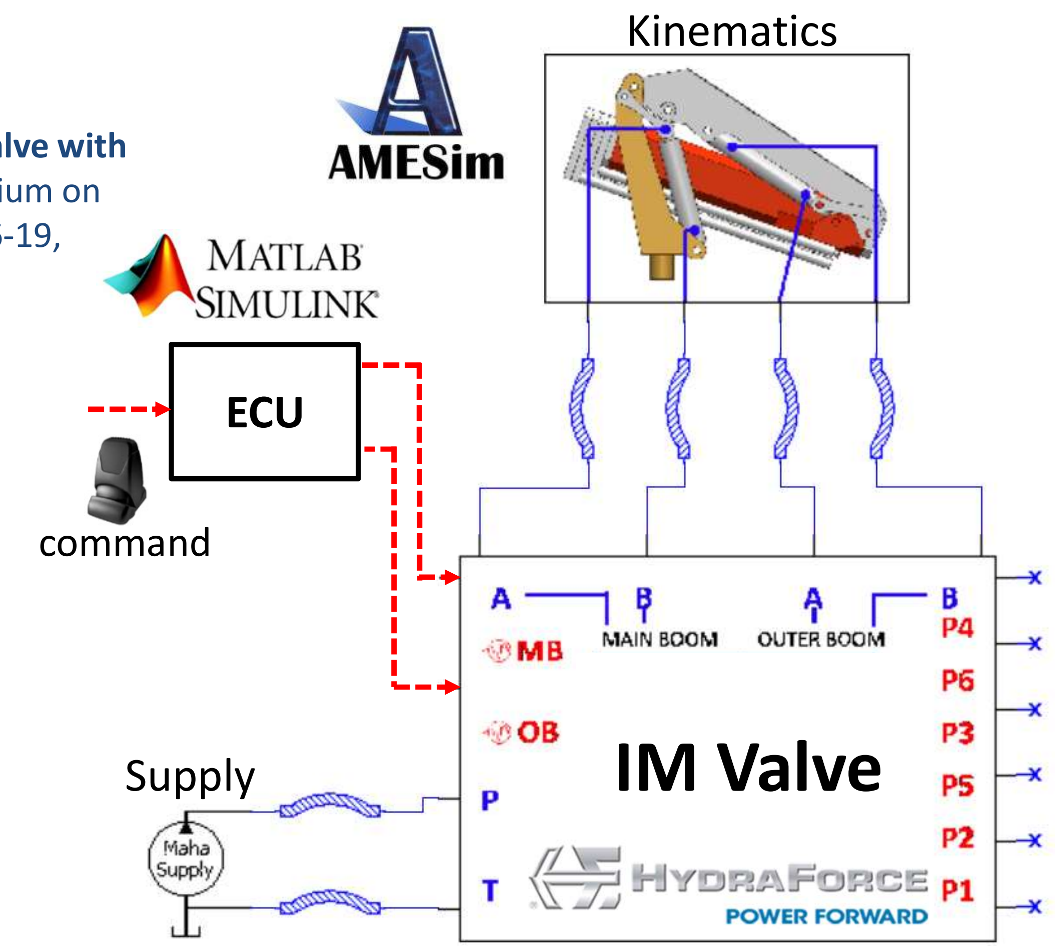
Fluid Power Innovation & Research Conference
October 10th - 12th 2016

Campanini, F., Bianchi, R., Vacca, A., Casoli, P., 2017, "**Optimized Control for an Independent Metering Valve with Integrated Diagnostic Features**" ASME/Bath Symposium on Fluid Power and Motion Control, FPMC 2017, Oct. 16-19, 2017, Sarasota, FL, USA

OB unfolding



Crane numerical model



16MO2 accomplishments

Fluid Power Innovation & Research Conference
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CCEFP Industry – University Summit, April 4th - 6th 2017

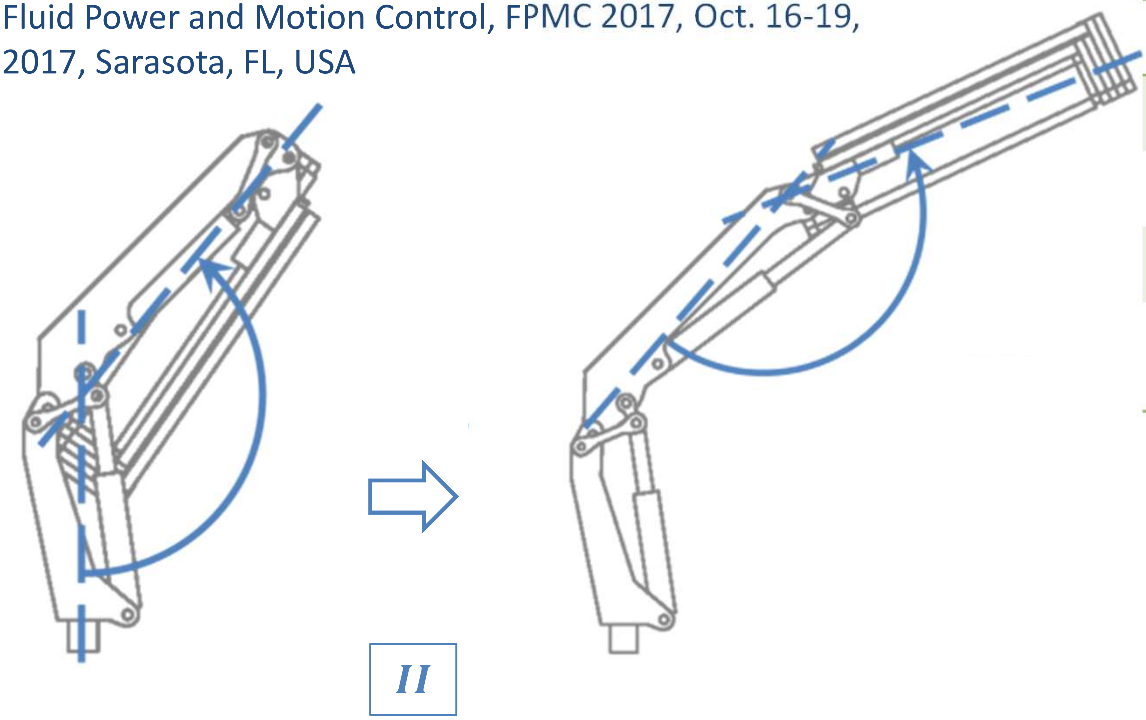
Campanini, F., Bianchi, R., Vacca, A., Casoli, P., 2017, "**Optimized Control for an Independent Metering Valve with Integrated Diagnostic Features**" ASME/Bath Symposium on Fluid Power and Motion Control, FPMC 2017, Oct. 16-19, 2017, Sarasota, FL, USA

Independent Metering controller

- Velocity control through the meter-in valve
- Pressure control through the meter-out valve
- Tunable PI control to minimize steady state error and plant uncertainities uncertainties

16MO2 accomplishments

Campanini, F., Bianchi, R., Vacca, A., Casoli, P., 2017, "**Optimized Control for an Independent Metering Valve with Integrated Diagnostic Features**" ASME/Bath Symposium on Fluid Power and Motion Control, FPMC 2017, Oct. 16-19, 2017, Sarasota, FL, USA



Outer boom extension

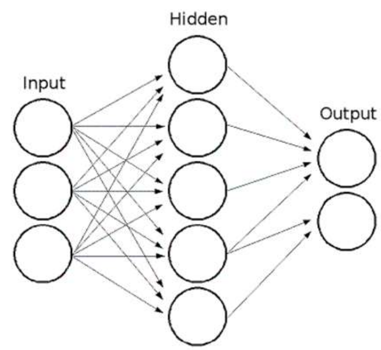
Correlation between controller cost functions and faults

	Healthy	Faulty
Volumetric efficiency	0.95	0.65
Meter-in friction	1	20
Cylinder friction	1000	7500
Unloading valve friction	1	20

16MO2 accomplishments

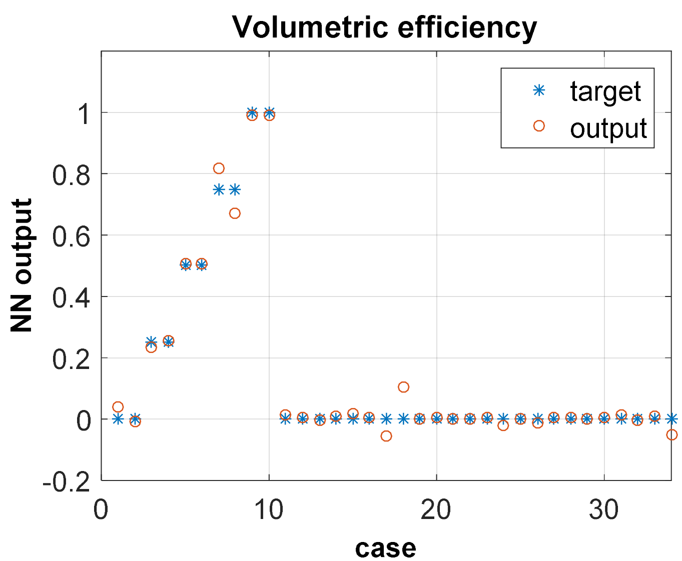
CCEFP Industry – University Summit
April 4th - 6th 2017

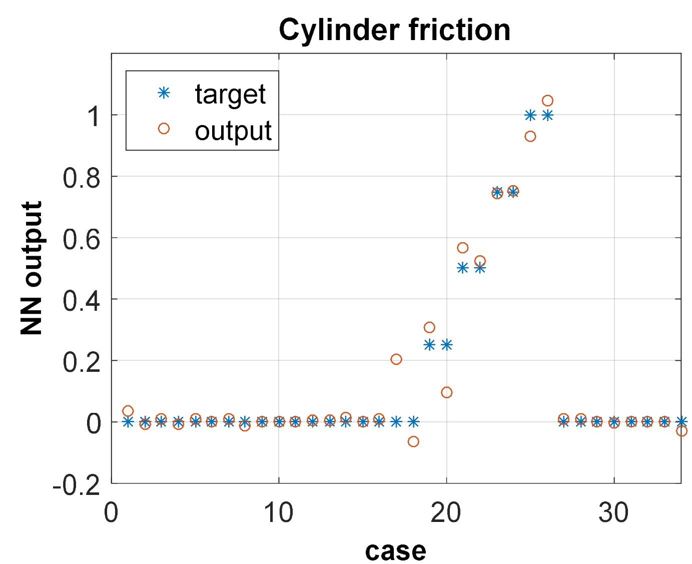
CCEFP Webinar
November 15th 2017



Diagnostic algorithm

- Selection of a data-driven approach (NN)
- Fault selection (pump, 2 valves, cylinder)
- Cost functions definition
- Progressive reduction of the number of sensors, 4 pressure sensors currently used





16MO2 accomplishments

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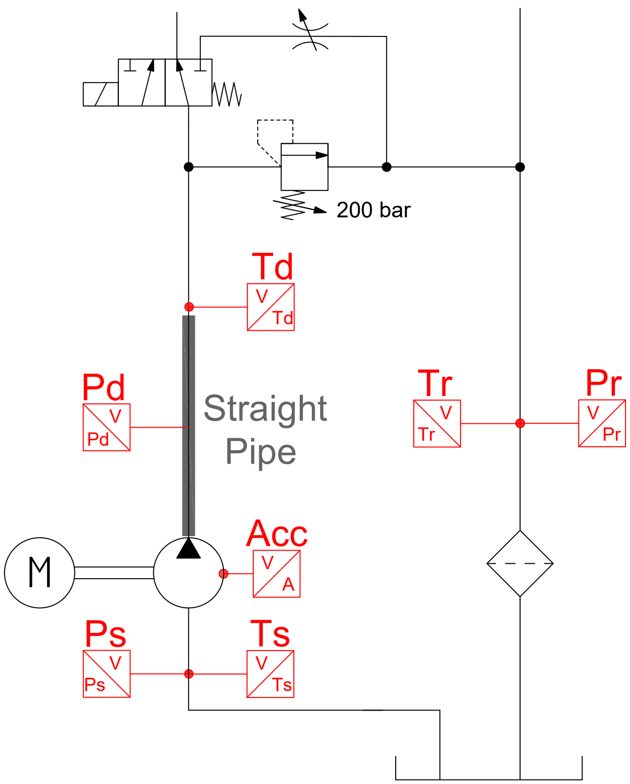
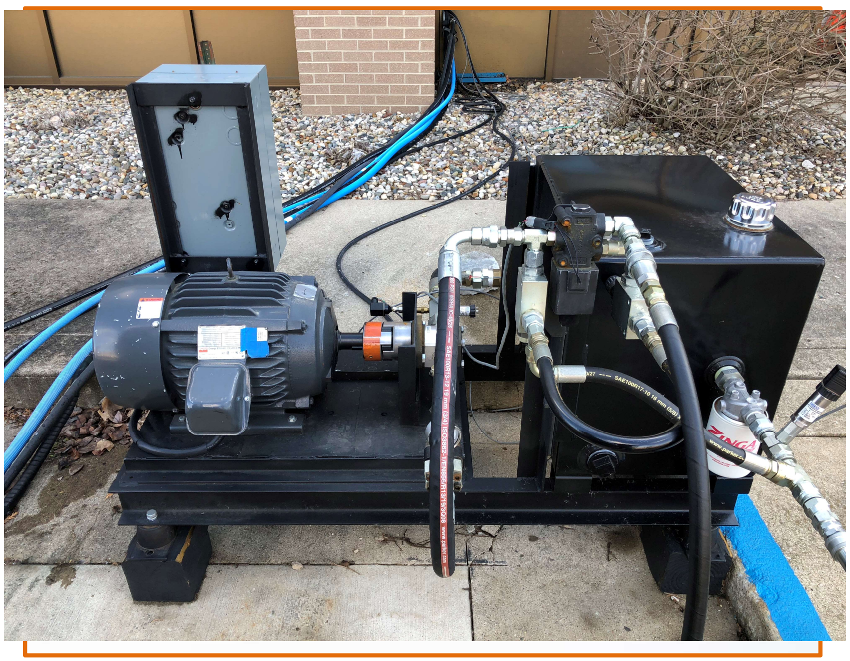


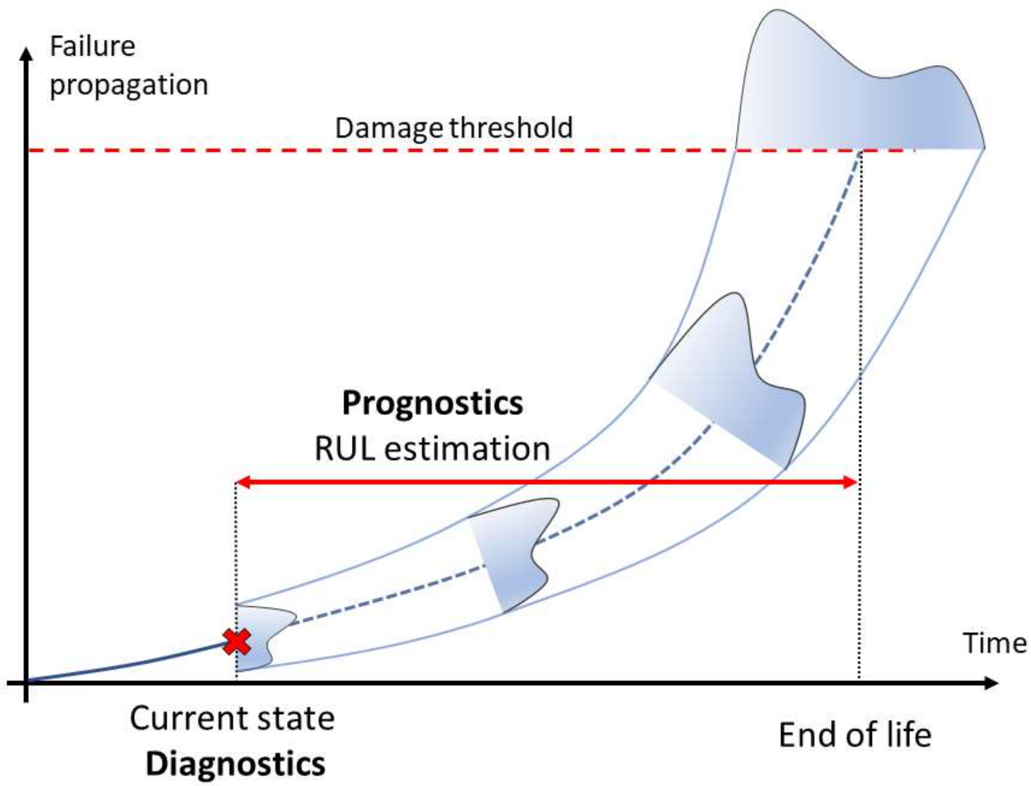
Experimental validation

- Dedicated experimental set up
- Reproduction of faults



Prognostics

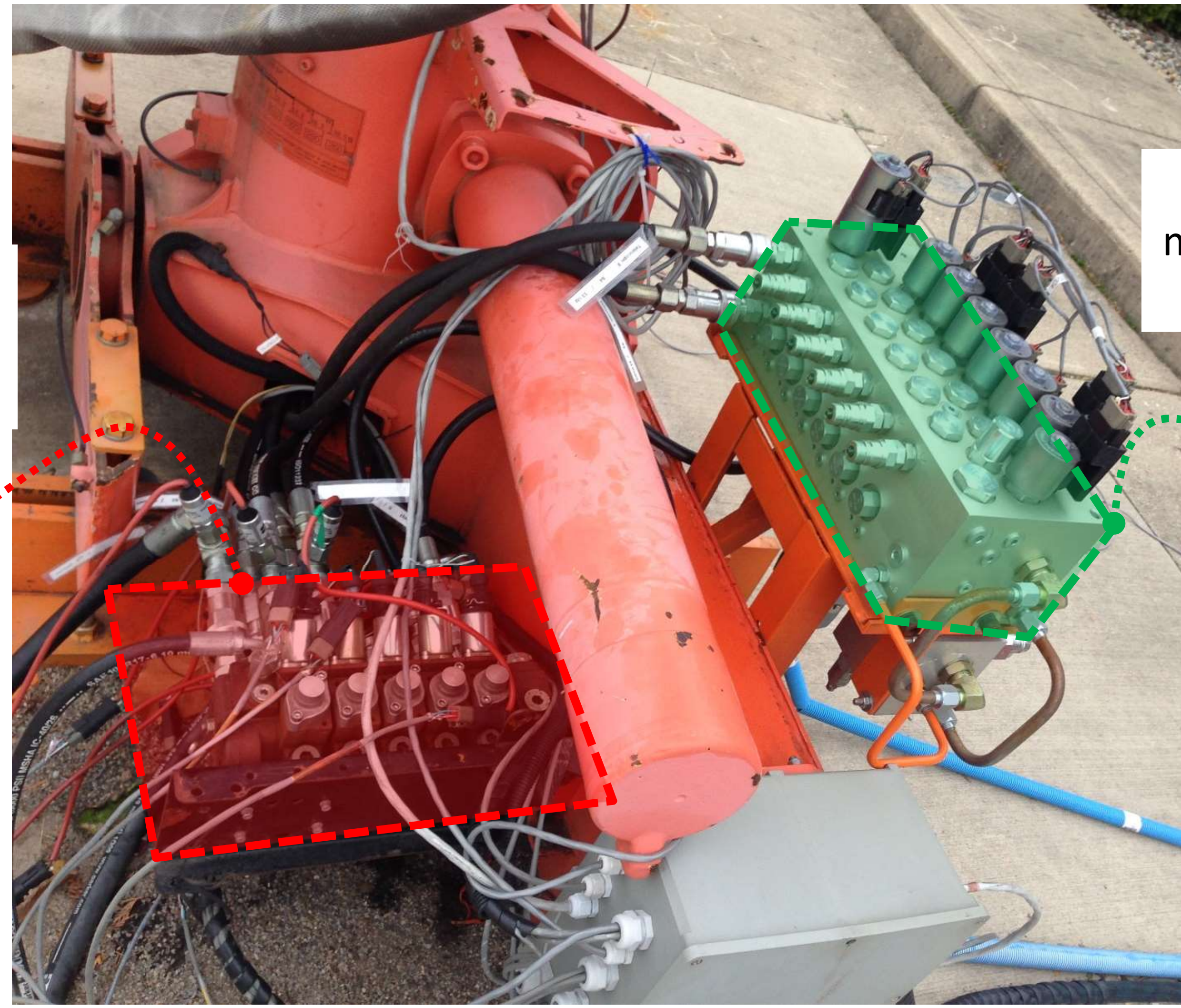
PROGNOSTICS
vs
DIAGNOSTICS



DEFINITION OF A PROGNOSTIC ALGORITHM WITH THE CAPABILITY OF ESTIMATING THE REMAINING USEFUL LIFE (RUL) OF THE HYDRAULIC COMPONENTS

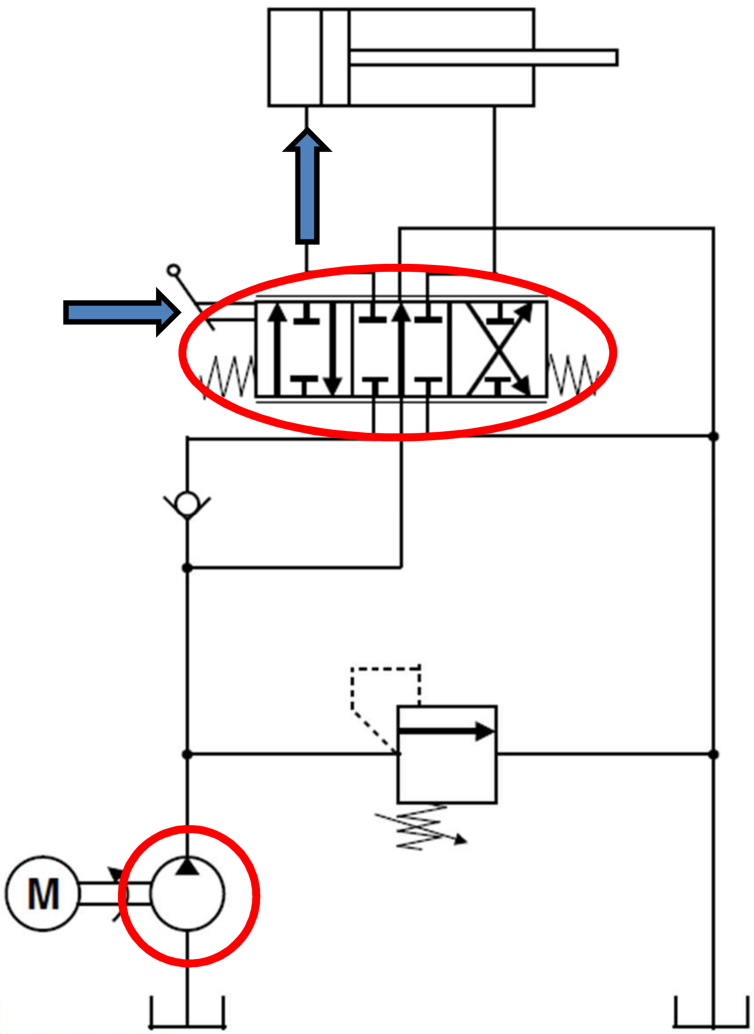
Prognostics

Open center control valve block



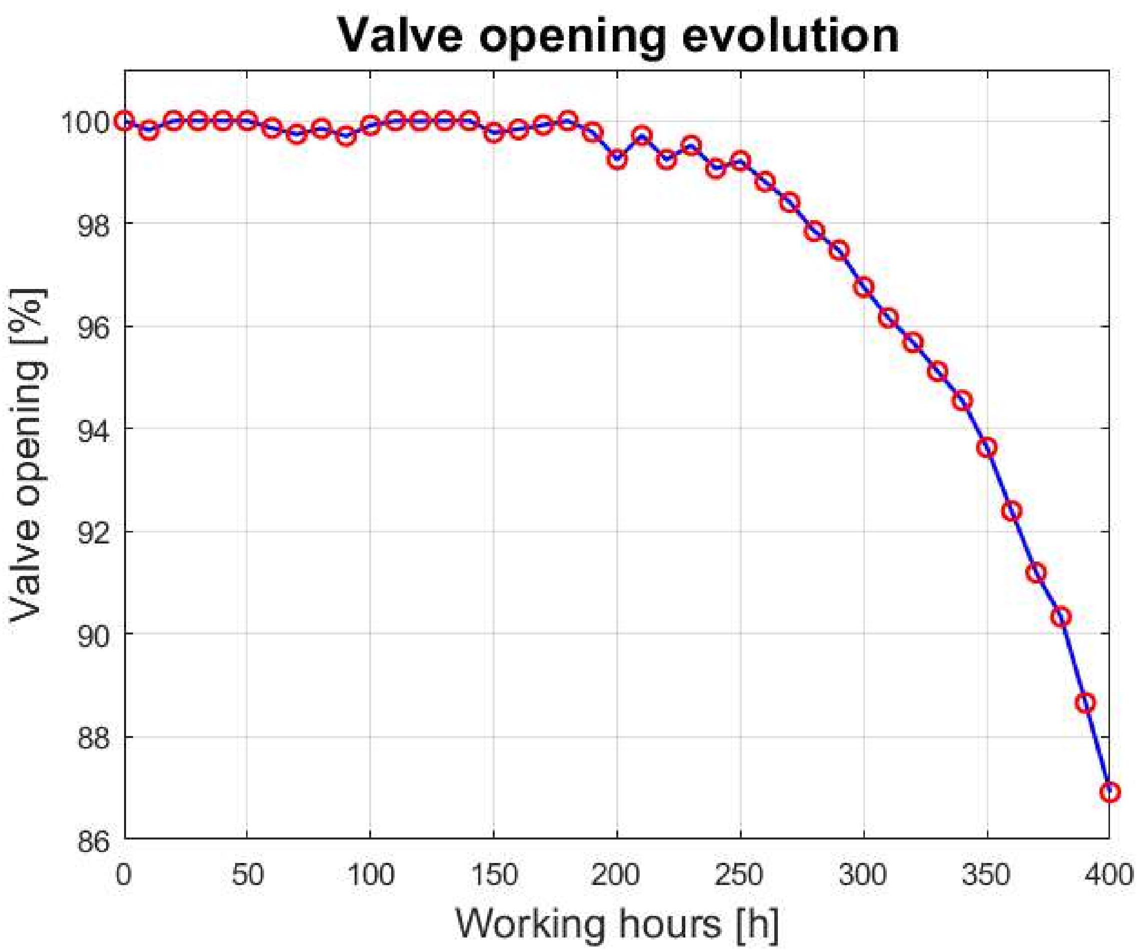
Independent metering control valve block

Prognostics



1. *SIMPLIFIED HYDRAULIC SCHEMATIC*
   - FIXED DISPLACEMENT PUMP
   - OPEN CENTER DIRECTIONAL VALVE
   - CYLINDER ACTUATOR
2. *FAULT INJECTION*
   - PUMP EFFICIENCY
   - VALVE SPOOL BLOCKAGE
3. *SIMULATION AND DATA ACQUISITION*
   - FLOW AT CYLINDER INPUT
   - VALVE INPUT CURRENT
4. *REMAINING USEFUL LIFE ESTIMATION*

Prognostics



- Weibull hazard function shape
- Several run-to-failure simulation
- Various working temperature as factor of influence:
  - 10 °C
  - 20 °C
  - 30 °C
  - 40 °C
  - 50 °C

Prognostics

OFF-LINE PHASE

F_i : Flow at current time

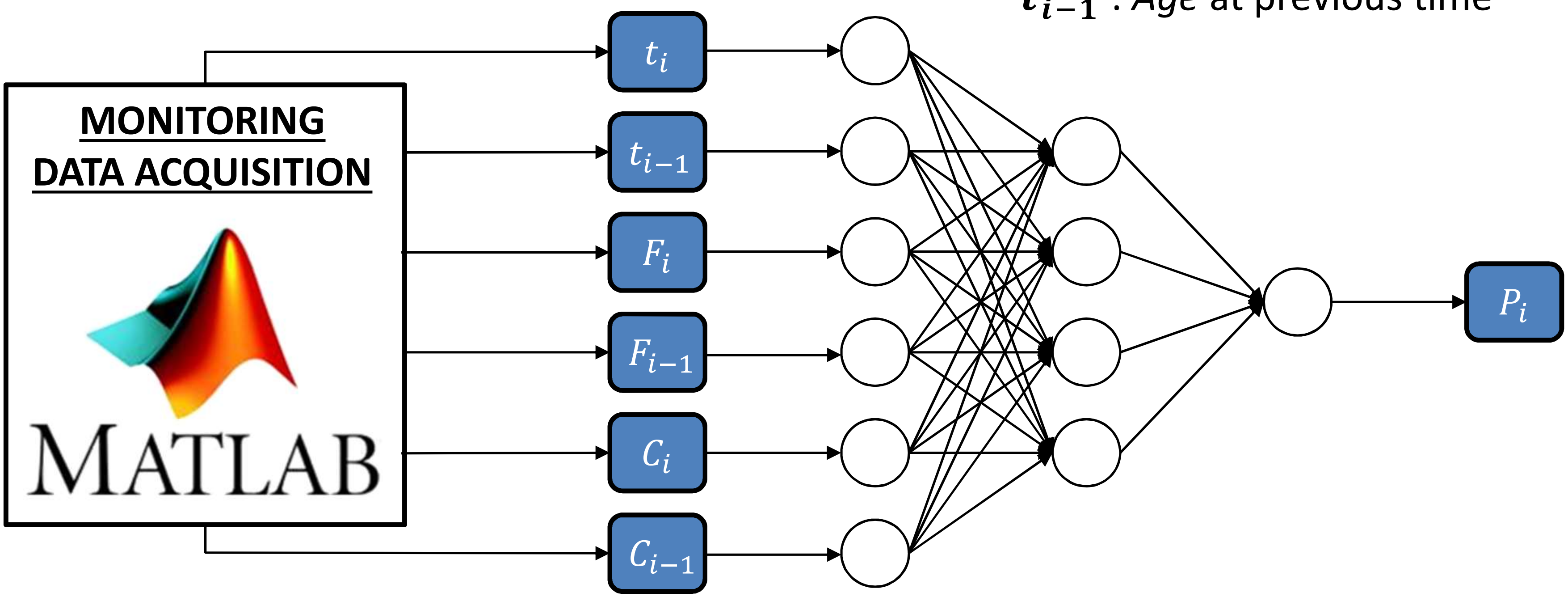
F_{i-1}: Flow at previous time

C_i : Starting input at current time

C_{i-1}: Starting input at previous time

t_i : *Age* at current time

t_{i-1} : *Age* at previous time



Prognostics

P_i: Life percentage at current working time

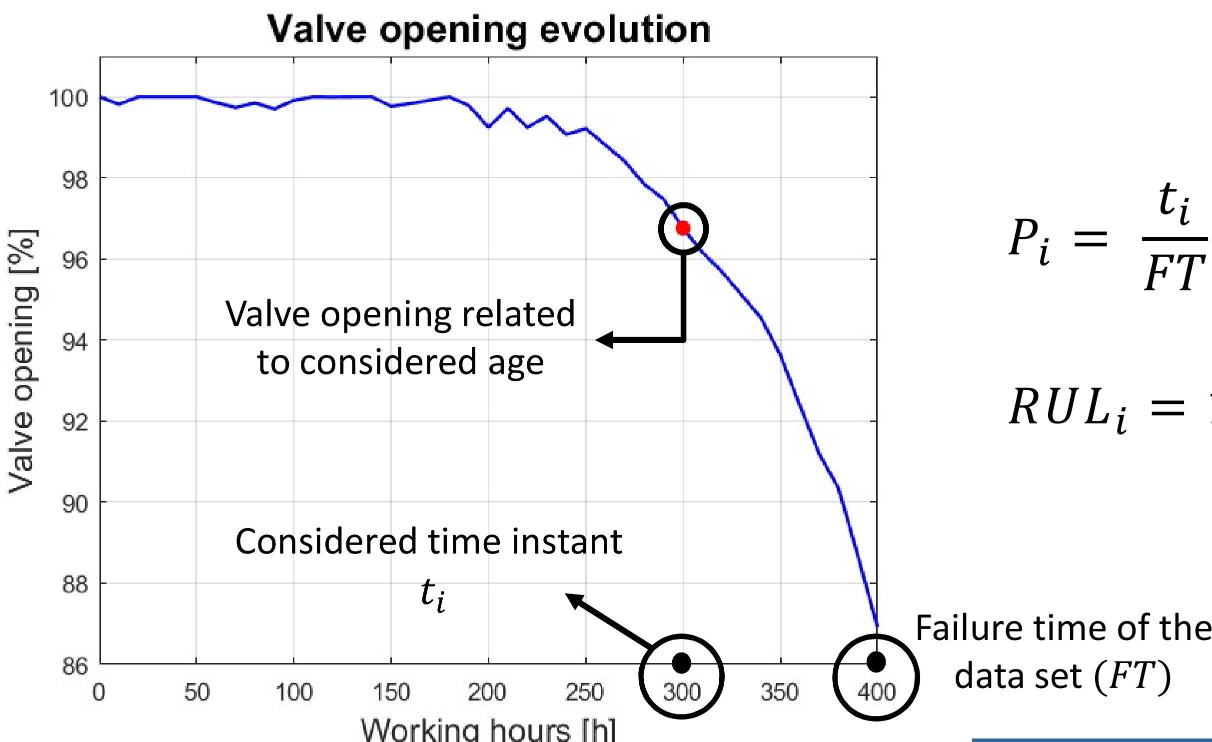
$$P_i = \frac{t_i}{FT} \cdot 100\ [\%]$$

where

t_i: considered monitoring time

FT: Failure time of the data set

RUL_i: Remaining useful life



$$P_i = \frac{t_i}{FT} \cdot 100 = \frac{300}{400} \cdot 100 = 75\ \%$$

$$RUL_i = 100 - P_i = 100 - 75 = 25\ \%$$

Prognostics

$\boldsymbol{P_i}$: Life percentage at current working time

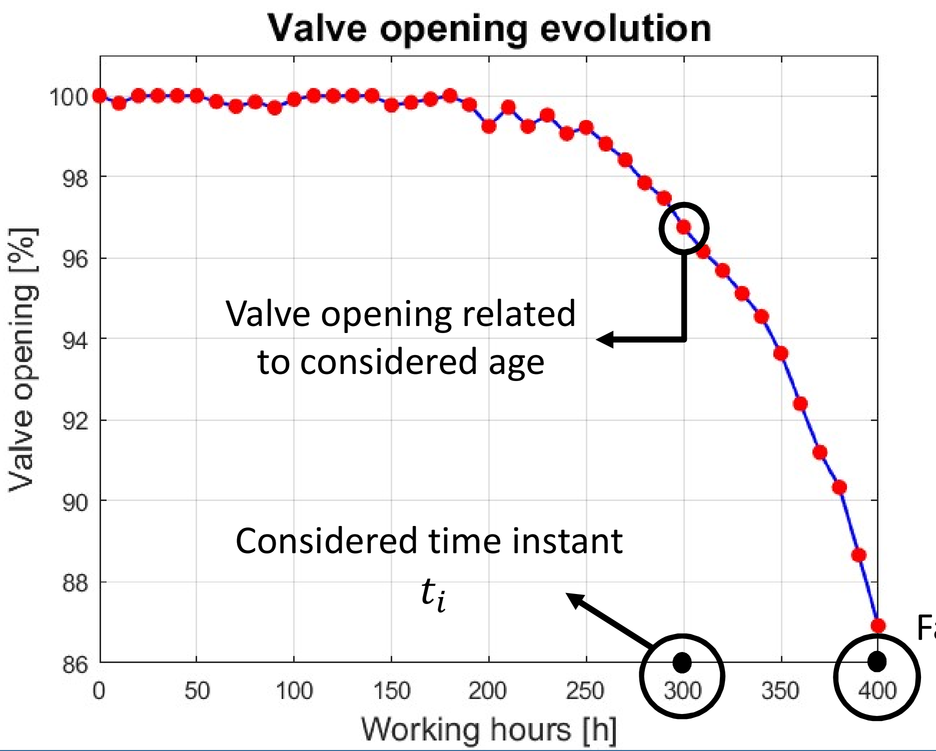
$$P_i = \frac{t_i}{FT} \cdot 100\ [\%]$$

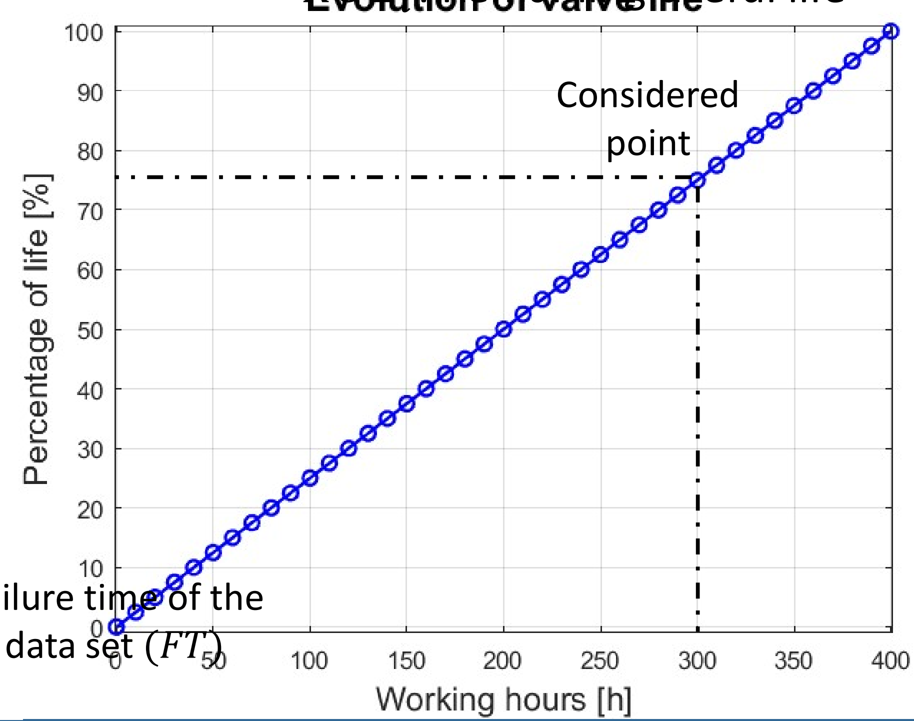
where

t_i: considered monitoring time

FT: Failure time of the data set

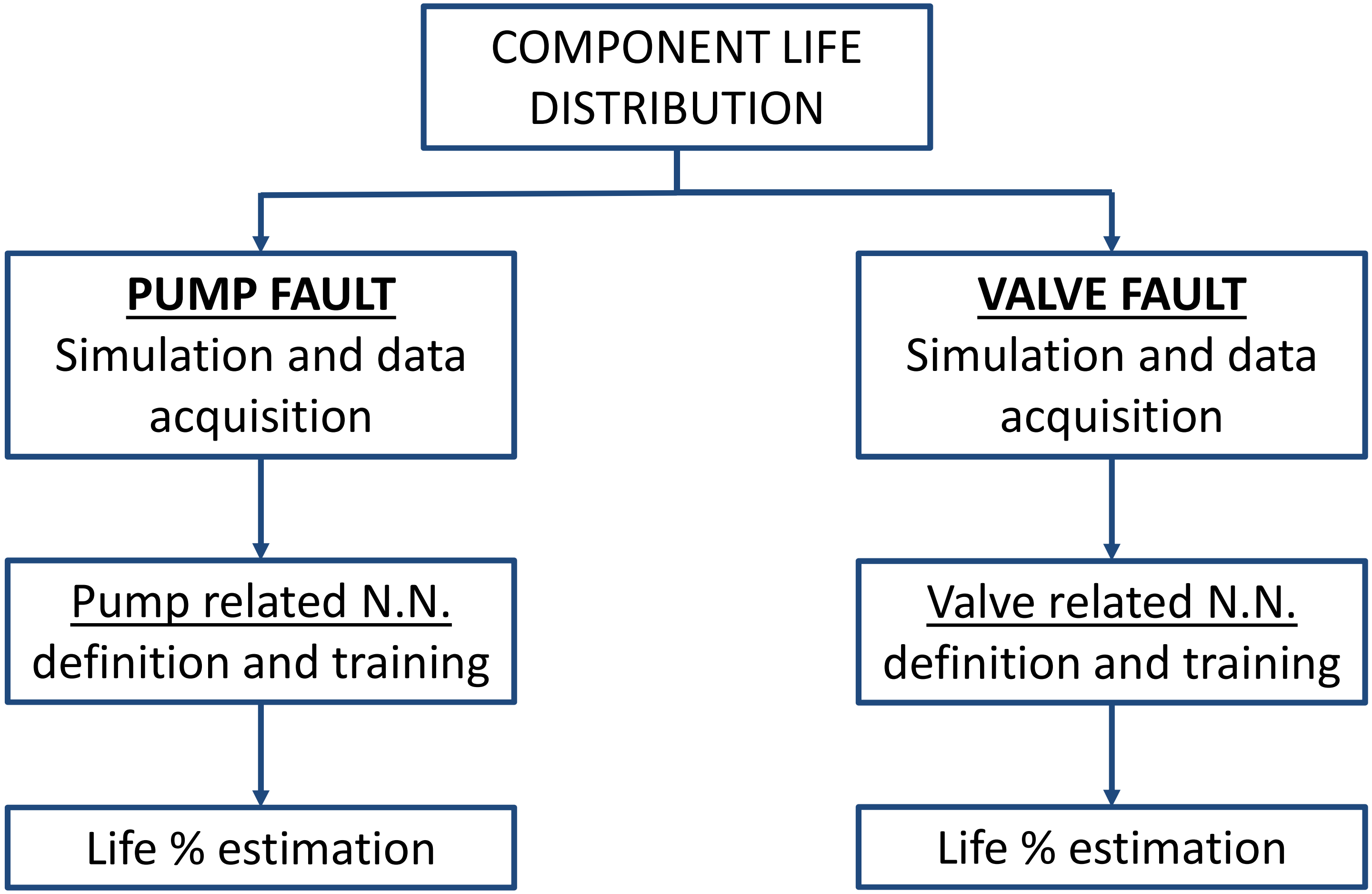
RUL_i: Remaining useful life





Prognostics

ISOLATED FAULT ANALYSIS

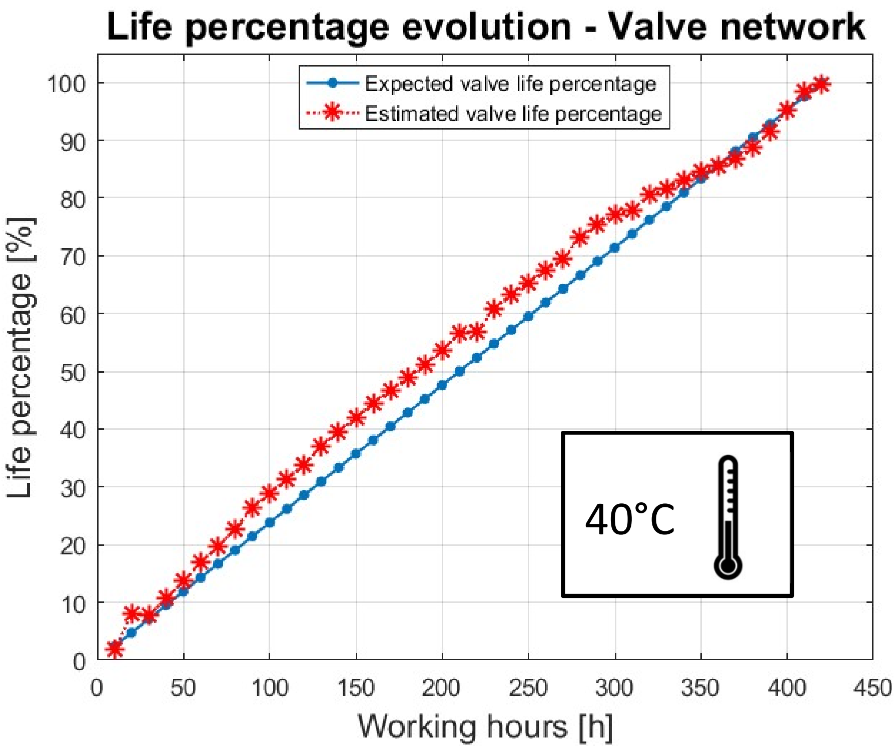


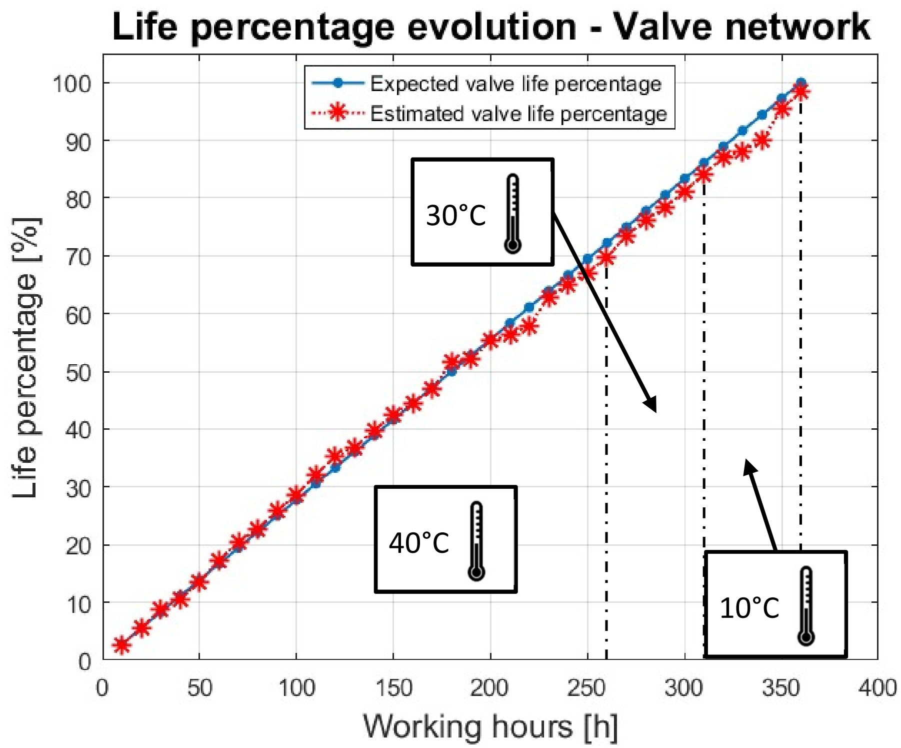
Maha Fluid Power RESEARCH CENTER · PURDUE UNIVERSITY

CENTER FOR COMPACT AND EFFICIENT FLUID POWER
A National Science Foundation Engineering Research Center

Prognostics

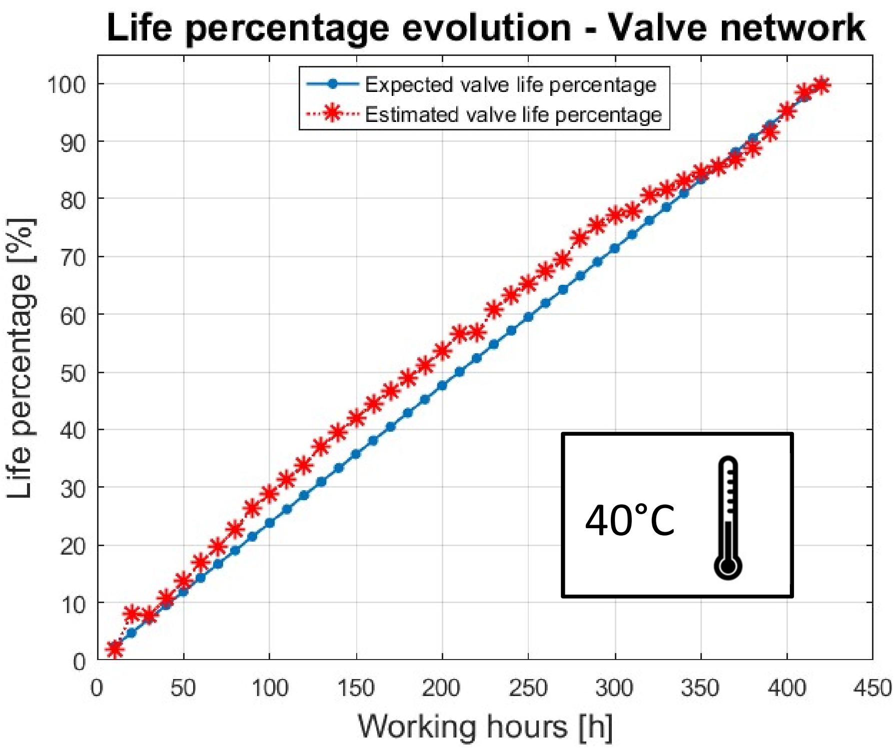
ISOLATED FAULT RESULTS
VALVE





Prognostics

ISOLATED FAULT RESULTS VALVE

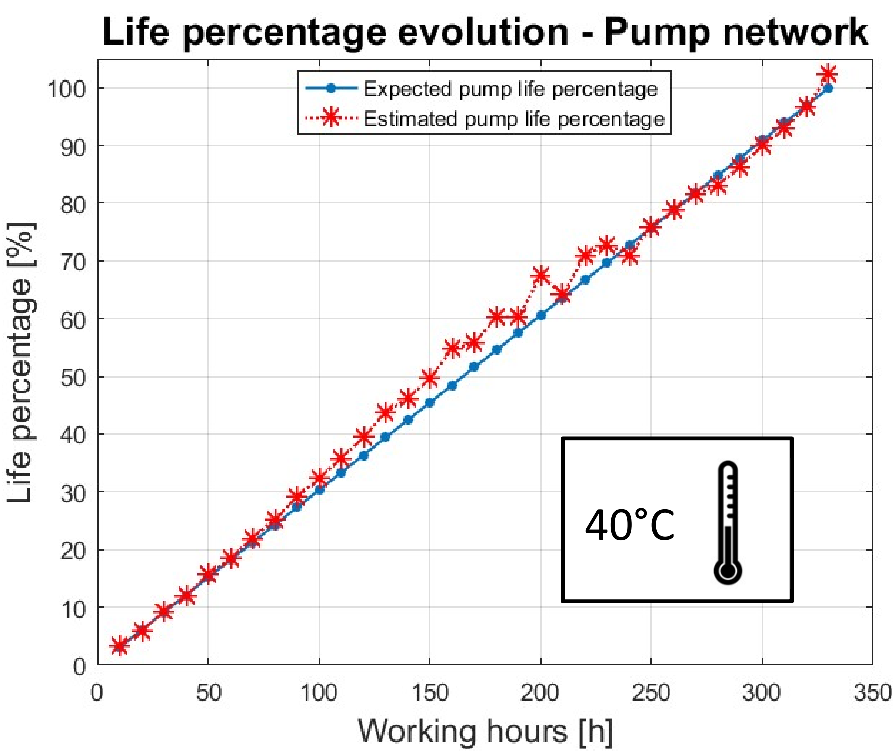


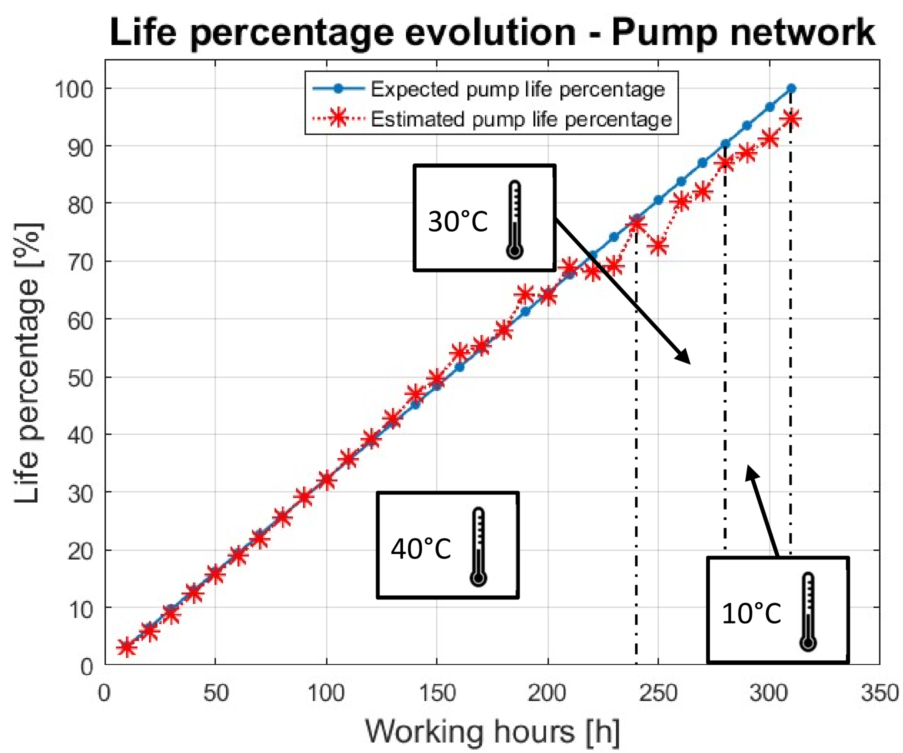
$$\text{RMS} = \sqrt{\frac{\sum_{i=1}^{n}(Y_{net}(i)-Y_{act}(i))^2}{n}} = 3.9779$$

$$E_{\%} = 100\,\frac{|Y_{net} - Y_{act}|}{Y_{act}} \Rightarrow 4\ \%$$

Prognostics

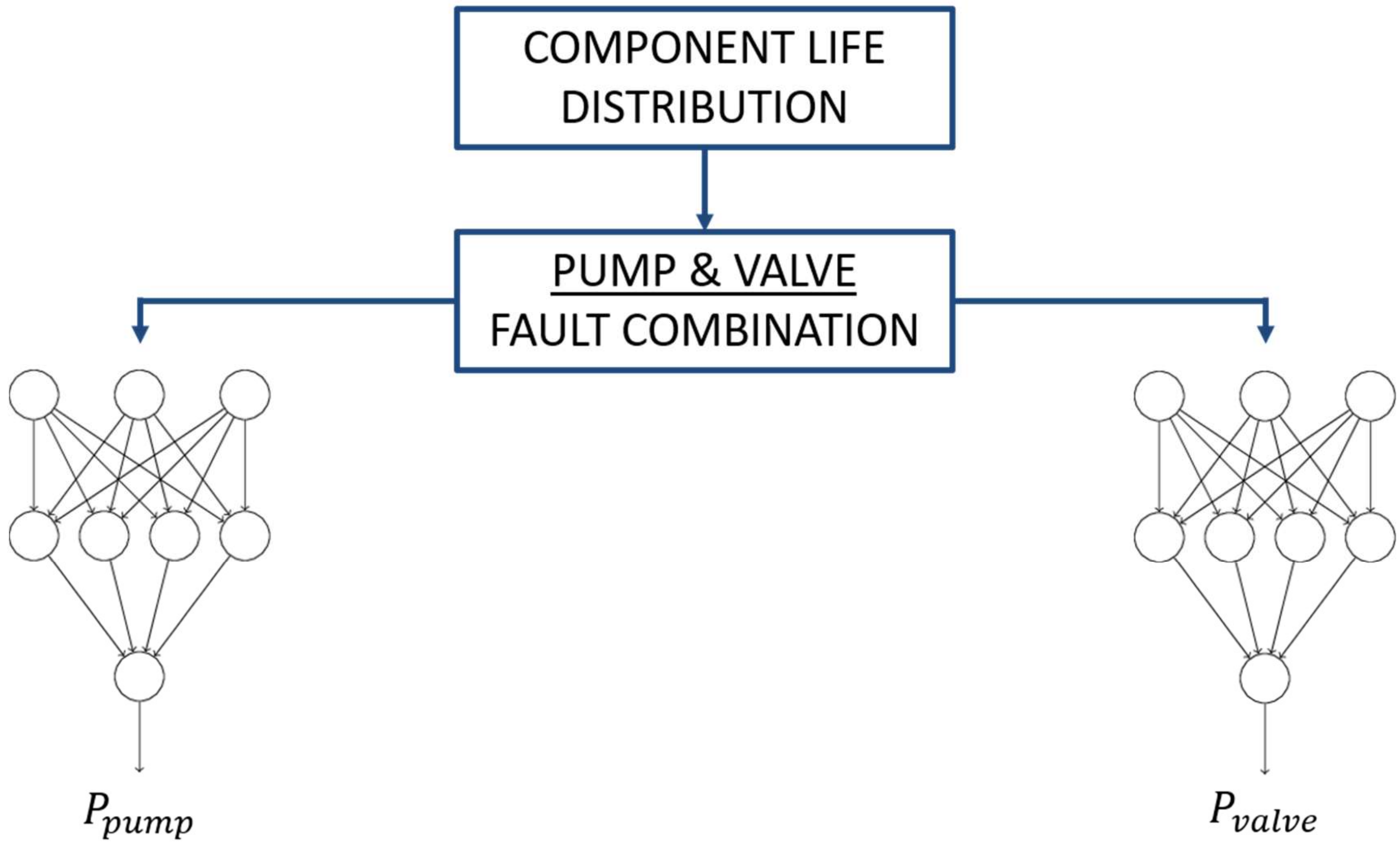
ISOLATED FAULT RESULTS PUMP



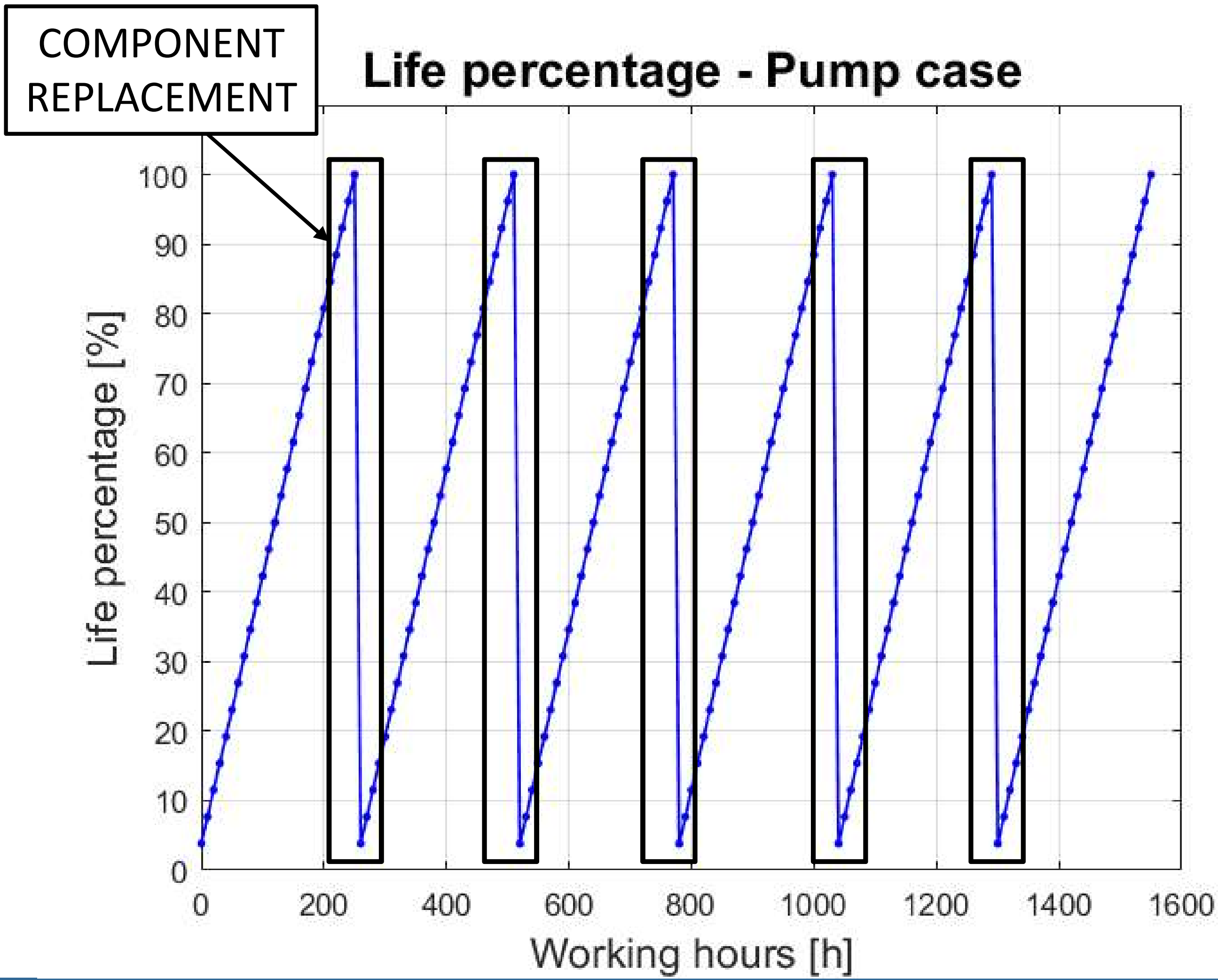


Prognostics

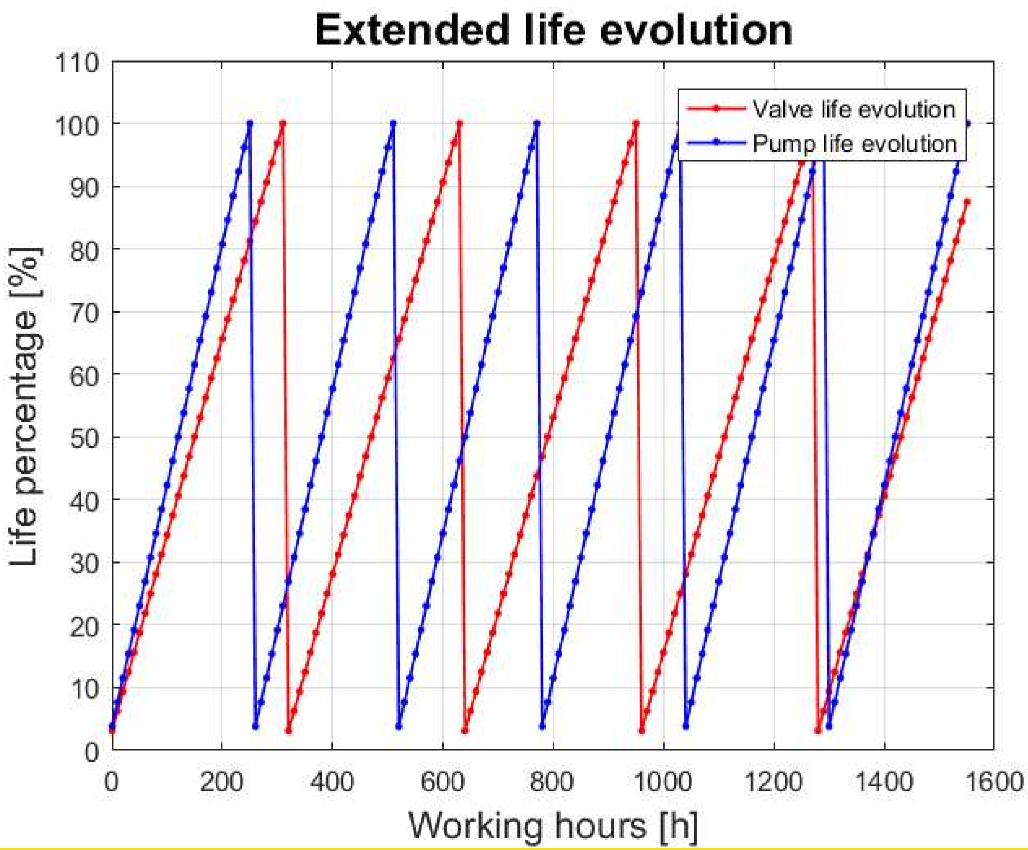
COMBINED FAULTS ANALYSIS



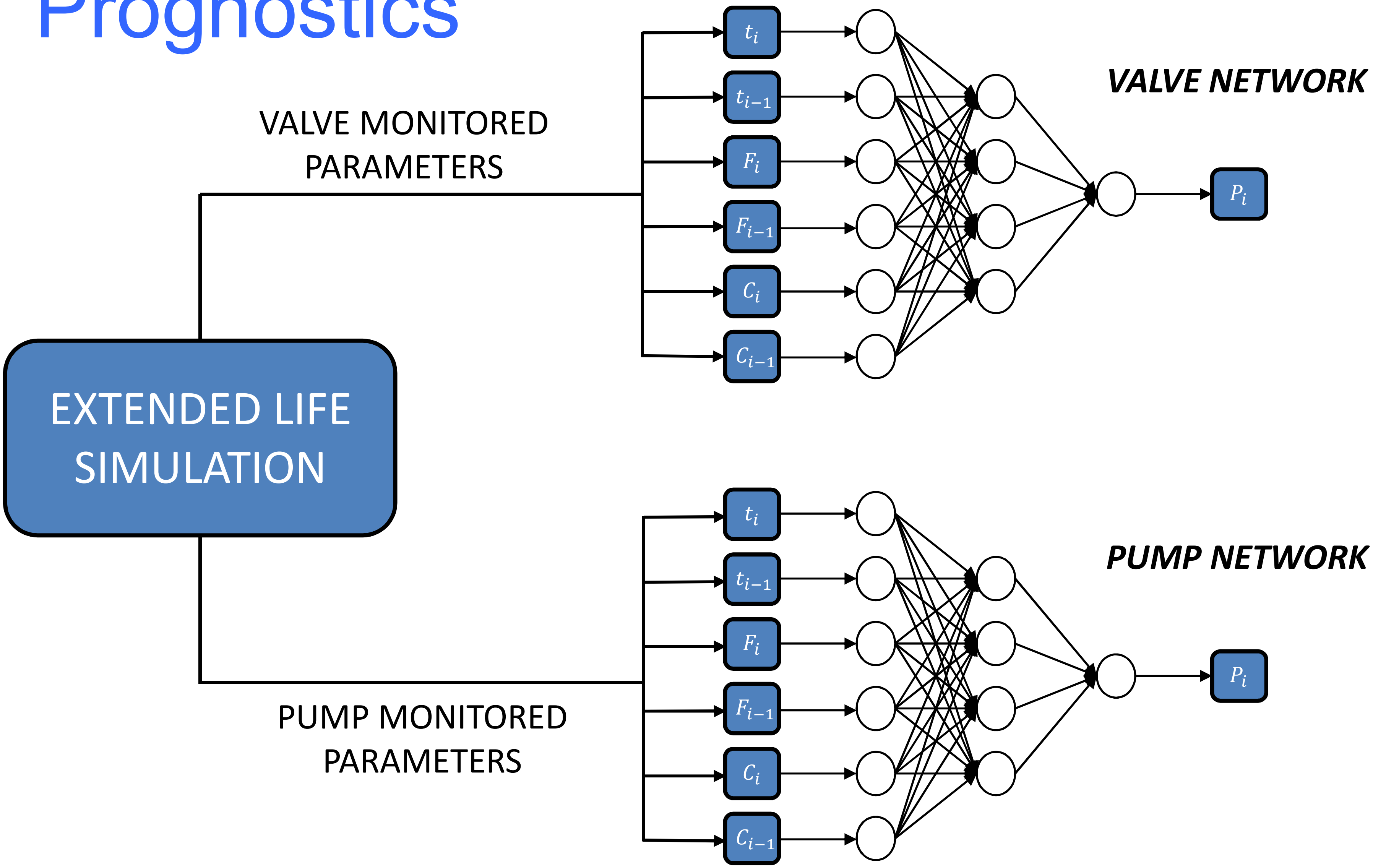
Prognostics



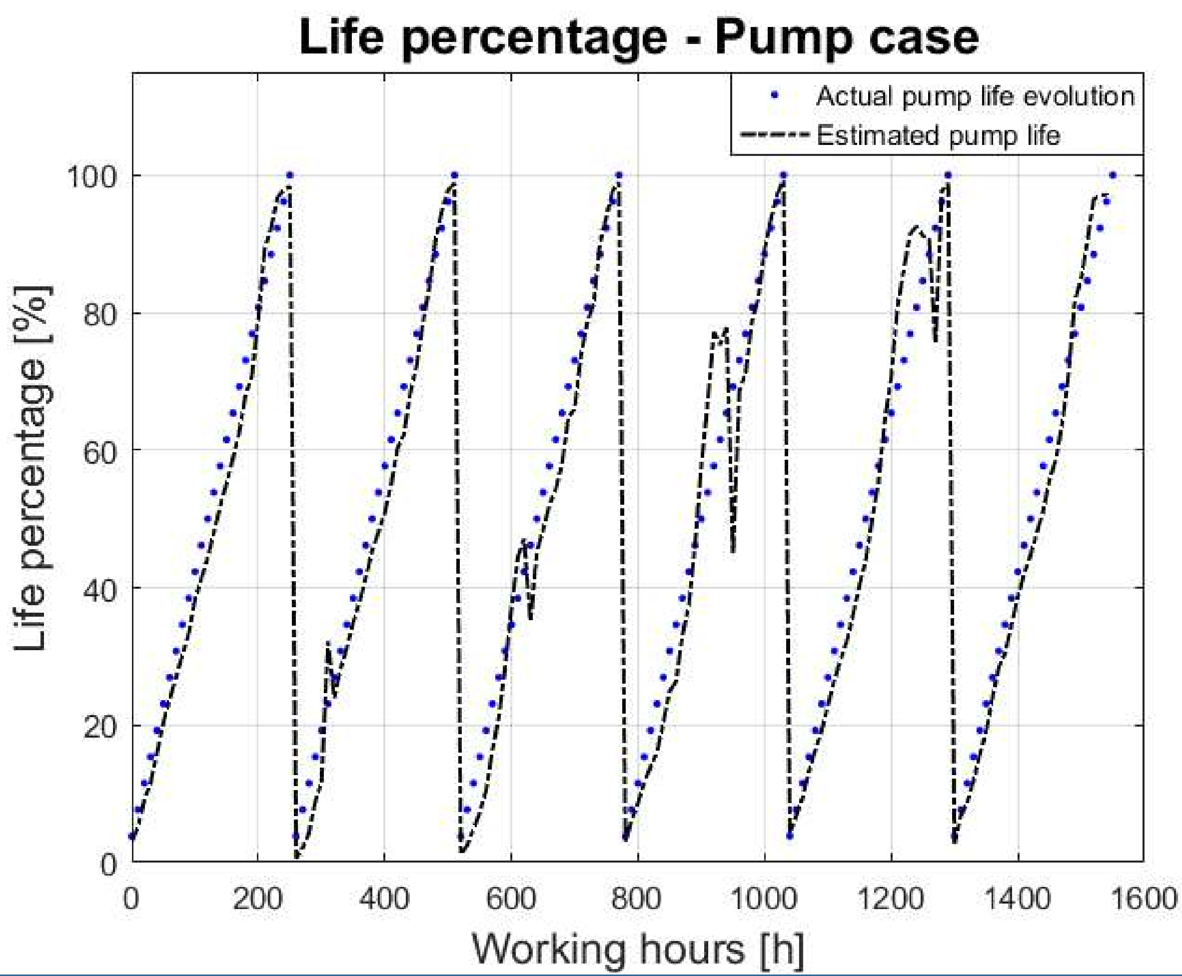
Prognostics



Prognostics



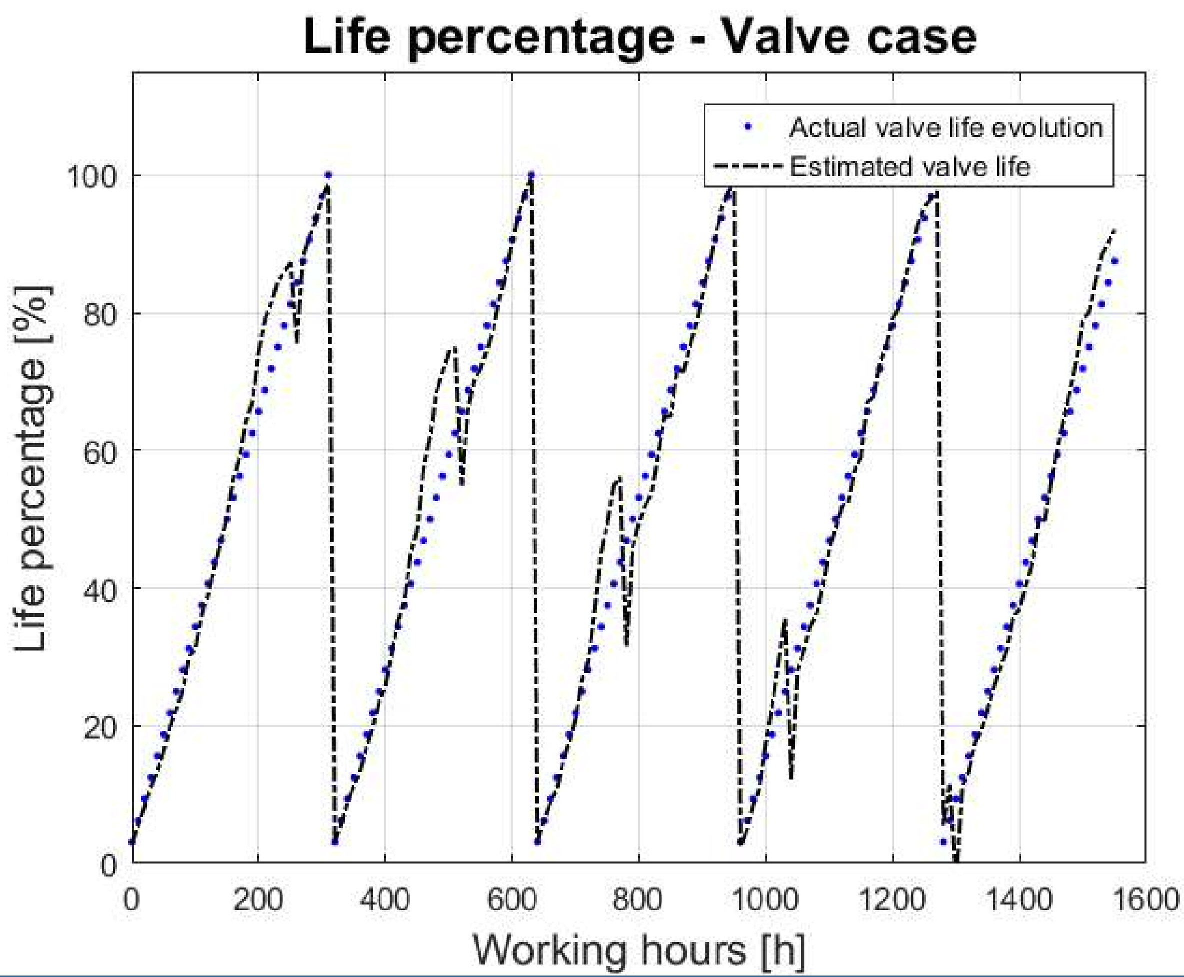
Prognostics



RMS = 6.03

$E_{\%}$ = 14.58%

Prognostics



RMS = 5.13

$E_{\%}$ = 10.27%

Prognostics

Algorithm improvement

FUZZY LOGIC

MOTIVATIONS

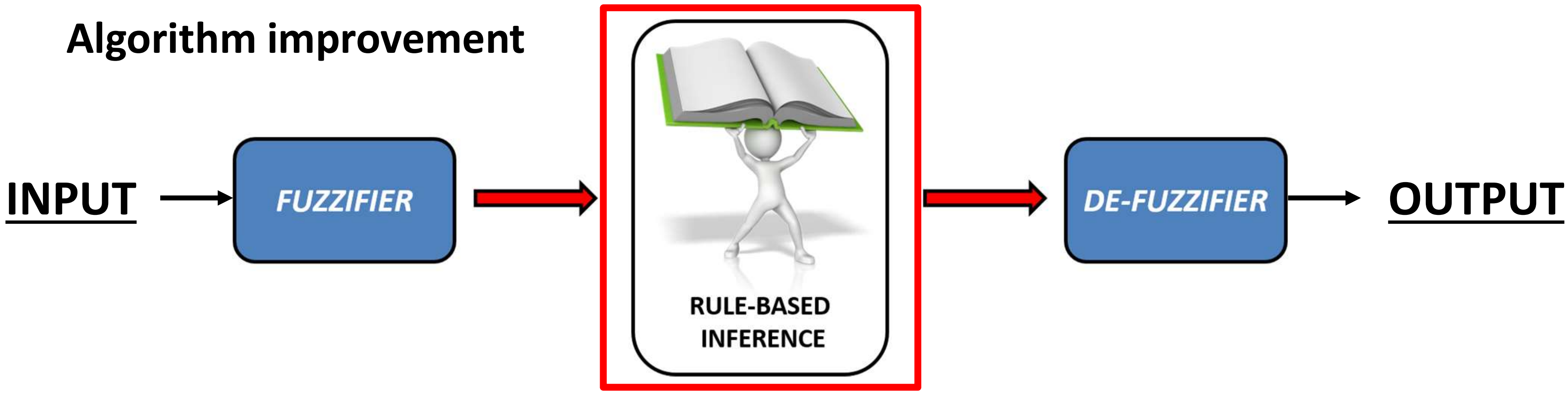
- Errors ***intuitively*** predictable
- ***Strict logic*** approach is ***not*** suitable
- Quite ***flexible*** structure

STRUCTURE

- It is composed by ***If (…) then (…)*** rules
- Input/output membership not strictly imposed
- Mimics ***human reasoning***

Prognostics

Algorithm improvement

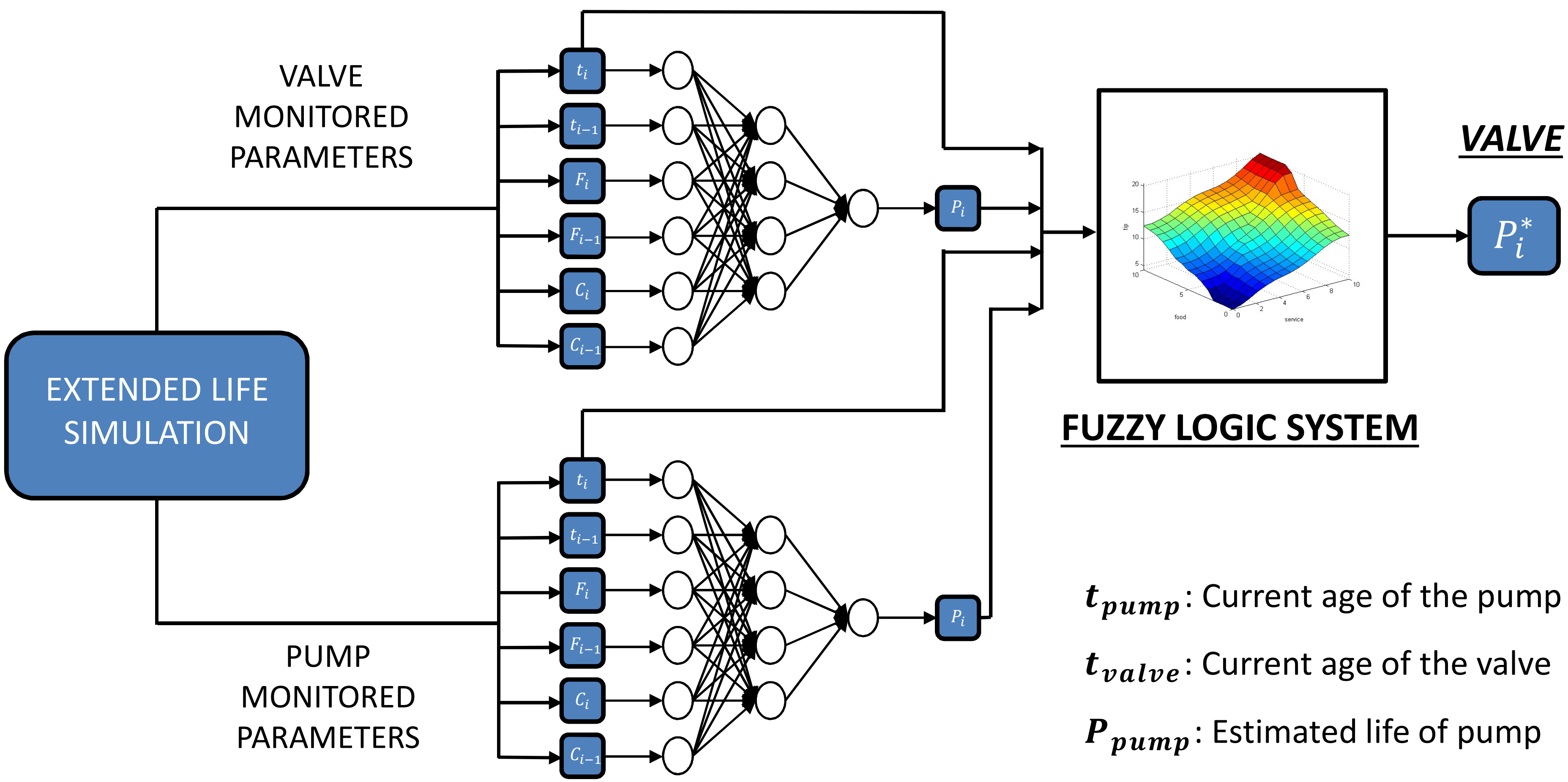


Definition of a set of ***If (…) then (…) rules***

- Computation of **MEMBERSHIP VALUE** with respect to **CONSEQUENT** statement
- Common **LOGICAL OPERATOR** can be implemented
- Rules are based on **EXPERIENCE** and mimic **HUMAN REASONING**

Prognostics

Algorithm improvement



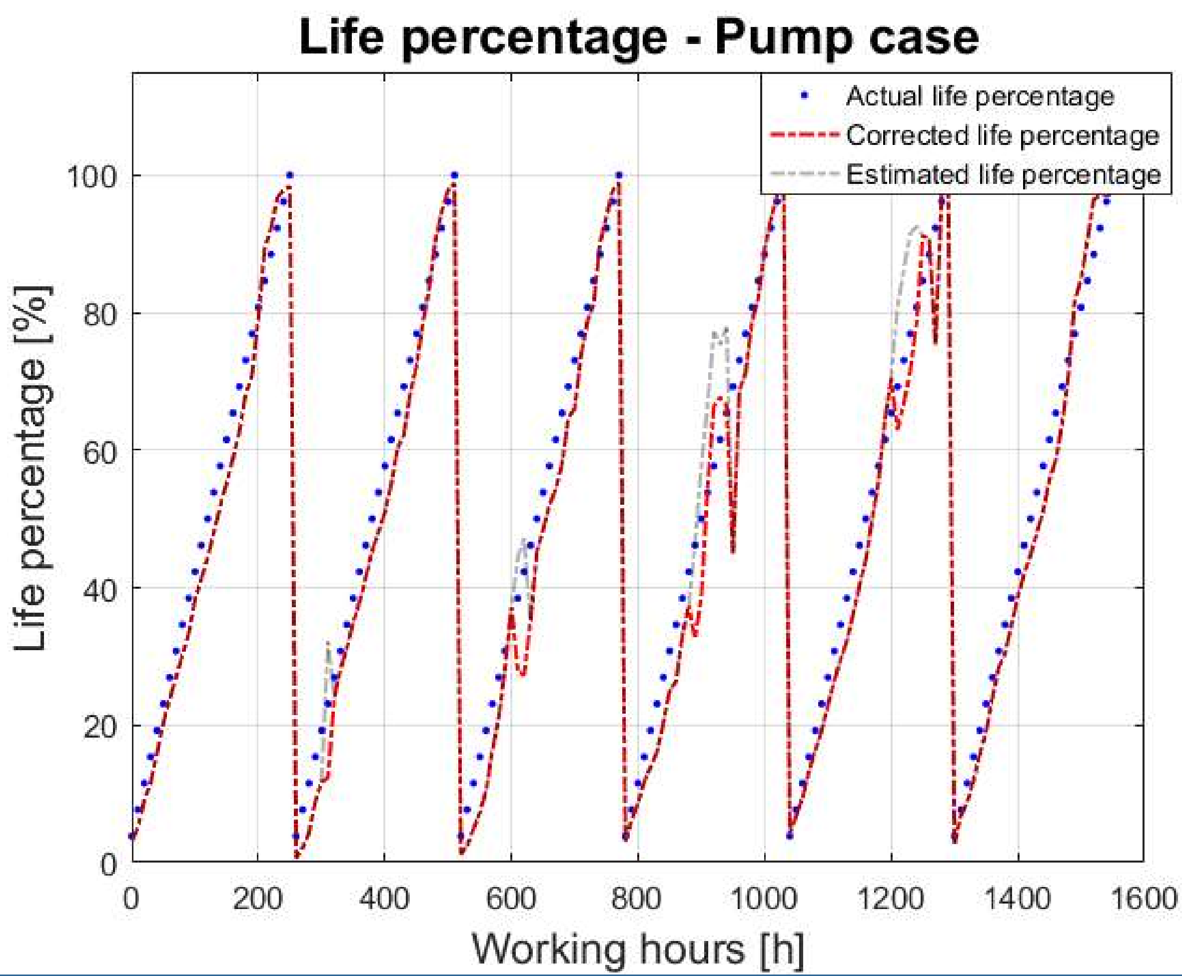
t_{pump}: Current age of the pump

t_{valve}: Current age of the valve

P_{pump}: Estimated life of pump

P_{valve}: Estimated life of valve

Prognostics



Conclusions

- 16MOC2 so far:
  - Instrumented reference machine with an independent metering system
  - Model validation
  - Definition of a control strategy for the independent metering
  - Diagnostic algoritm with data driven method (neural network)
- Today's presentation:
  - Basic idea for prognostic algorithm
  - Verification tests on open-center system
  - Introduction of fuzzy logic tobetter handle cuncurrent component degradation

Future work

- Extension of the prognostic algorithm to the complete crane model
- Experimental validation of both diagnostics and prognostics methods

Project Overview At A Glance

Research goal

To formulate a diagnostic algorithm for load handling machines that combines diagnostic and prognostics with control features present on the machine

Research approach

The proposed approach for diagnostic and prognostics is based on a neural network and considers cost functions as features for evaluating the state of the system.

The cost functions are defined to be a representation of the action of the controller on the machine.

This project is in line with CCEFP vision to "Increase energy efficiency in FP applications", "Improve the reliability of fluid power systems" and "Build smart fluid power components and systems".

Major Objectives or Deliverables

- To formulate a general and self-tuning control algorithm suitable for oscillation damping and for control of valve controlled systems, including independent metering systems.
- Identification of a prognostic method suitable to handle concurrent component degradation.

Next Steps

- Experimental validation of the diagnostic technique.
- Test of the prognostic technique on the complete model of the reference machine.
- Perform tests for the validation of the prognostic algorithm.

Thank you !

Control and Diagnostic of Electro-Hydraulic Machines

Project PI & presenter

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