WP6: Model-based Control and Operation Optimization

WP Leader: Dr. M. Moser, T. Moeller

Objectives

<u>Modeling & simulation:</u>

Reduction of emission, increased efficiency at part load, enhanced dynamic performance

- Model-based control
- Cylinder cut-out
- Expanding operation range emission reduction technologies
- Lubrication injection system

<u>OPEX-cut:</u>

Reduction of operating an maintenance costs

- Develop systems, methods an processes for improved engine lifetime performance

Partners:

University of Bremen

Vienna University of Technology

Karlsruher Institute of Technology

Linköping University

Aventics GmbH

Technical University of Denmark

National Technical University of Athens

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Structure: subprojects, partners, roles

<u>Modeling & simulation:</u> Reduction of emission, increased efficiency at part load and enhanced dynamic performance

University Bremen: Build up a mathematical engine model, development of model predictive control

TU Vienna: Thermodynamical analysis of cylinder cut out, engine model for validation

Linköping University: Development of EGR simulation model and EGR-control

NTUA: Development of detailed SCR simulation model

Technical University of Denmark: Lube oil injection and transport model development and validation

MAN-ES: Data preparation, engine test, manoeuvring analysis of more then 200 vessels, implementation of EGR O_2 controller, test EGR controller on vessel Maran Aphrodite, implementation an validation of model predictive control by simulation

<u>OPEX-cut:</u> Reduction of operating an maintenance costs

Aventics: Electronically controlled actuator for fuel injection prototype sample (retrofit solution)

Karlsruher Institute of Technology: Development of intelligent algorithms for failure detection and plant analysis, Intelligent algorithms for data compression and tailor subspace-search methods

MAN-ES: Data preparation, engine test, validation, data competence

Outline of work performed

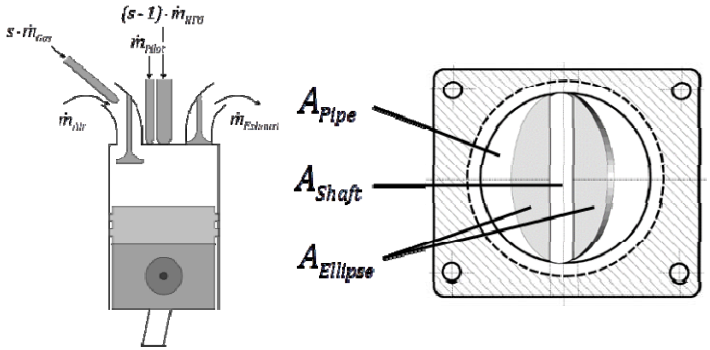
Data preparation
- Preparation of measurement data (SCE, MCE, field)
- Collection of mechanical and boundary conditions

Modelling
- Build up of the model
- Determination of calibration parameters

Control design
- Design and implementation of the control logic
- Unit testing of the control function

Validation
- Validation and verification by simulation
- Validation on the vessel / on the engine

Outline of work performed

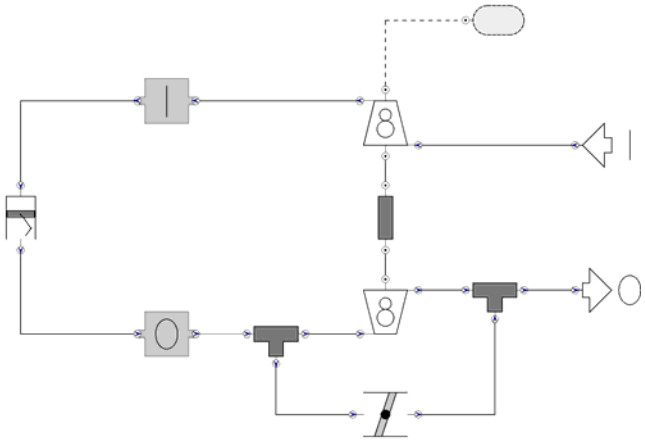


Measurement data preparation

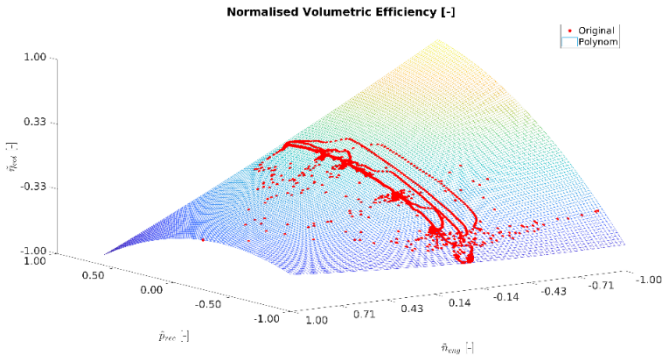
- SCE and MCE data

Development of physical-based models for MB control

- Mean Value Model:
  - Zero dimensional (no spatial information)
  - Most components modelled by physical equations
  - Combustion Torque and Temperature modelled as polynomials (data related)



- Components:
  - Turbocharger (compressor, turbine, shaft)
  - Intercooler
  - Inlet & outlet receiver
  - Combustion & volumetric Pump
  - Wastegate
  - Intersection & Junction with WG pipe



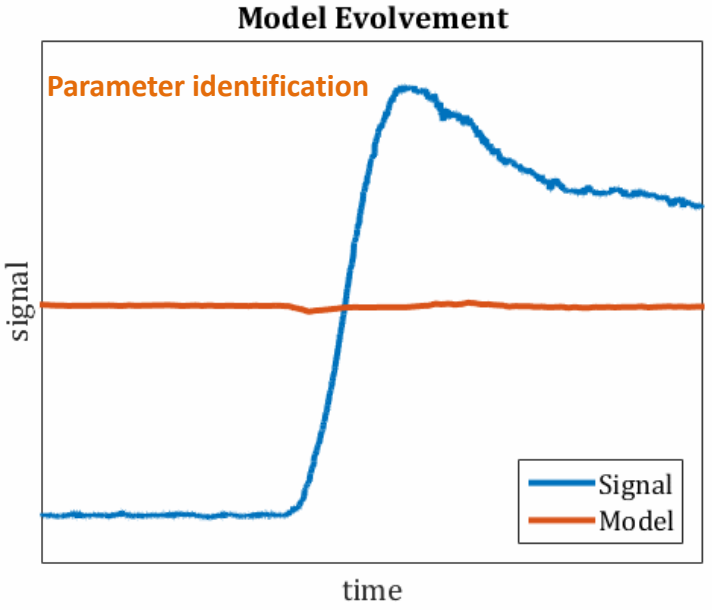
Outline of work performed

Parameter identification

- Definition of cost function

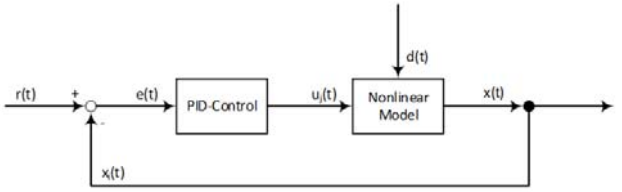
$$\min_p F(p) := \frac{1}{n}\sum_{i=1}^{n}(f(x_i,p)-y_i)^2$$

- Parameter identification by minimization of the cost function with TransWORHP
- Identification of polynomials with PriMO

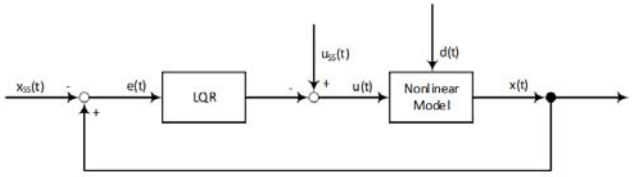


Control design

- PID + LQR in C++ & Simulink, MPC in C++
- Map-based: Pilot fuel mass, Pilot injection time
- Free controls: charge air pressure, gas amount



PID control system



LQR control system

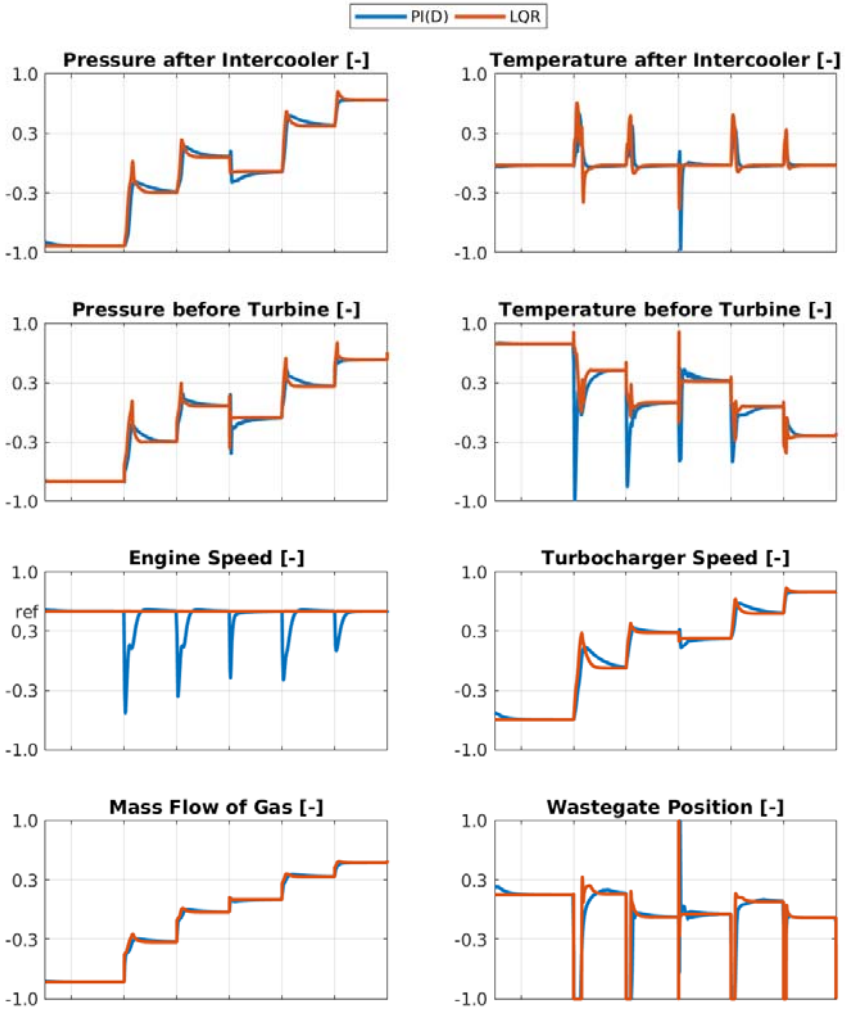
Final results and achievements

Validation

- Validation by simulation (SL, SL+GT)
- Load jumps chosen in order to stay in the range of the combustion model

Results

- LQR control performs better then PID
- Less speed undershot and more precise actuation of the devices
- Actual LQR control tends to be unstable at full load
- Huge effort to build up the model for the LQR control
- Model-borders must be taken into account



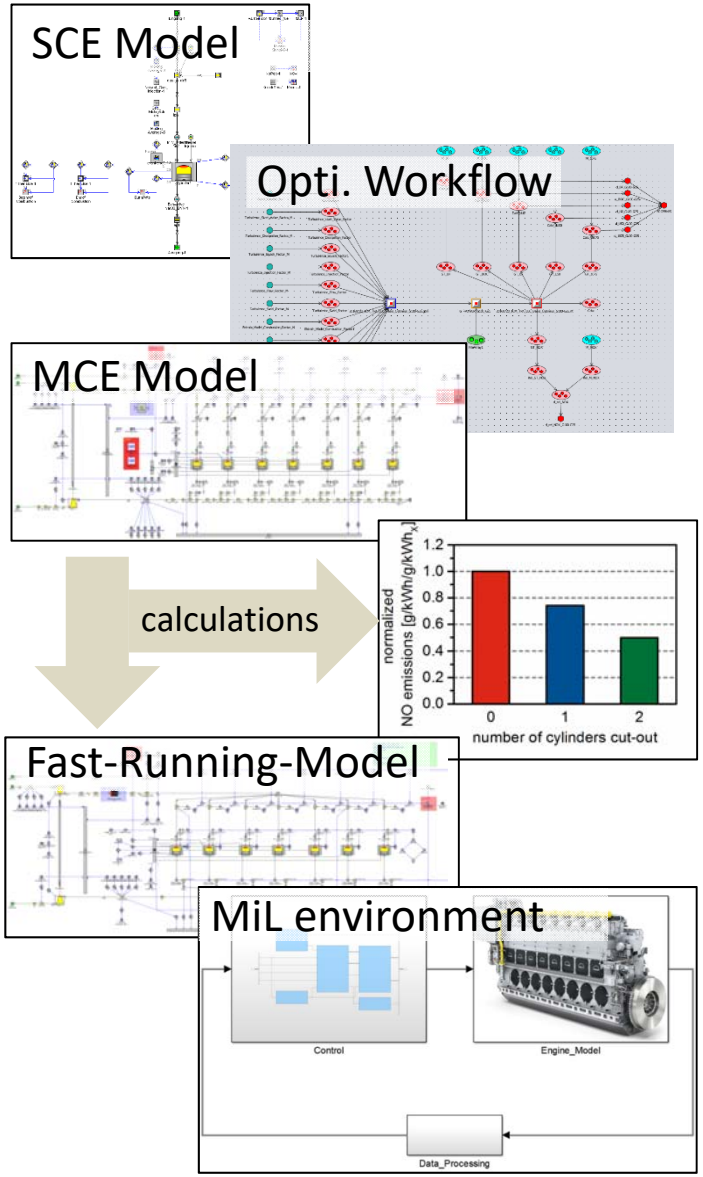
Outline of work performed

Thermodynamic and fluid mechanic 1-D modeling

- Predictive dual fuel combustion-, knock-, and NO-models are adjusted according to test bench data
- development of optimization workflow for calibrating the model
- Simulation engine operation according to defined load-profiles
- Effects on engine behavior with special focus on turbocharger were analyzed

Fast-Running-Model is derived from full 1D-model

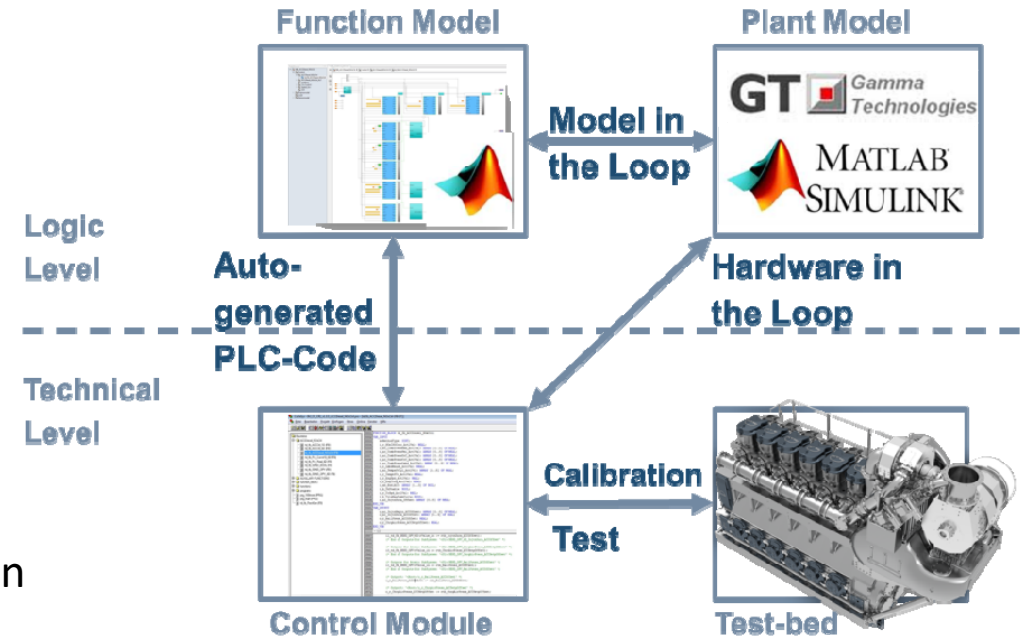
- Substitution of predictive models by Neural Nets
- FRM model runs 16-times faster then full 1D-model (important for MiL simulations)



Outline of work performed

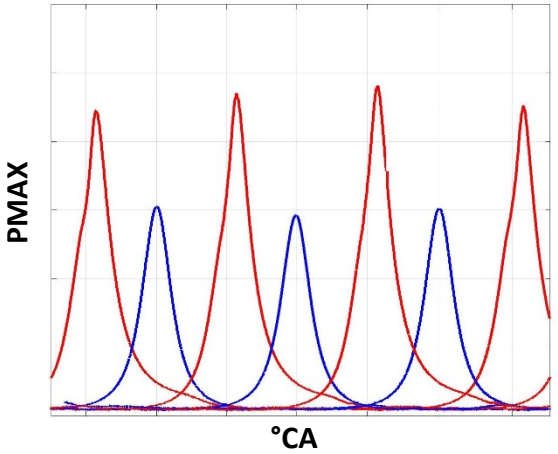
Engine model for MiL environment

- Engine control for cut-out operation implemented in Matlab/Simulink
- MCE model linked to engine control



Test bed measurements

- Auto code generation of cut-out function
- Implementation in control HW
- HiL tests performed to ensure SW quality
- Test runs
  - Investigation of static and dynamic cylinder cut out
  - At different loads, cylinder amounts, w/o pilot injection
  - Different cut out scenarios and different engines speeds
  - Engine start up and load jumps
  - Different Methan numbers



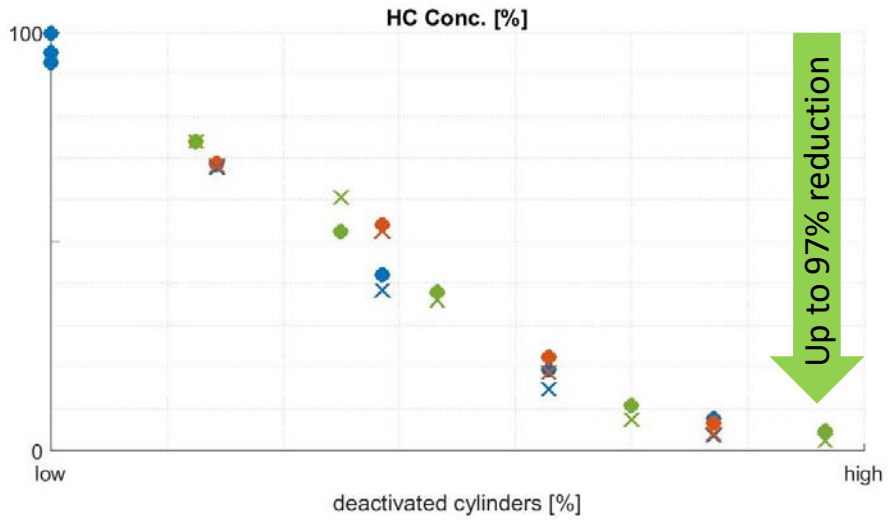
Final results and achievements

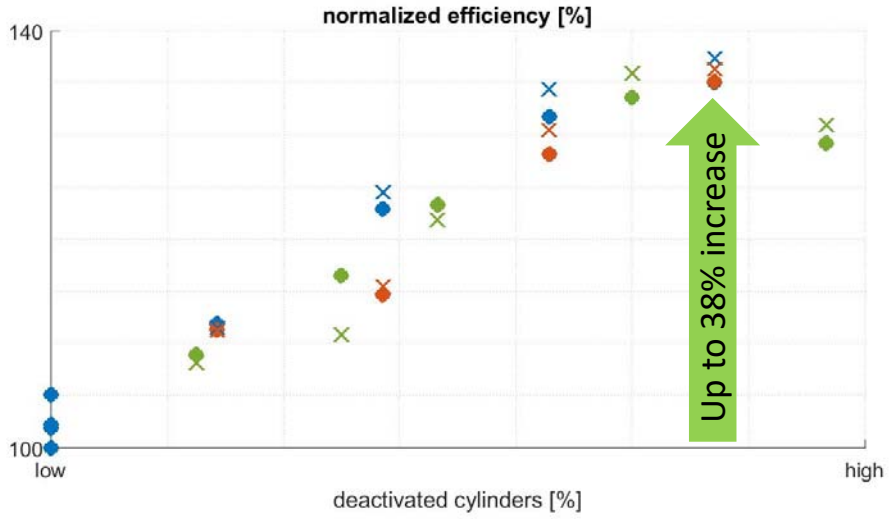
Effects on engine performance

- Combustion is shifted from partial diesel to gas premix combustion
- Increased fraction of burned fuel
- Increased turbocharger efficiency
- Richer combustion
- Reduced pumping work
- Less friction loss
- Reduced wall heat loss

Results based on cut out scenario and load

- Up to 97 % reduction of HC emission
- Up to 38% efficiency increase
- Up to 50% reduction of NOx emission
- Increased combustion stability

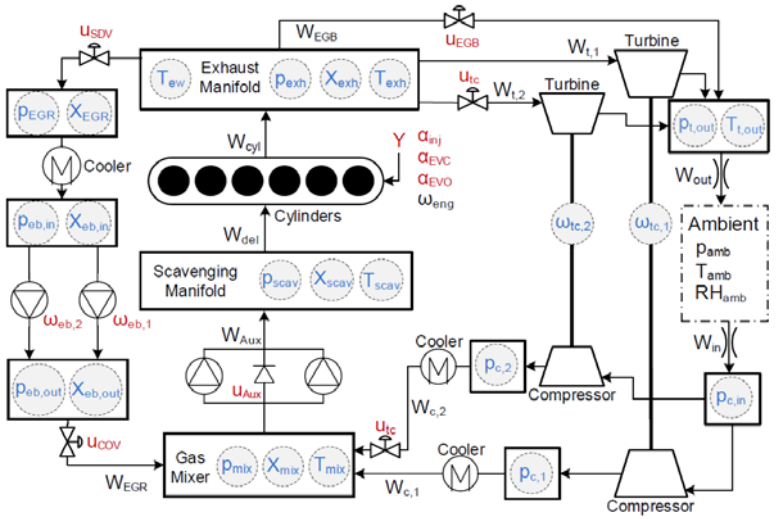




Outline of work performed

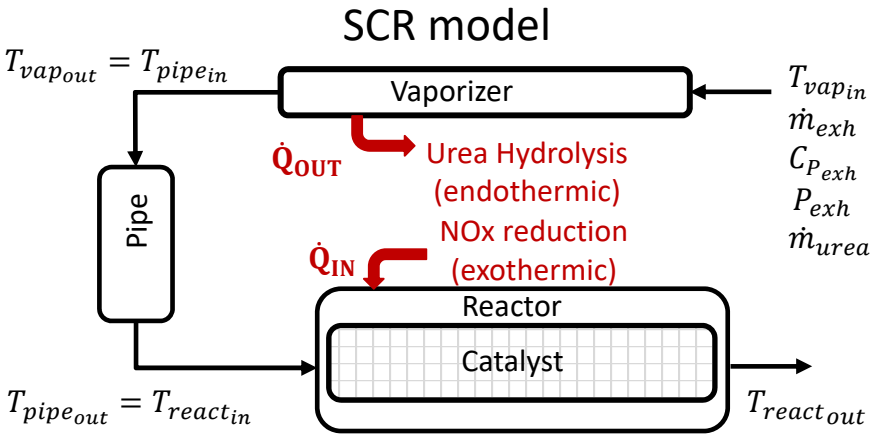
- Development of detailed simulation models of engine air path for controller development
- EGR: Mean value model of engine air path implemented in Matlab/Simulink
- EGR: Simulation model was used for validation and sensitivity analysis of new O_2 controller concept

EGR model



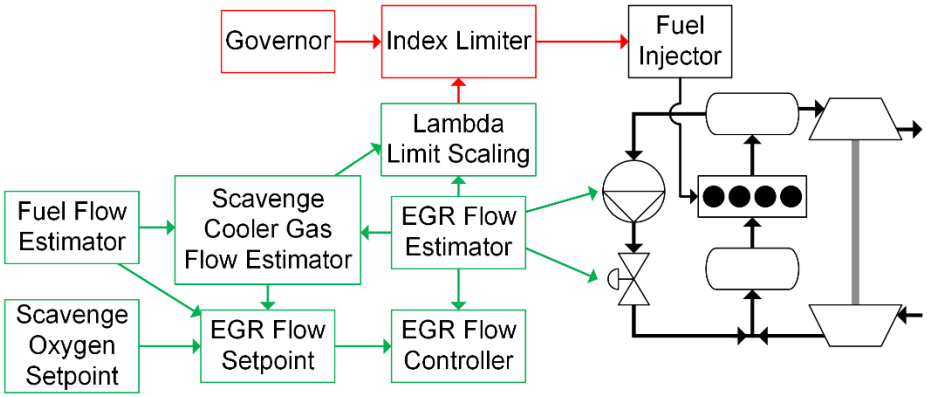
- SCR: Flow and heat transfer model of SCR vaporizer, pipe and catalyst implemented in Matlab and integrated to existing MOTHER engine simulation code, propeller model and ship surge model
- SCR: Model used for investigation of thermal oscillation issues

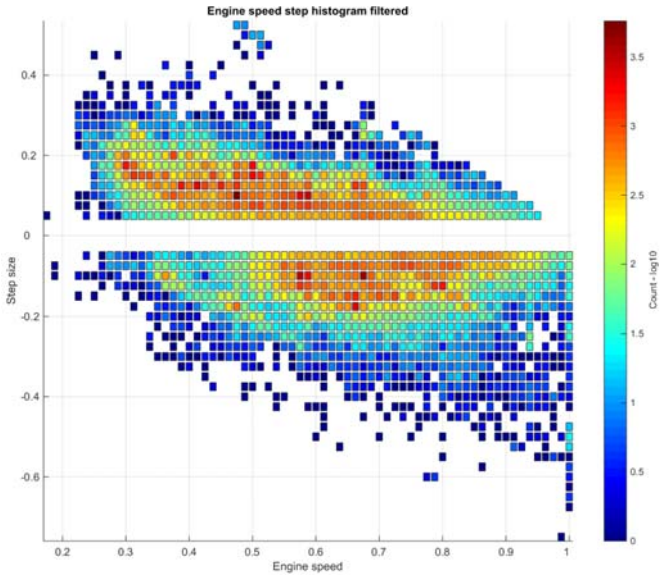
SCR model



Outline of work performed

- Manoeuvring analysis of 200+ vessels to determine reference engine operation pattern
- Implementation and test of state-of-the-art EGR O_2 controller to cope with challenging engine load transients

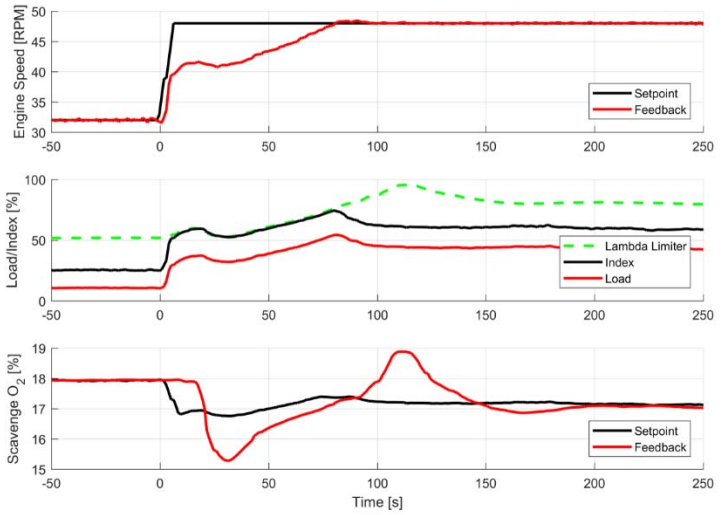


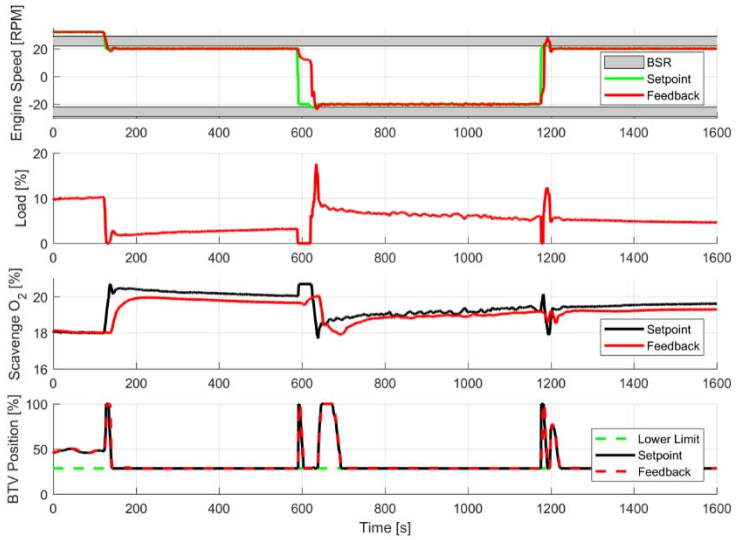


Final results and achievements

Tests on the vessel Maran Aphrodite

- Acceleration with new EGR controller
  - ➢ Strong reduction of smoke emissions
  - ➢ Acceptable O2 control performance
- EGR at low load and reversing
  - ➢ No control issues detected.





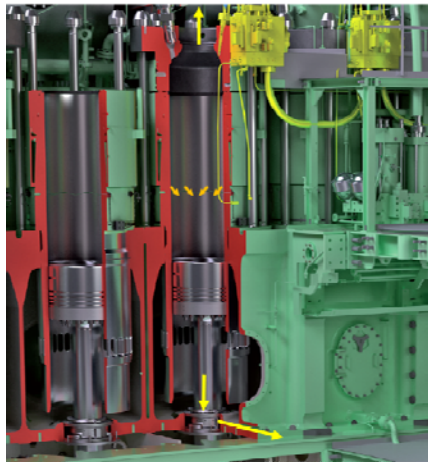
General achievements

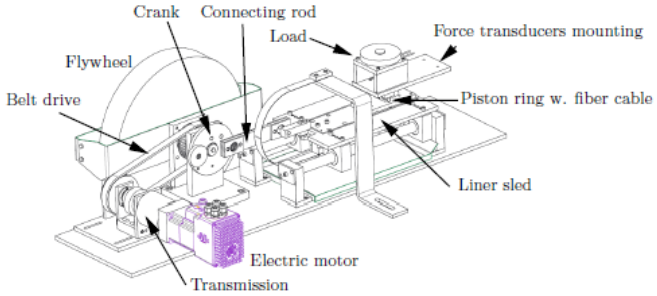
- Developed simulation models were sufficiently accurate for controller development
- EGR and SCR operation range are expanded

Outline of work performed

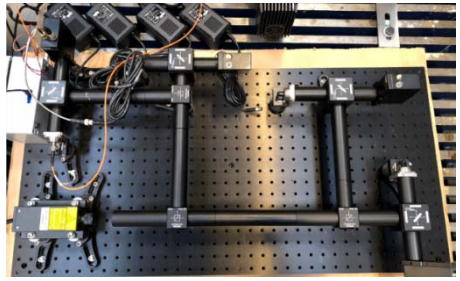
Development of a lube oil injection strategy in order to improve engine lifetime performance and cost

- Reducing of lubricant consumption
- Reduction of asperity friction force
- Reciprocating test rig utilizing laser induced fluorescence for measuring oil film thicknesses
- A numerical model was established in order to evaluate the piston ring lubrication situation and asperity contact friction between piston rings and cylinder liner

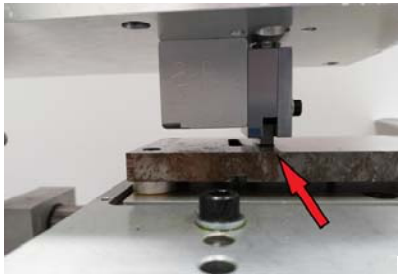




Reciprocating Test Rig.



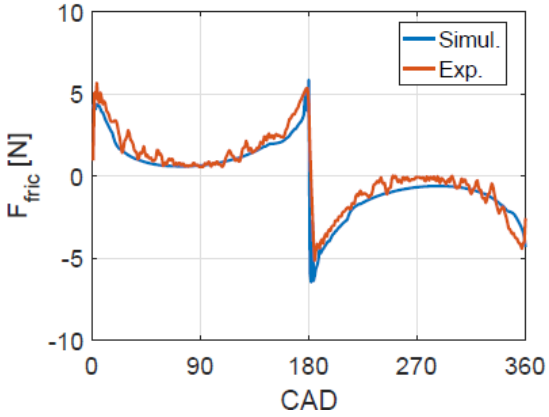
Laser Induced Fluorescence



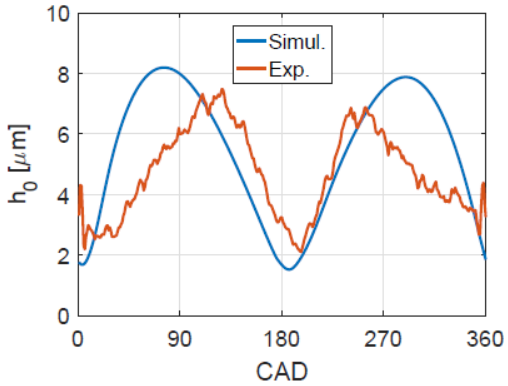
Piston Ring Segment in Test Rig

Outline of work performed

- The numerical model was validated using two different existing test rigs with respect to friction forces
- A test rig located at the Technical University of Denmark was modified in order to measure the oil film thicknesses between the piston ring and liner sample
- A comparative study was performed with satisfactory result
- A parameter study was performed utilizing the validated numerical model
- The relationship between piston ring asymmetries, lubricant consumption and asperity contact friction was investigated



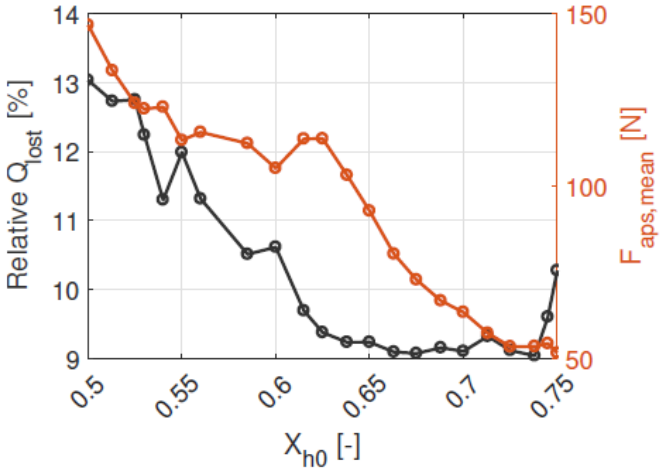
Simulated and Experimental Friction Forces



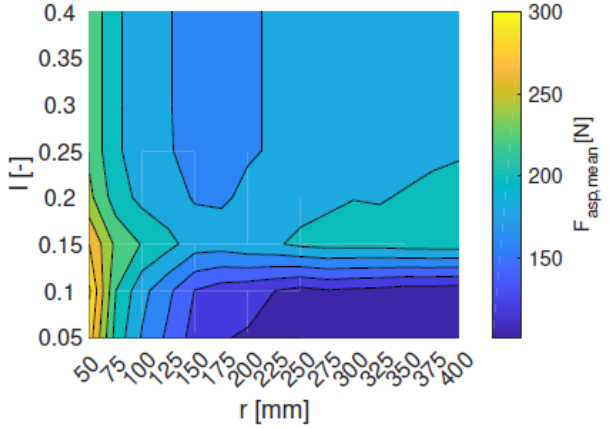
Simulated and Experimental Minimum Oil Film Thickness.

Final results and achievements

- Prediction of lube oil consumption possible
- The lubricant consumption and asperity contact friction was established numerically
- Interrelation of asperity contact friction and lubricant consumption investigated
  - ➢ Both parameters depend on the operating conditions such as lubricant injection position, piston ring curvature and piston ring asymmetry
- An optimum between lubricant consumption and asperity contact friction was found
- The knowledge can be utilized for new lubrication strategies



Correlation between piston ring asymmetry (X_h0), lubricant consumption (Q_lost) and asperity contact friction (F_asp,mean).



Mean Asperity Contact Friction correlation with Piston Ring Curvature (r) and Lubricant Injection Position (I).

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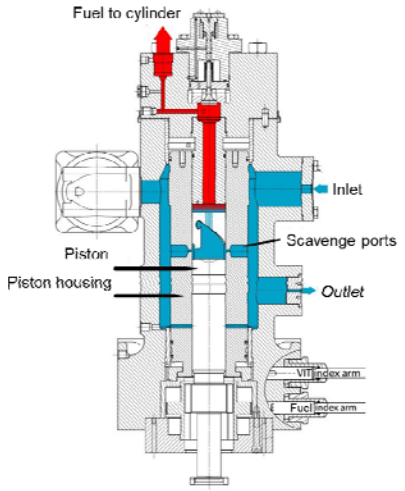
Karlsruher Institute of Technology: Development of intelligent algorithms for failure detection and plant analysis, Intelligent algorithms for data compression and tailor subspace-search methods

MAN-ES: Data preparation, engine test, validation, data competence

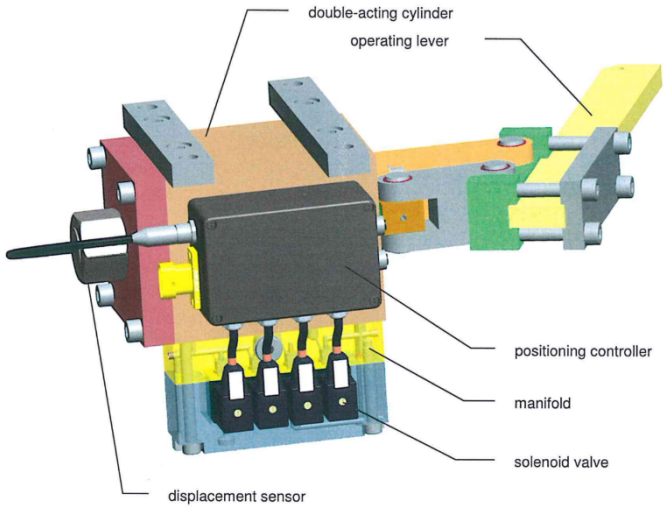
Outline of work performed

Development of a retrofit solution for continuous engine performance optimization for mechanical controlled engines

- Electronically controlled actuator for fuel injection
- Design of the actuator has ben performed
- Prototype sample was produced
- Prototype sample tested on the test bed
- Tests on vessel Jeppesen Maersk have been performed



Cross section of a fuel pump

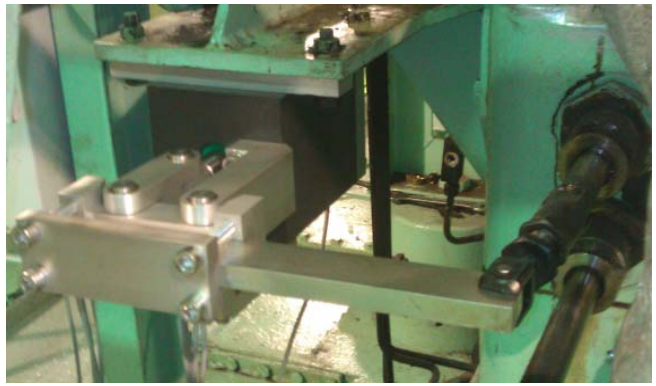


Prototype actuator with integrated electronics

Final results and achievements

Rig tests

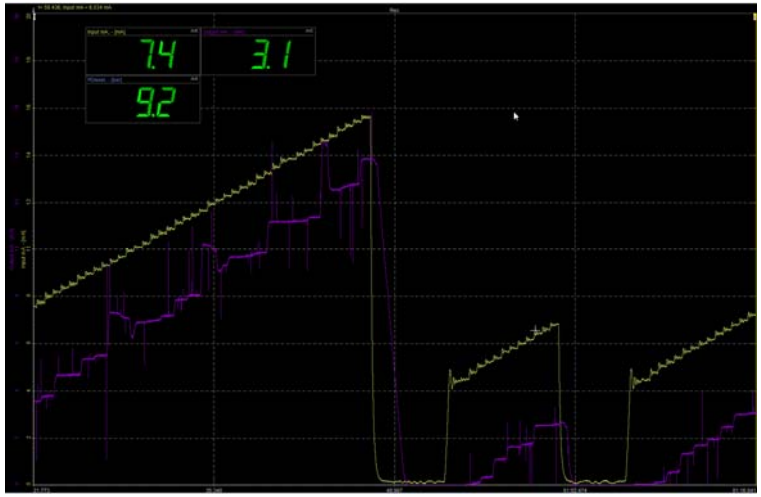
- Functional testing has been done
- Fail safe behavior was investigated
  - Power supply interruption
  - Air supply interruption
  - Different valves activitied during power supply interruption
- Long term test



Actuator prototype

Tests on a vessel

- Test on vessel Jeppesen Maersk (MAN B&W 7K90MC-C engine)
  - Overall concept evaluated is technically feasible

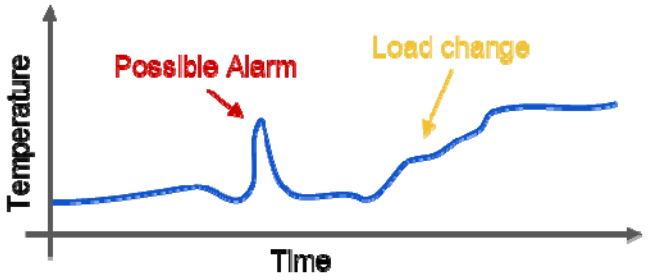


Test results

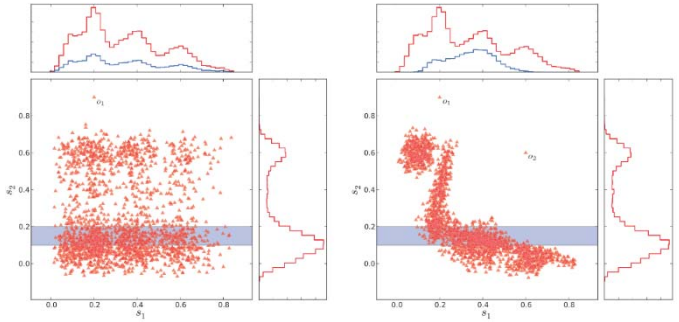
Outline of work performed

New outlier-detection and subspace search methods for improve engine lifetime performance

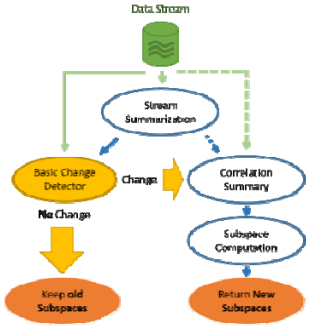
- Data preprocessing concerning static and dynamic features
- Proposed frameworks investigated
- Frameworks validated based on evaluation metrics
- Development of a stream based sub space search method witch allows to analyze data streams
- Investigations concerning compression rate and sub space search quality
- Investigations concerning compression rate and sub space search quality was carried out



Alarm detectors continuously adapt their concept



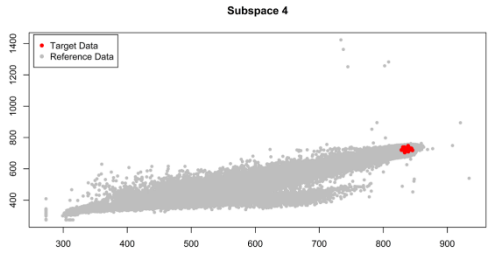
High vs. low contrast subspaces

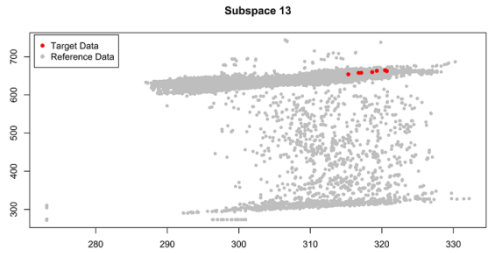


Stream based approach

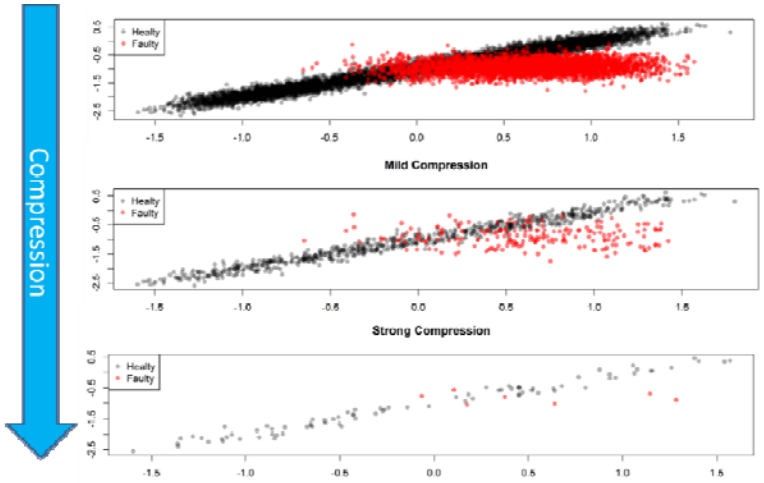
Final results and achievements

- Various evaluation metrics which are based on errors and successes defined
- The currently most promising framework is HiCS-mCD. This model performed best regarding the specified evaluation metrics
- Tailored sub space search algorithms investigated
- High compression rates prevent from finding high-contrast subspaces.
- Above 60% compression the data quality gets to worse for sub space search (To overcome this: utilize dependency of sensor measurements in compression)





High contrast sub spaces



Data compression vs. accuracy

Conclusions

In the WP 6 Model-based Control and Operation Optimization

- Advantages of model-predictive control has been shown
- Feasible solution for actuator retrofit and reduction of operating and maintenance costs
- Emission reductions has been reached by
  - Deeper understanding of the lubrication behavior
  - Cylinder cut-out
  - EGR and SCR operation range increase