A Nonlinear Model Predictive Controller for Reactivity Controlled Compression Ignition in Marine Engines

Jeremias Pohjola* Amin Modabberian* Mohammad Raisi Esfarjani** Amir Talebi Sheikhsarmast**

Aneesh Vasudev** Arto Visala* Jari Hyvönen*** Maciej Mikulski**

* School of Electrical Engineering, Aalto University, Espoo, Finland

** School of Technology and Innovation, University of Vaasa, Vaasa, Finland

*** Wärtsilä Finland Oy, Vaasa, Finland

Aalto-yliopisto
Aalto-universitetet
Aalto University

Flexible Clean Propulsion Technologies

IFAC 2026 BUSAN

27.8.2026

Background: Marine propulsion and RCCI

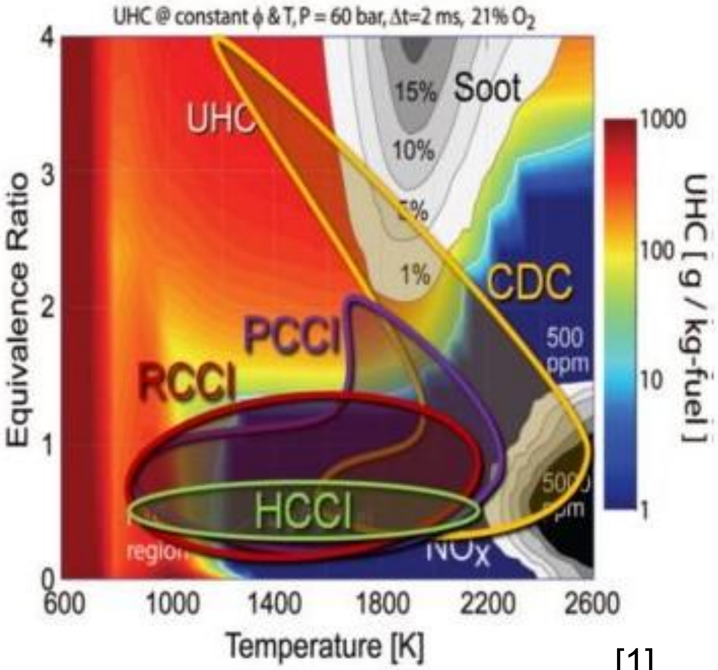
- Marine transport is essential to global trade, but it is also a significant source of global emissions.

- While new propulsion technologies (e.g., electric and hydrogen) are emerging, combustion engines are expected to remain the dominant prime movers for the foreseeable future.

- Among advanced combustion concepts, Reactivity Controlled Compression Ignition (**RCCI**) is emerging as a promising pathway for reducing emissions.

Background: Why RCCI?

- **Low-temperature Dual-Fuel** combustion concept
- Provides **low emissions** and **high thermal efficiency** when compared to conventional combustion strategies.
- Improved combustion control in comparison to other **LTC** strategies, such as **HCCI**, with simillar benefits of **low NOx** and **soot** emissions



[1]

[1] Solouk, A., Tripp, J., Shakiba-Herfeh, M. and Shahbakhti, M. (2017) ‘Fuel consumption assessment of a multi-mode low temperature combustion engine as range extender for an electric vehicle’, *Energy Conversion and Management*, 148, pp. 1478–1496. doi:10.1016/j.enconman.2017.06.090.

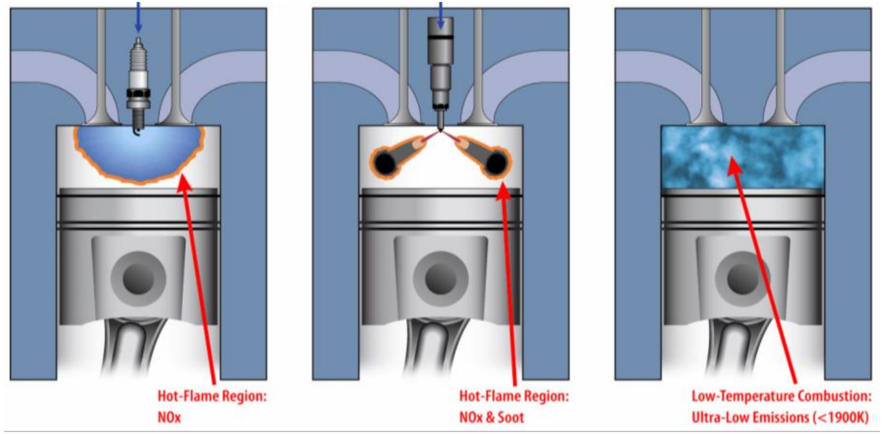
Background: How RCCI works?

- Low-reactivity fuel (e.g. **methane**) via port-fuel injection (**PFI**)
- High-rectivity fuel (e.g. **diese**l) via early direct injection (**DI**)

- The fuel mixture is compressed and auto-ignited, resulting in spread-out low temperature combustion

- **Combustion timing** is controlled by adjusting **fuel reactivity**, i.e. the blend ratio of the two fuels

[1]



Aalto-yliopisto
Aalto-universitetet
Aalto University

[1] Luong, M.B., Sankaran, R., Yu, G.H., Chung, S.H. and Yoo, C.S. (2017) 'On the effect of injection timing on the ignition of lean PRF/air/EGR mixtures under direct dual fuel stratification conditions', *Combustion and Flame*, 183, pp. 309–321. doi:10.1016/j.combustflame.2017.05.023.

Background: Previous control approaches

- **RCCI** has multi-input-output behavior, constraints, and nonlinear dynamics
  - **->** Model predictive control (**MPC**) emerged as the leading strategy.
- Most RCCI control approaches rely on **data-based**, or linear, such as **LPV** models
- High nonlinearity and multiple dimensions require large and detailed maps.
  - **->** High calibration and storage requirements for the model
- Fuel flexibility increases problem even further by introducing additional complexity

Proposed solution: Nonlinear prediction model

- Instead of a data-based or linearized model, a **nonlinear** combustion model could be used for RCCI combustion modeling.

- Nonlinear Model Predictive Control (**NMPC**) using a nonlinear combustion model enables a substantial reduction in model size.
    - **->** A single model works in the whole engine operating range

Methodology: Data

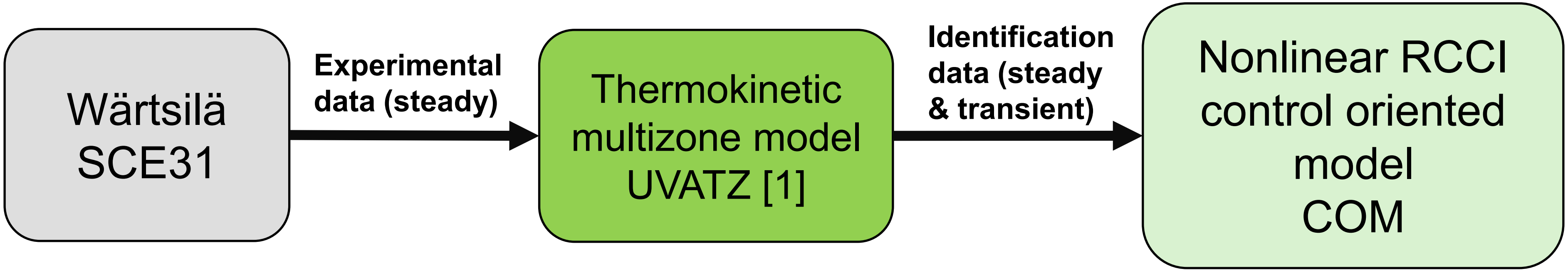


Table 1. Specification of the Wärtsilä SCE31 used for the UVATZ model validation.

Displacement	32.45 l
Nominal speed	720 rpm
Stroke/bore	1.39
Air system	External air compressor with air temperature & pressure control (up to 10 bar)
Valvetrain	4 valves with swirl + tumble ports variable intake valve closure (VIC) fixed exhaust valve opening (EVO)
Engine control	Rapid prototyping platform
Test fuels	ISO 8217 compliant LFO / LNG (MN=80)

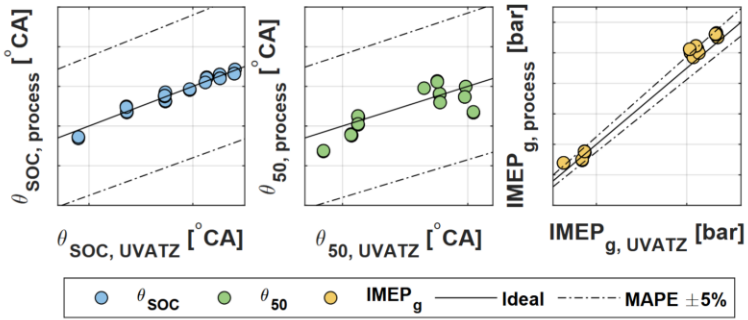


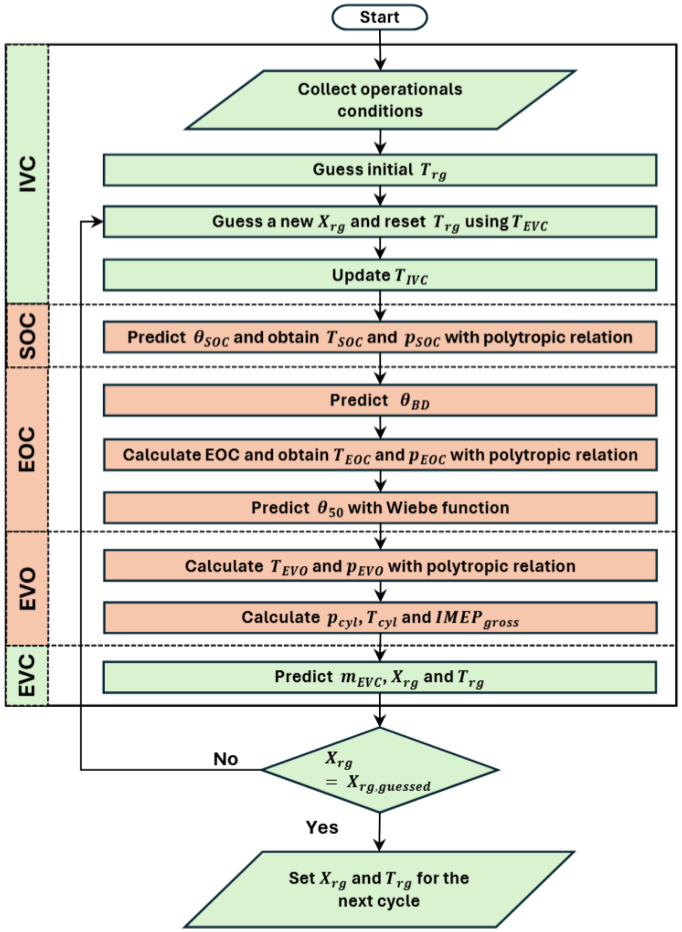
Fig. 2. Overall estimation accuracy of the nonlinear dynamic process model.

Aalto-yliopisto
Aalto-universitetet
Aalto University

[1] Vasudev, A., Cafari, A., Axelsson, M., Mikulski, M., andHyv¨onen, J. (2022). Towards next generation control-oriented thermo-kinetic model for reactivity controlledcompression ignition marine engines. In Proceedings ofthe SAE Powertrains, Fuels & Lubricants Conference &Exhibition. SAE International, Warrendale, PA, USA.

Methodology: Model

- **Process model** used in this work is a physics-based, nonlinear model which computes an **RCCI** operating cycle from intake to exhaust stroke. (GREEN + RED)
- To experiment using a static model to control the RCCI, only the closed cycle was used as **prediction model**. (RED)
- In control, the unmodeled cycle-to-cycle dynamics are accounted via feedback



The model is a combination of previous works in literature [1],[2].

Aalto-yliopisto
Aalto-universitetet
Aalto University

[1] Sadabadi, K.K. and Shahbakhti, M. (2016). Dynamicmodelling and controller design of combustion phasingfor an rcci engine. In Dynamic Systems and ControlConference, volume 50701, V002T20A004. AmericanSociety of Mechanical Engineers.
[2] Turesson, G. (2018). Model-Based Optimization of Combustion Engine Control. Doctoral thesis (monograph), Department of Automatic Control, Lund University.

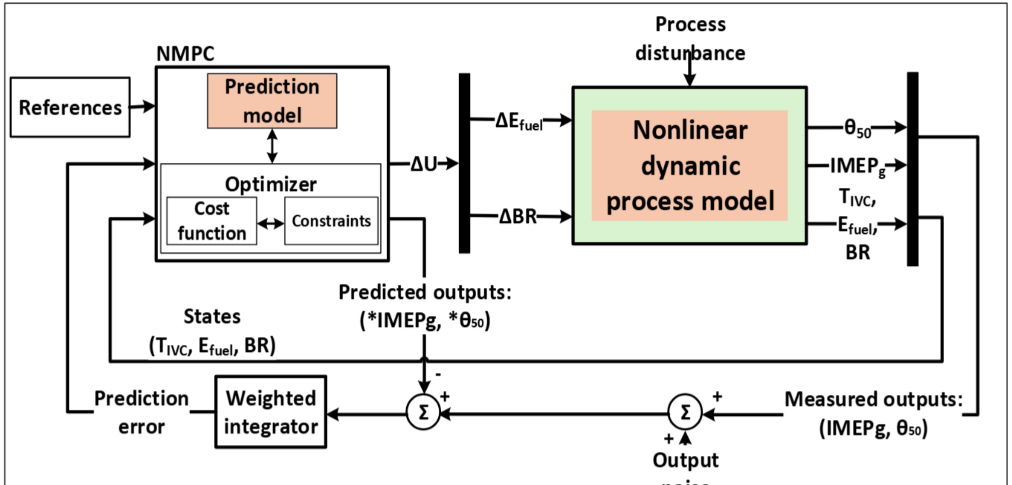
Controller setup: NMPC

- Prediction model is defined in equations 6 and 7.
  - *h()* is the nonlinear combustion model
  - *E* is a correction term, integrated from prediction error
- **Control-** and **prediction horizons** set to **two**
- **SQP solver**, with two solver iterations

$$X_{k+1} = f(\cdot) = X_k + \Delta U_k \quad (6)$$

$$Y_k = g(\cdot) = h(X_k) + E_k \quad (7)$$

$$E_k = E_{k-1} + K_I(Y^*_{k-1} - Y_{k-1}) \quad (8)$$

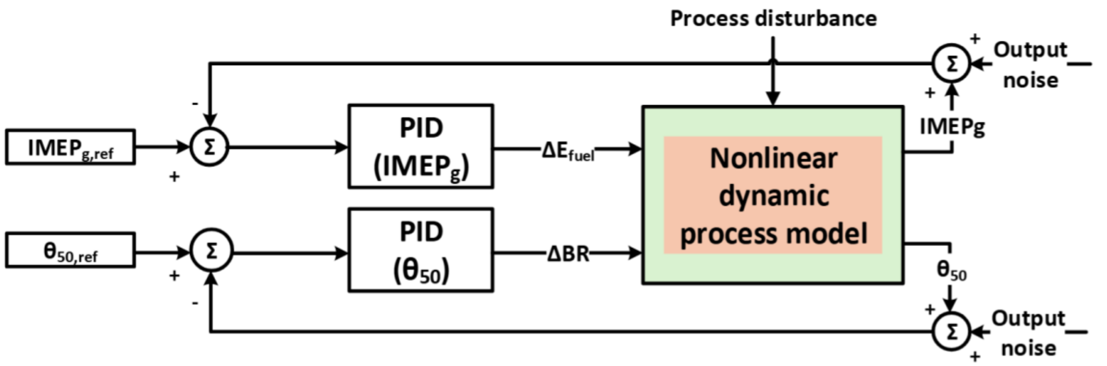


a. Nonlinear model-predictive control system

Controller setup: PID

- **NMPC** controller is the one being developed, where as **PID** provides a simple comparison for evaluating the NMPC performance

- **IMEP** is controlled by **Efuel**
- **CA50** is controlled by **BR**



b. Decentralized PID control system

Test setup

- Implemented and tested in **Matlab Simulink** simulation environment
- In all cases same engine transient from **mid-** to **high-** load
- Different disturbances and control constraints
    - Chosen to represent real engine behavior

Test nro.[a]	**Setpoint change**		**Disturbances**							
	θ_{50} [°CA]	IMEP_g [bar]	T_{intake} [K]		m_{EGR} [kg]		θ_{50} [°CA]		IMEP_g [bar]	
			μ	σ^2	μ	σ^2	μ	σ^2	μ	σ^2
I	-2	+9	0	1	0	10^{-4}	-	-	-	-
II	-2	+9	-	-	-	-	0	0.5	0	0.2
III	-2	+9	-	-	-	-	-	-	-	-

[a] I: Transient with process disturbance, II: Transient with output disturbance, III: transient with strict constraints.

Results: Test I & II

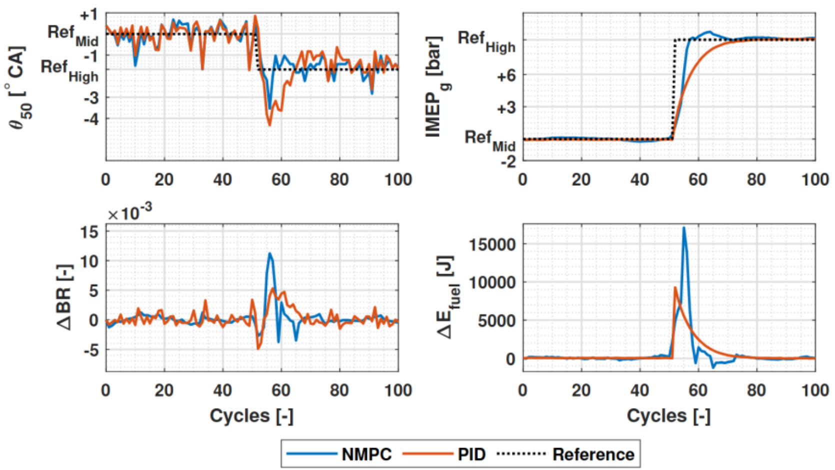


Fig. 4. Test I, load transient with process disturbance.

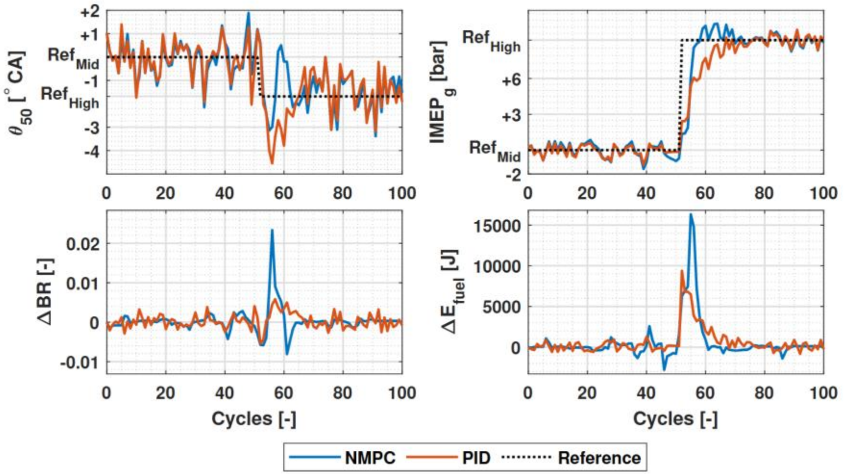


Fig. 5. Test II, load transient with output disturbance.

- NMPC has faster response and settling time, with less noise in CA50 output
- NMPC has smoother control signals

Aalto-yliopisto
Aalto-universitetet
Aalto University

Results: Test III

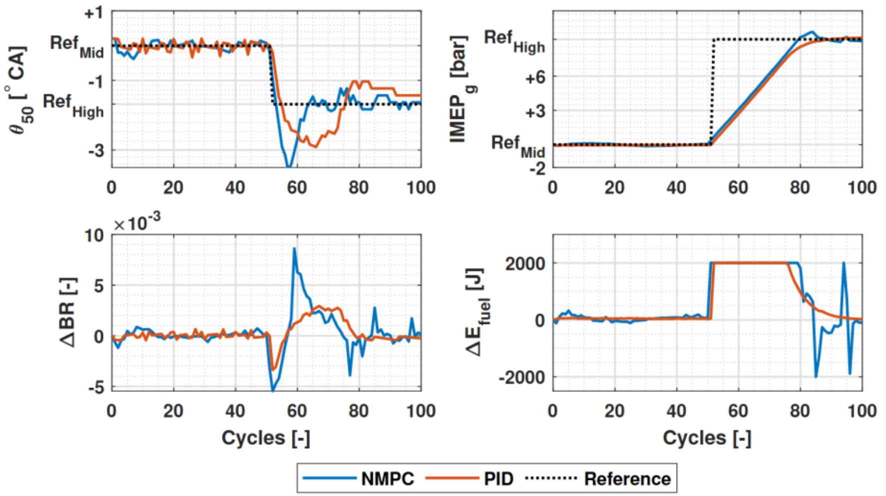


Fig. 6. Test III, load transient with strict constraints.

- NMPC again has faster settling time, with more aggressive control and overshoot

Results: Summary

- The developed **NMPC** achieved reasonable performance
- The controller achieved computation speed of below 1 second per cycle
- The engine operating point remained confined, so nonlinear behavior not so significant.
  - **-> PID** performed OK in comparison

Table 4. Performance metrics averaged over all test cases.

	NMPC	PID
$\text{MAE}_{\theta_{50}}$ [°CA]	0.42	0.48
$\text{MAE}_{\text{IMEP}_\text{g}}$ [bar]	0.80	0.89
$\text{t}_{f\theta_{50}}$ [cyc]	1	1
$\text{t}_{r\text{IMEP}_\text{g}}$ [cyc]	10.67	16
$\text{t}_s(2\%)_{\theta_{50}}$ [cyc]	9.33	11.67
$\text{t}_s(2\%)_{\text{IMEP}_\text{g}}$ [cyc]	14.67	24.67
$\text{Undershoot}_{\theta_{50}}$ [°CA]	1.82	2.23
$\text{Overshoot}_{\text{IMEP}_\text{g}}$ [bar]	0.91	0
Final $\Delta\text{E}_{\text{fuel}}$(%)	53.41	53.67
Sim. time [s]	66.20	4.06

Aalto-yliopisto
Aalto-universitetet
Aalto University

Conclusions: What's next?

- Introducing more constraints to the controller, such as **combustion stability**, **emissions** and **maximum pressure**

- Improve the computation speed of the **NMPC**

- Preparing the system for **hardware-in-the-loop** and **engine-in-the-loop tests**

Thank you!

- This research is part of the Flexible Clean Propulsion Technologies -project (Flex-CPT) funded by Business Finland (ref.9719/31/2023). The experimental data was provided by Wärtsilä Finland Oy.