上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

大发动机研究中心
LARGE ENGINE RESEARCH CENTER

Singapore Maritime Research Conference (SMRC) 2025

A Six-Dimension Framework for Digital Twin of Marine Engine Systems

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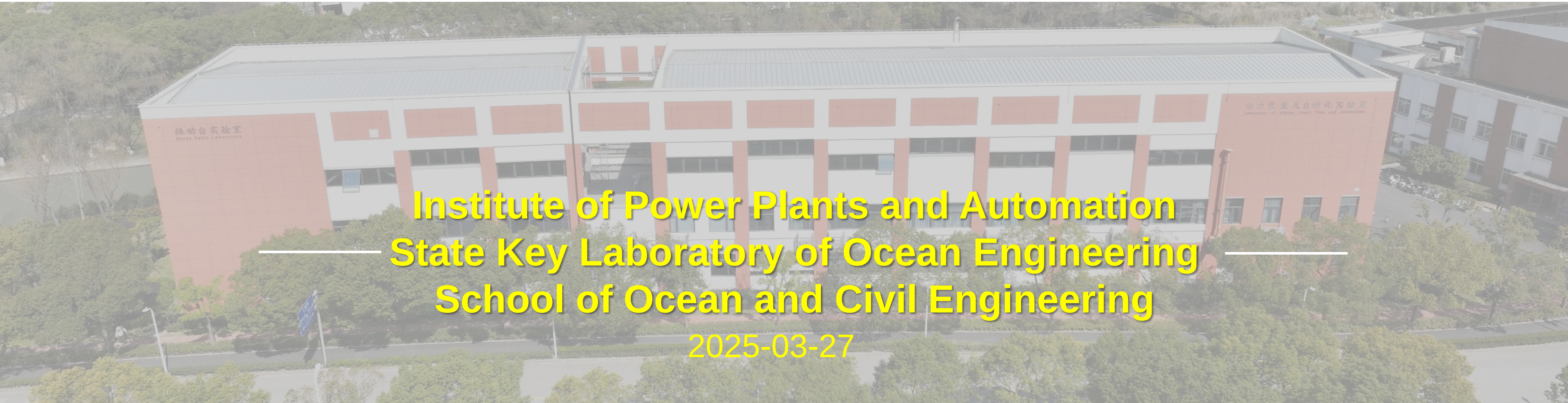


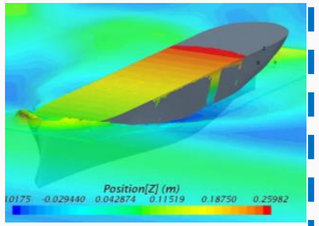
Institute of Power Plants and Automation
State Key Laboratory of Ocean Engineering
School of Ocean and Civil Engineering

2025-03-27

What is digital twin (DT)?

Digital Twins are virtual replicas of a physical devices, systems or processes, that are used to leverage real-time data, advanced analytics and machine learning to create dynamic models to mirrors its real-world counterpart in real-time.

Computer Aided Engineering



CAE   CAD

Tools of DT

Digital Twins

- **Purpose:** analysis, prediction, understanding, etc.
- **Scope:** specific scenarios, research & design, etc.
- **Data integration:** off-line, predefined inputs
- **Static:** snapshot of objects for specific conditions

- **Purpose:** optimization, predictive maintenance, etc.
- **Scope:** entire lifecycle, real-time interactions
- **Data integration:** real time, ML-/physical-models
- **Dynamic:** continuously updating real-world data

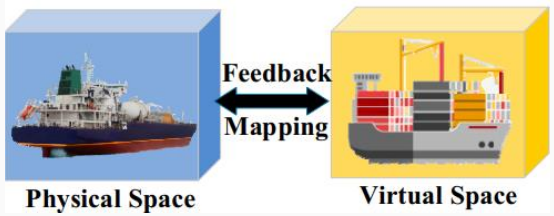
History of digital twin

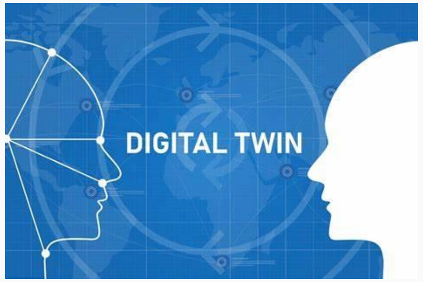
1970
NASA used a virtual model to help restore Apollo 13 [1]

PLM
PRODUCT LIFECYCLE MANAGEMENT

The concept of digital twin was first proposed - Product Lifecycle Management（PLM）[2]
（University of Michigan）
2003

2005
Mirrored Spaces Model was proposed [3]





'Digital Twin' is officially named [4]
（NASA）
2010

2011
Digital twin was applied for Air Force aircraft health management [5]

Digital twin has become a key research point in industries [4]
2012-

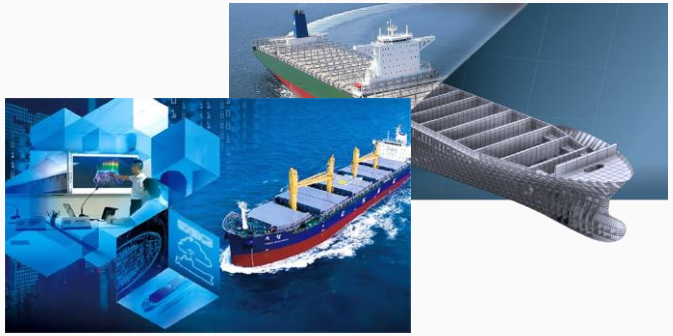
Year

1. Apollo 13: The First Digital Twin | Simcenter (siemens.com)
2. Grieves M. Digital twin : manufacturing excellence through virtual factory replication. White paper; 2014.
3. Grieves MW. Product lifecycle management: the new paradigm for enterprises. Int J Prod Dev 2005;2(1–2):71–84.
4. Chinese digital twin white paper, 2020
5. Tuegel EJ, Ingraffea AR, Eason TG, Spottswood SM. Reengineering aircraft structural life prediction using a digital twin. International Journal of Aerospace Engineering 2011.

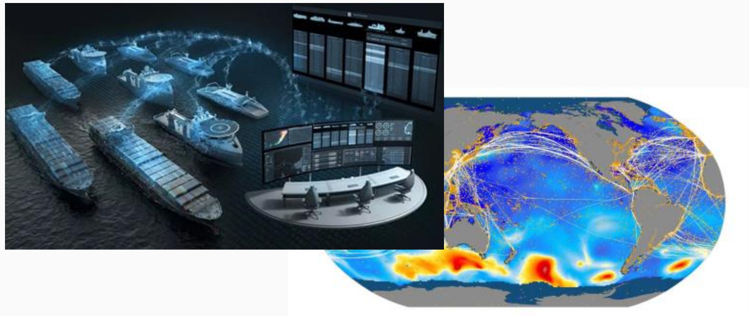
Benefits of digital twin in maritime industries

Digital Twin

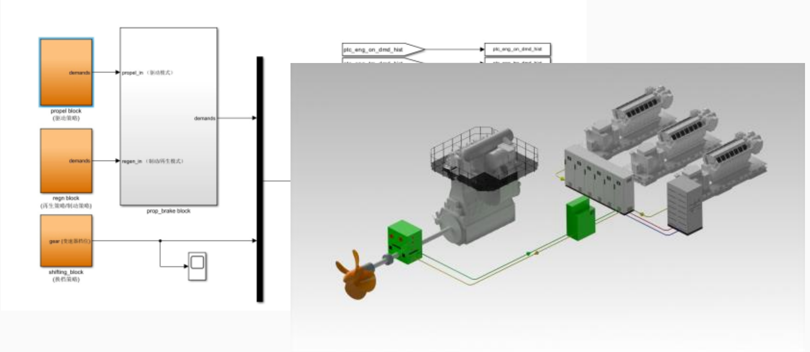
MBSE Aided ship design in early stage w/ LCA



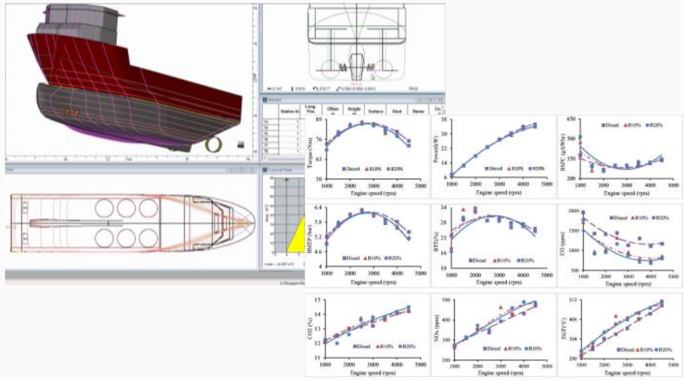
Predictive maintenance during ship operation



Model-based control and energy flow management



Real-time monitoring & predictive FMECA

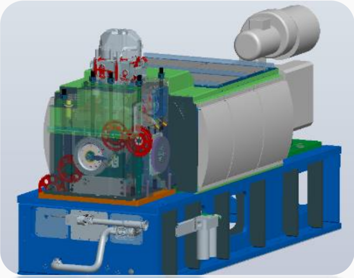


Mariners training in the digital world

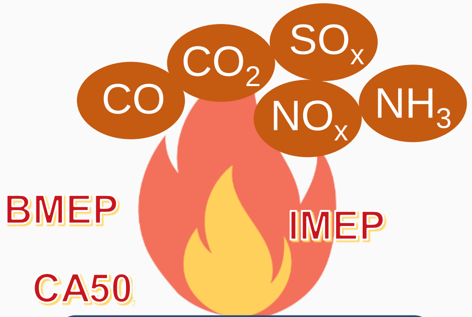
Support classification for new marine technologies

Benefits of digital twin for zero-carbon ships

Function of digital twin for marine engine system

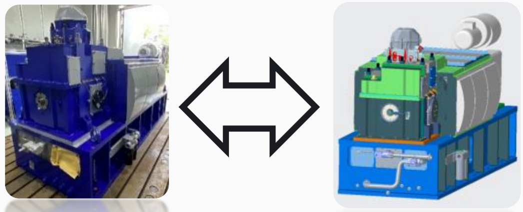


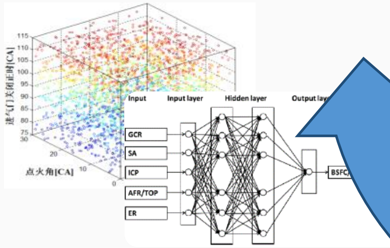
Aided design



Performance prediction

Whole system architecture





Iterative optimization

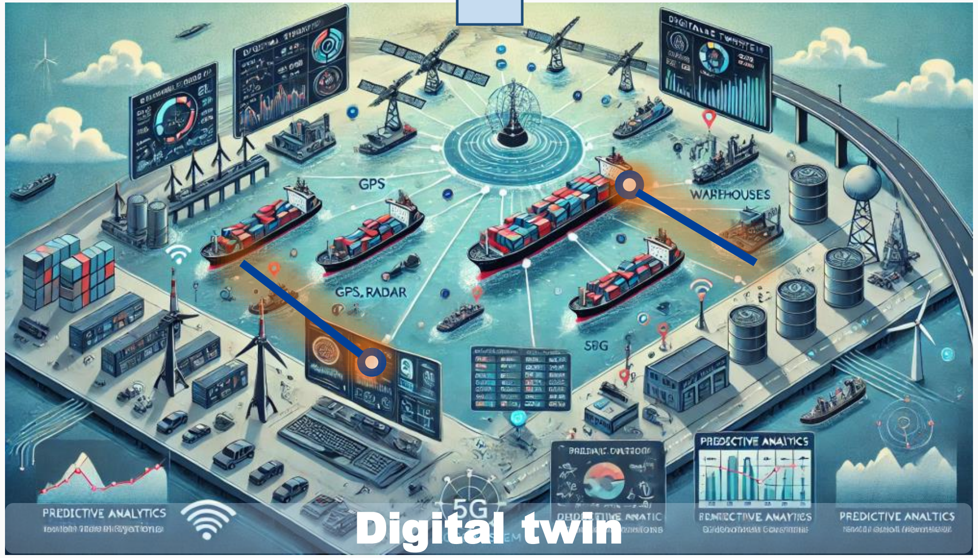
Full life cycle

Health management

- Unmanned operation
- Opportunities for changing
- Intelligent decision
- Iterative optimization
- Reliability promotion
- Energy efficiency improvement

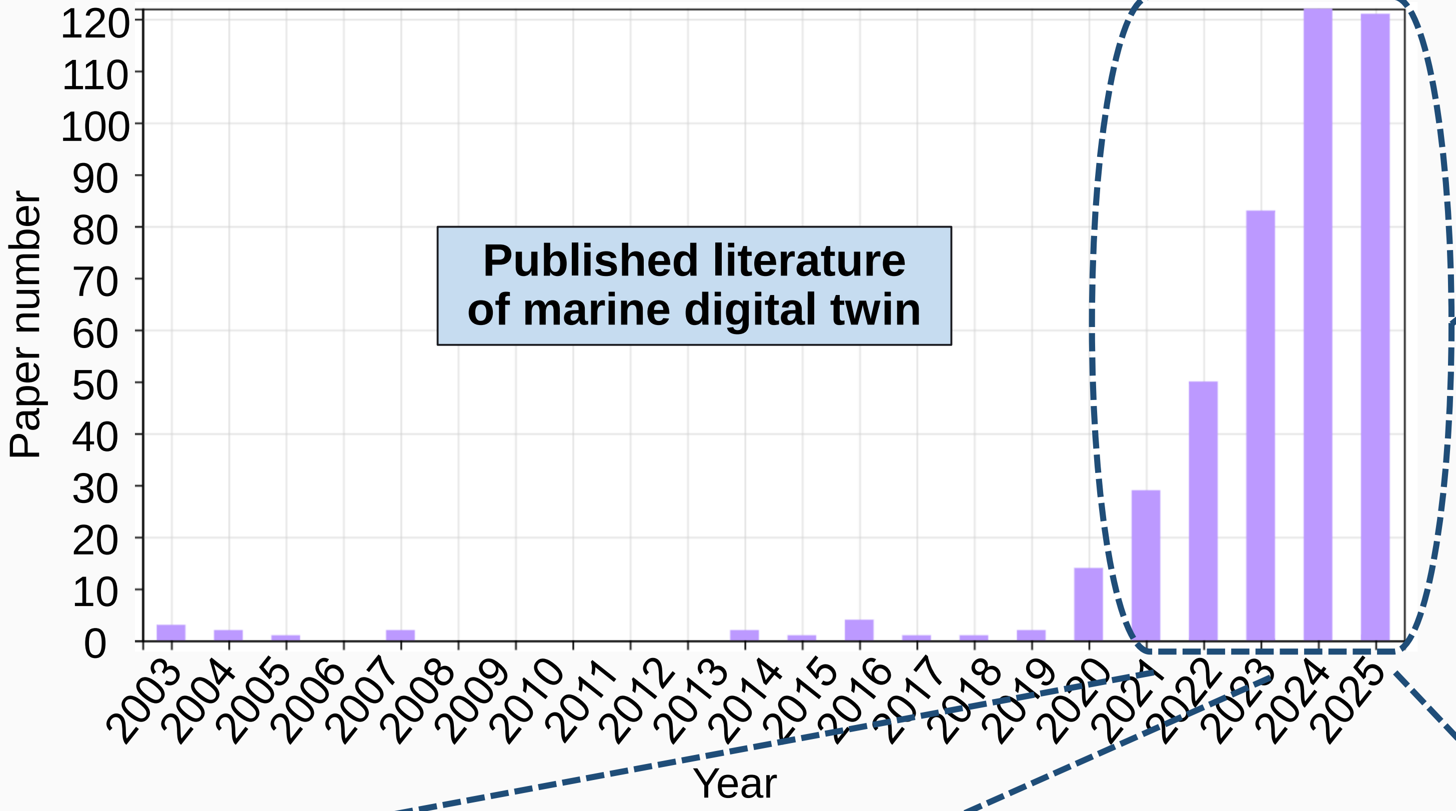
Status monitoring | Performance analysis | Fault warning | Lifetime predict

Intelligent operation and maintenance

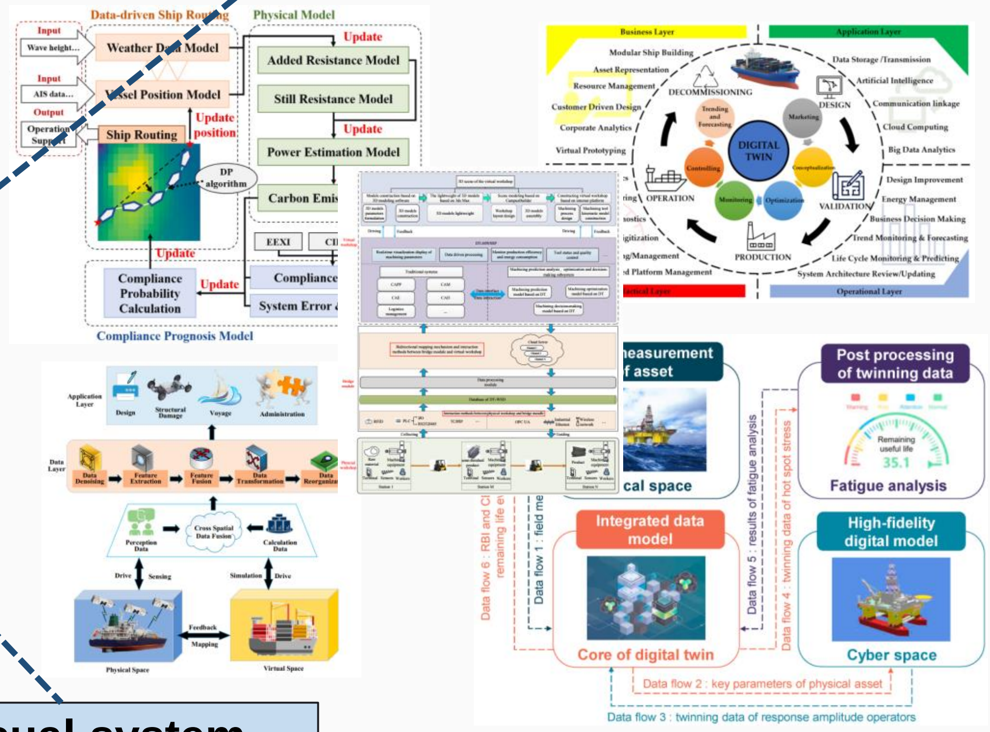


Digital twin is one of key technologies to realize the intelligent, digital, and green marine engine systems.

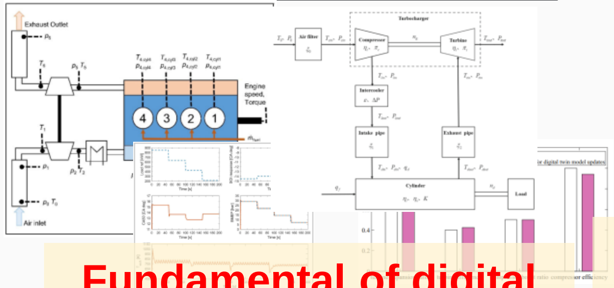
Progress in DT researches for marine engines



Framework



Real-time model



Fundamental of digital twin prediction function

Semi-physical bench

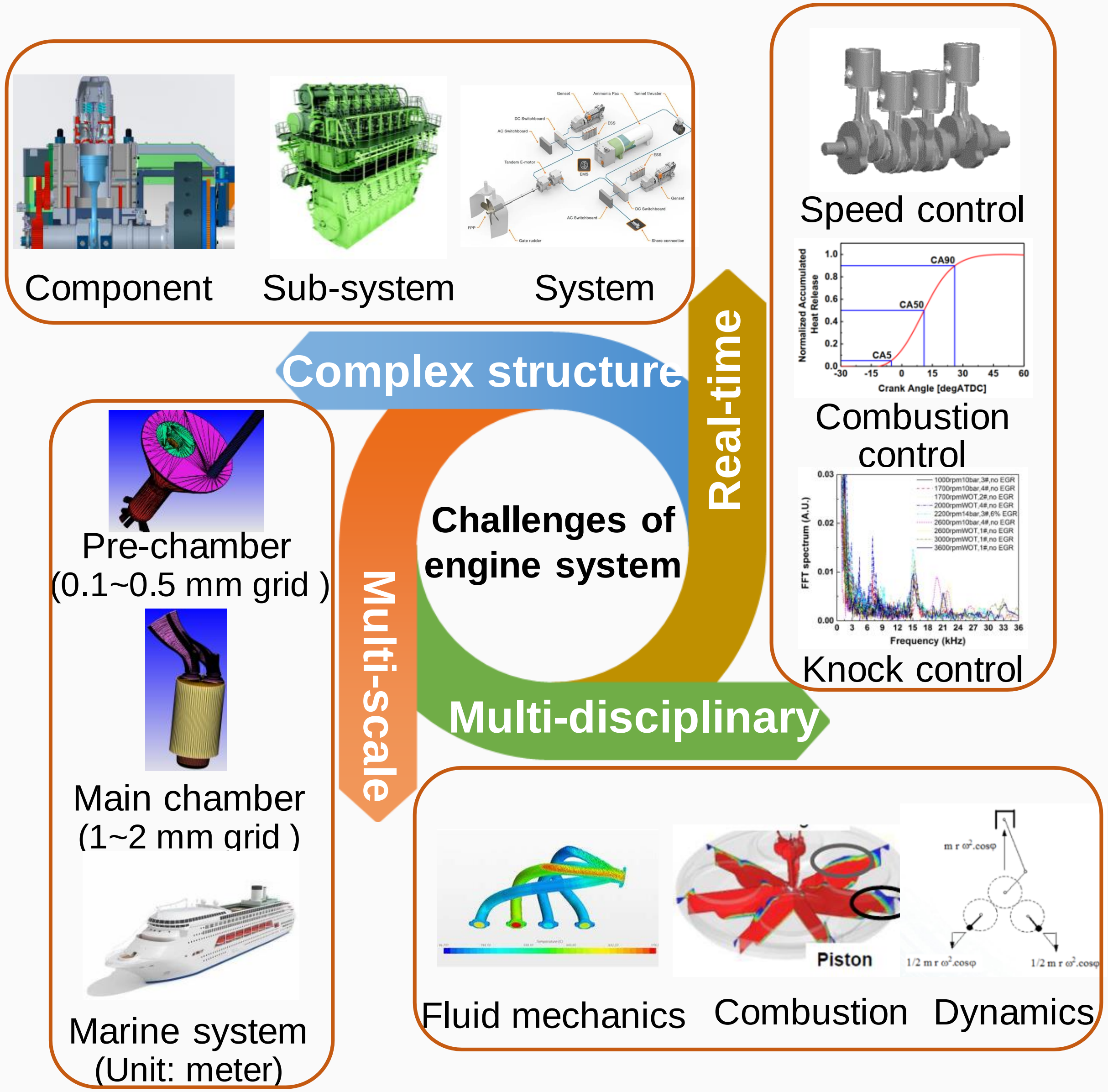
Lack of information interaction with real product and prediction model

3D visual system

Lack of prediction model

GAP: There is still a big gap in the application of digital twin, especially for the complex equipment of the marine system

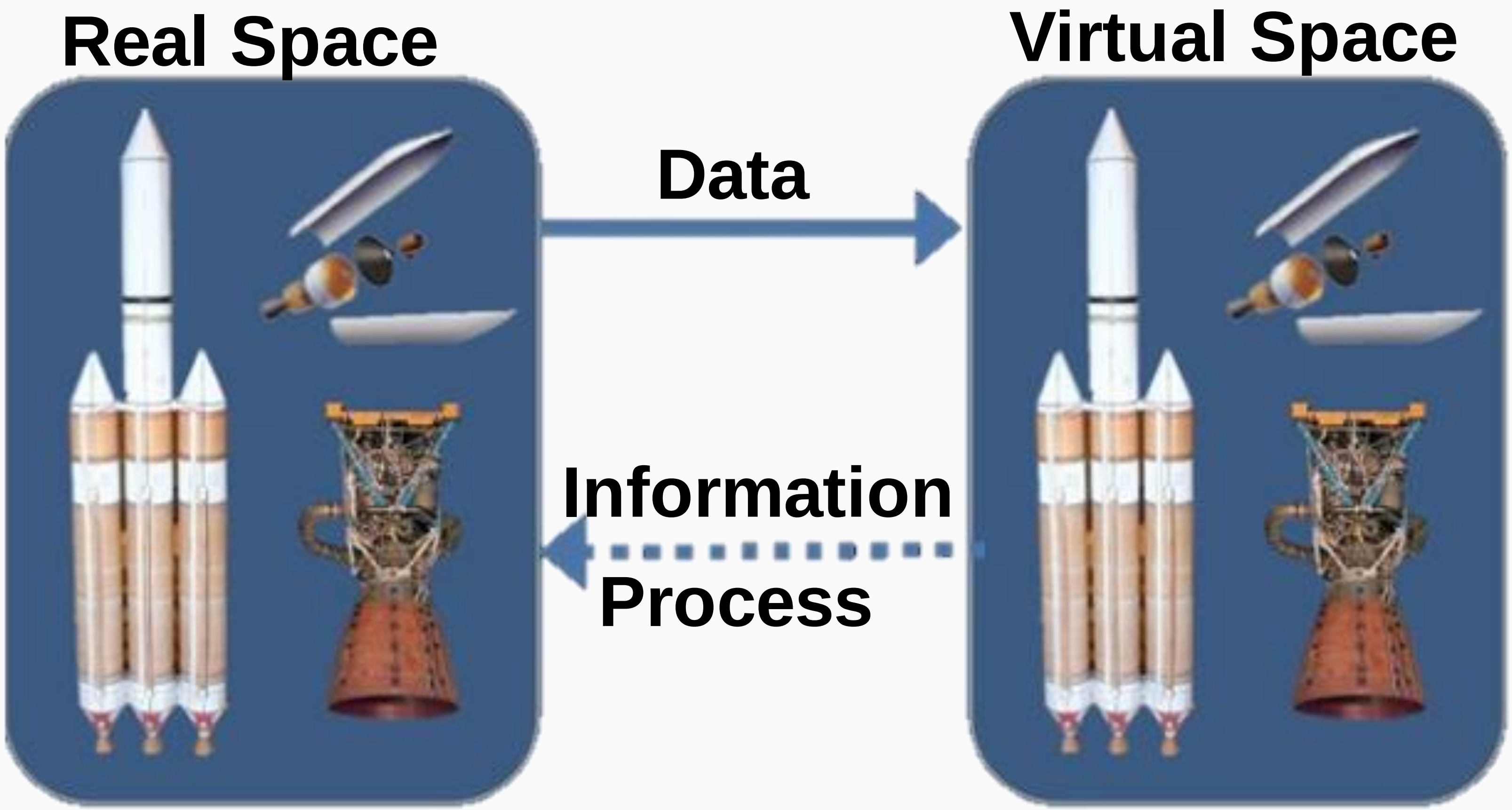
Challenges in building DT for marine engines



Challenges of digital twin models for marine system
Fidelity
Predictive
Real time
Reusability
Portability
Maintainability

How to construct high-fidelity real-time quasi-predictive twin model of marine system?

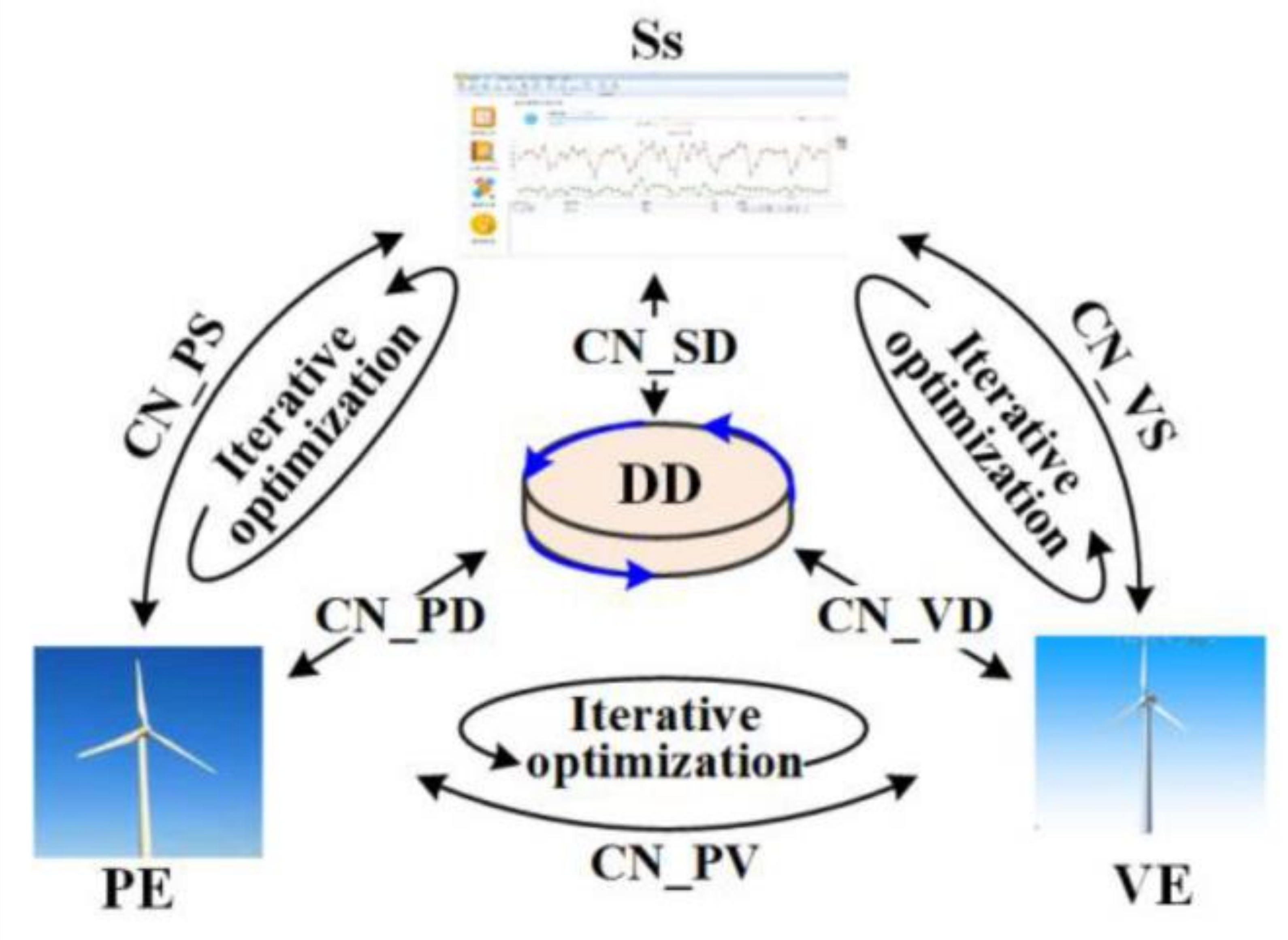
Three-dimension digital twin framework



- Real Space
- Virtual Space
- Connects between the real and virtual space

1. M. Grieves, “Digital Twin: Manufacturing excellence through virtual factory replication,” Whitepaper 2015.

Five-dimension digital twin framework



PE: Physical entity

VE: Virtual equipment

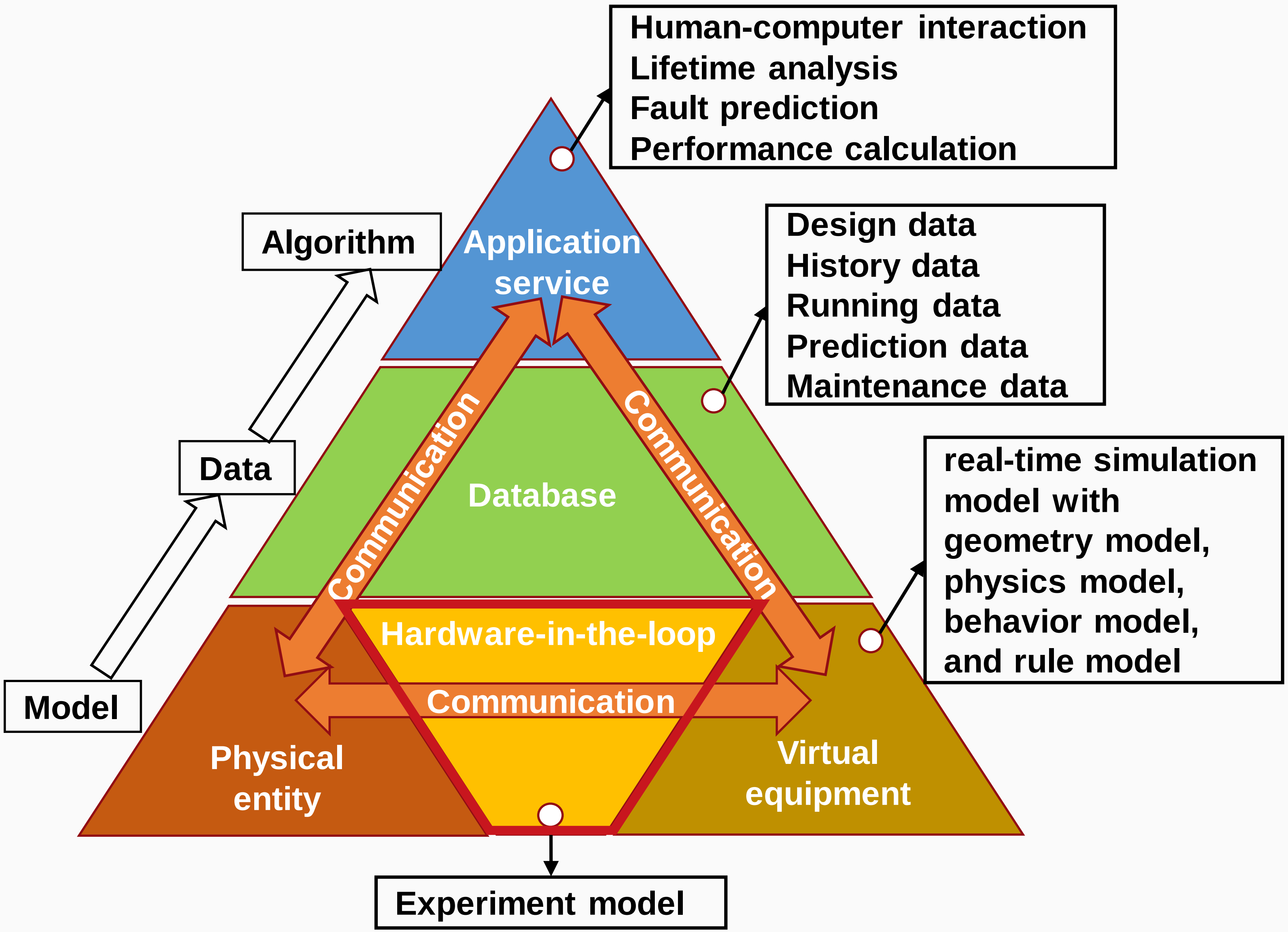
DD: Digital twin data

Ss: Services

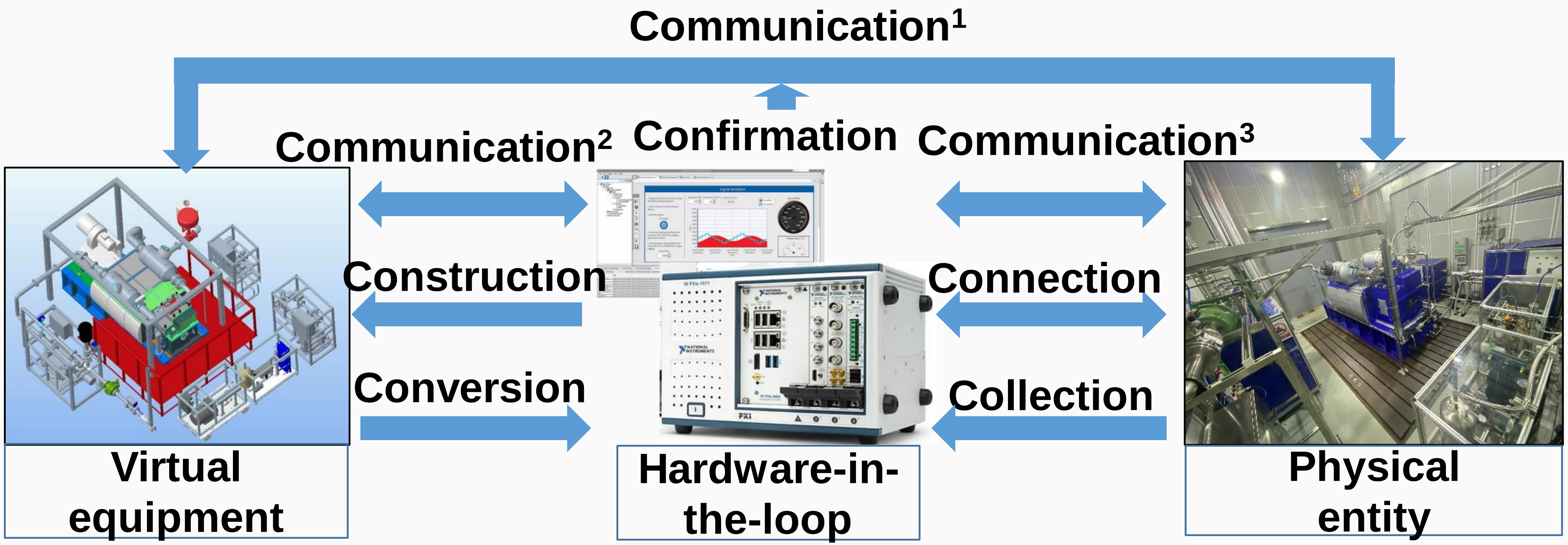
CN: Connection

1 Tao F, Zhang M, Liu Y, Nee AYC. Digital twin driven prognostics and health management for complex equipment. CIRP Ann-Manuf Techn 2018;67:169-172.

Six-dimension digital twin framework



HIL in six-dimension digital twin framework



Communication:

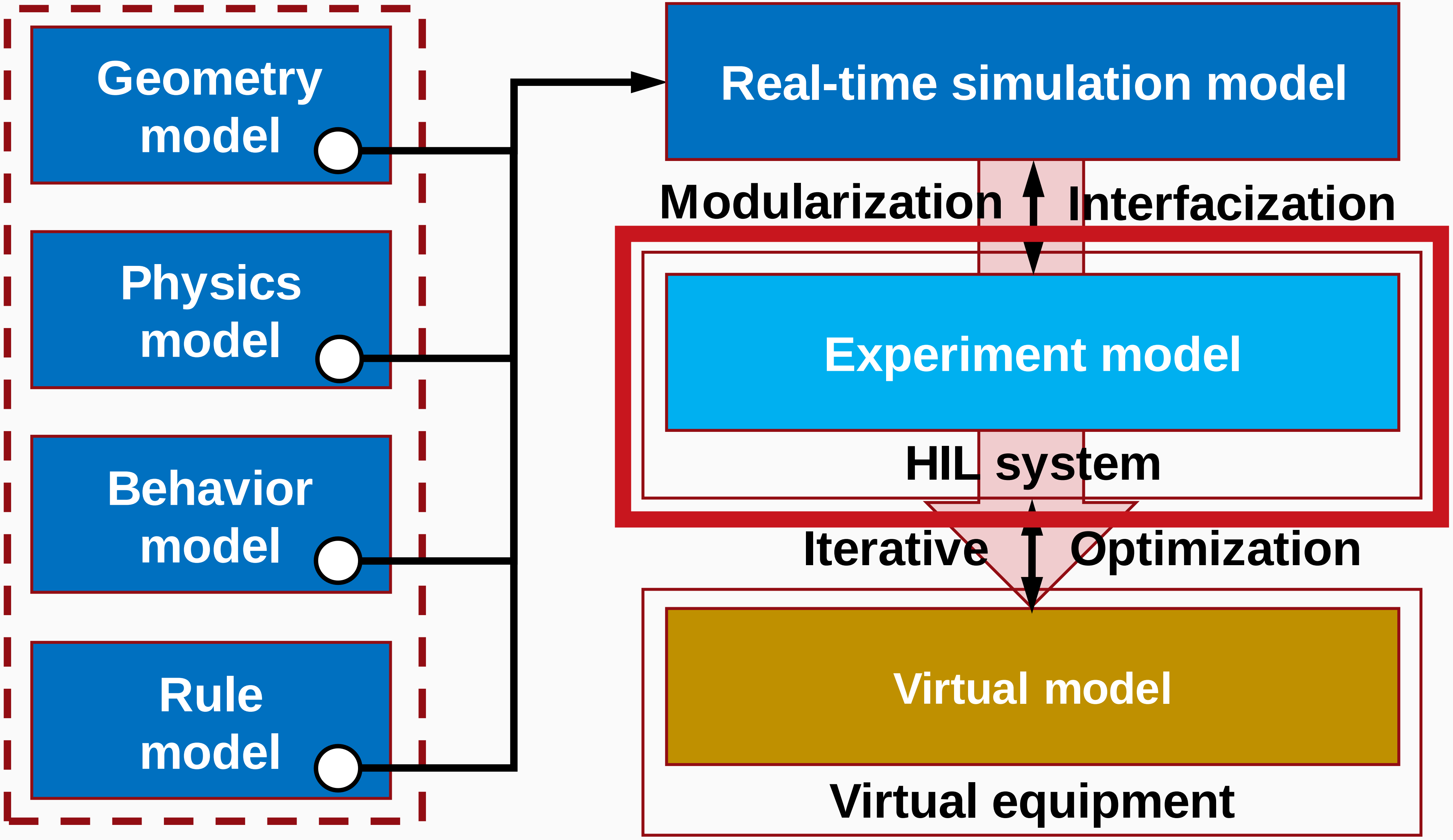
1. Real-time signal, optimized control parameter to physical entity

2. Optimized model parameter to virtual equipment, real-time signal for HIL in validation of control strategies

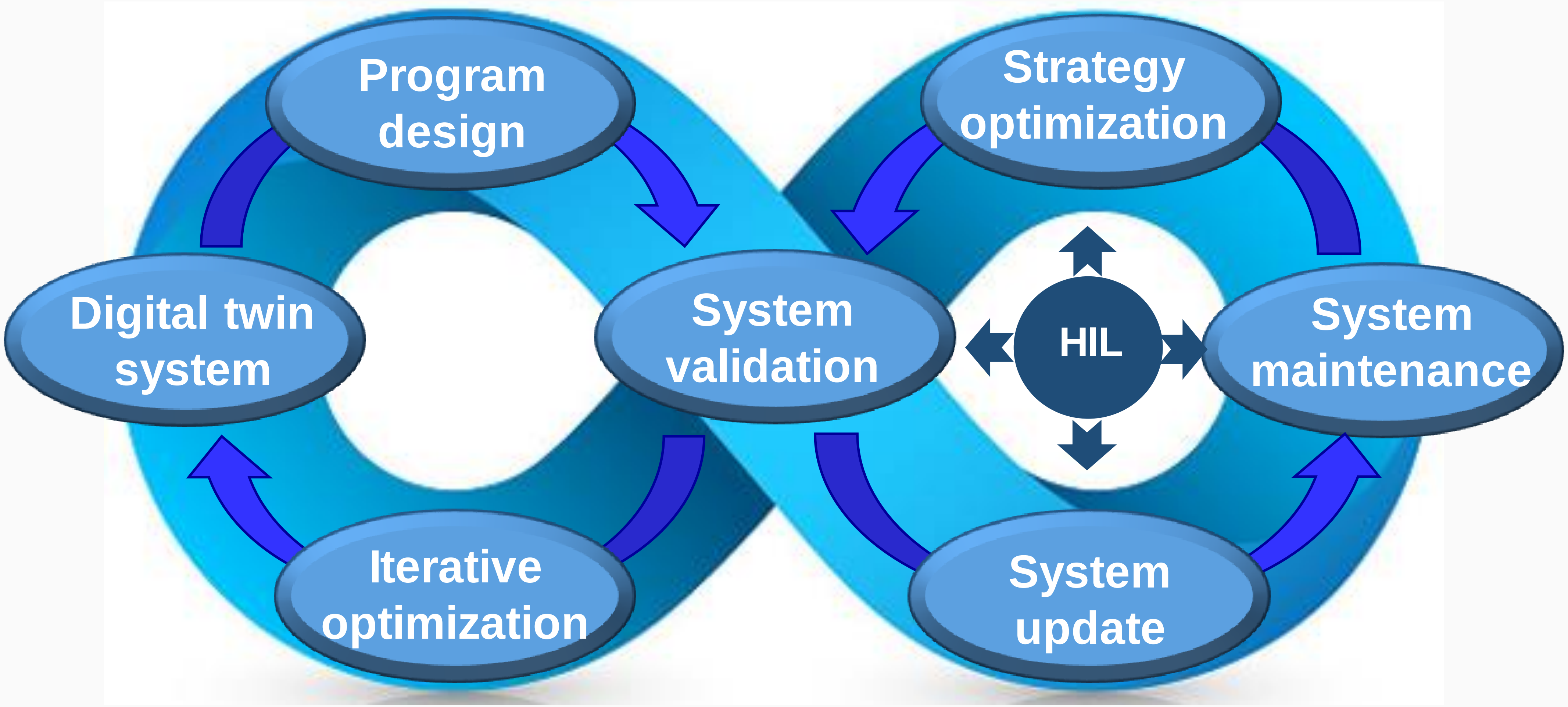
3. Real-time signal

6C: Communication, Connection, Collection, Construction, Conversion, Confirmation

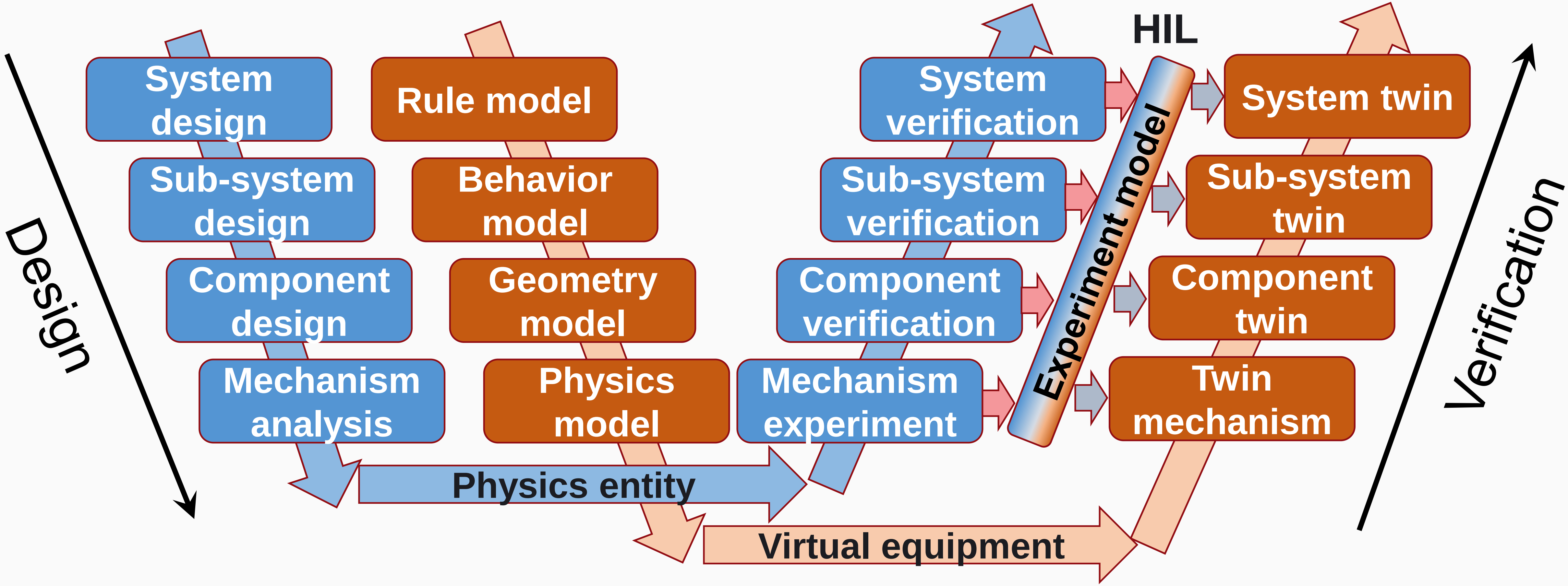
Models for virtual equipment and HIL



Digital twin system design and verification

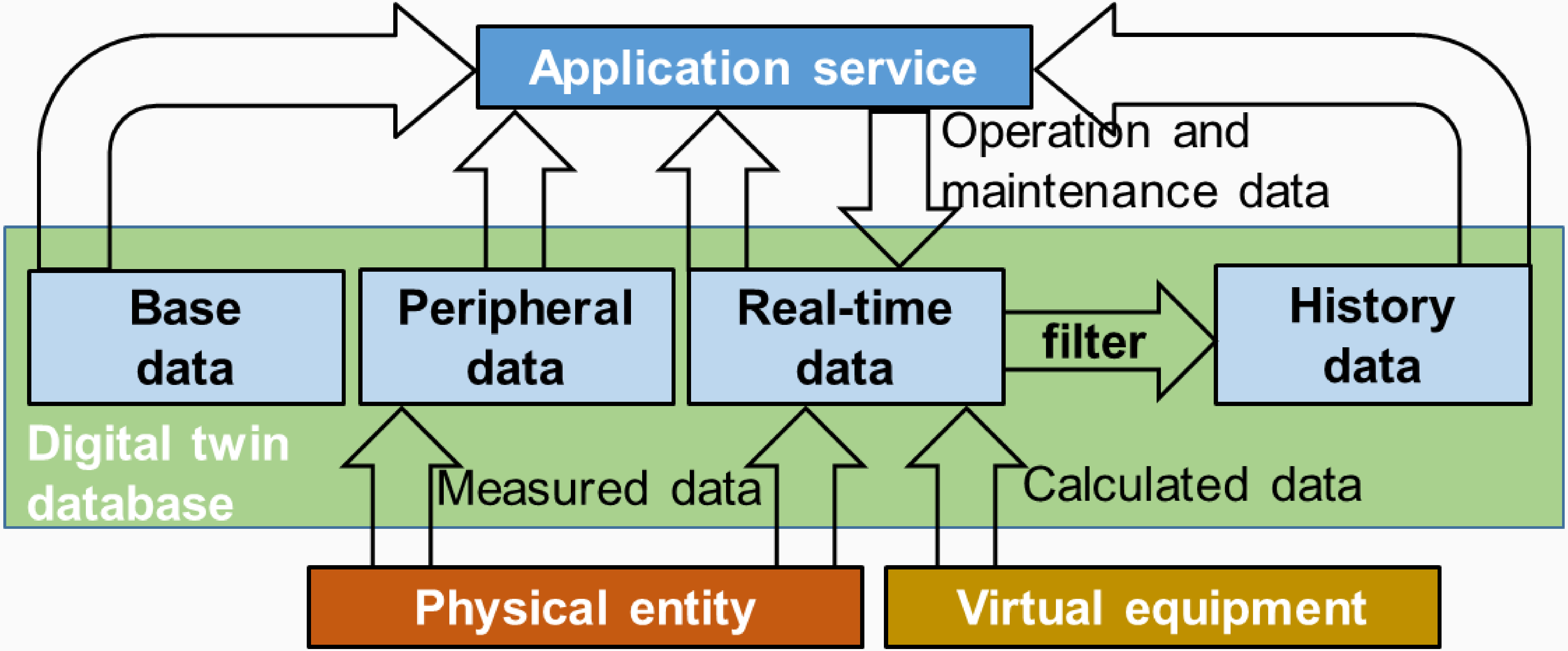


Double V-shaped digital twin modeling

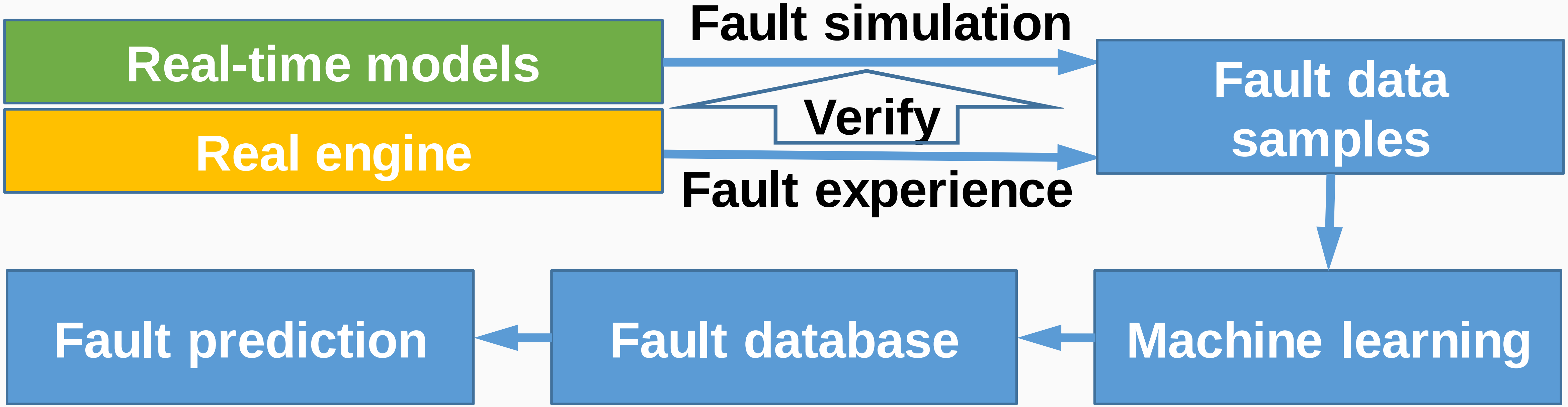


Double V-shaped digital twin modeling method

Database in digital twin system



Application of digital twin system

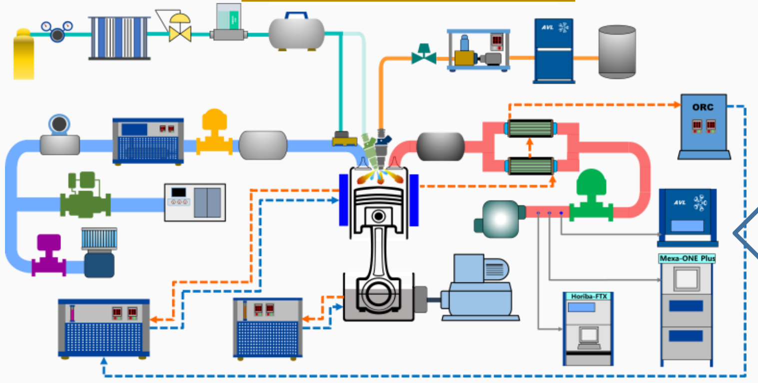


Fault prediction method based on digital twin

Application of digital twin system

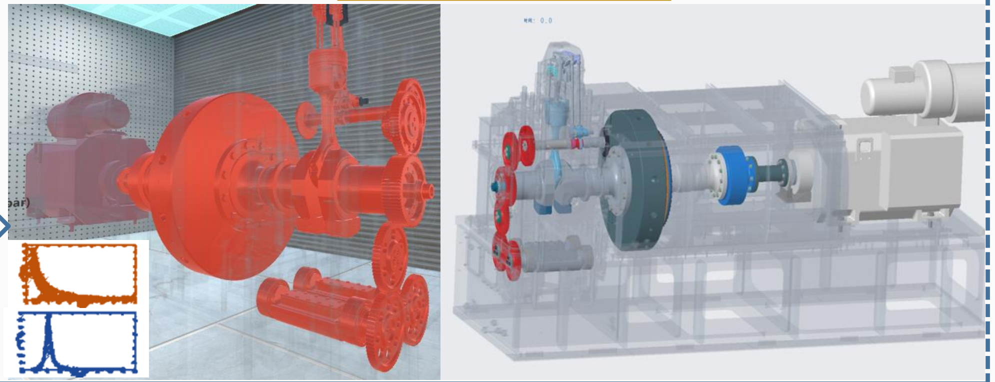
Display of measured and calculated system parameters

QT, VC++, etc.



Display of predicted performance parameters

Unity 3D engine



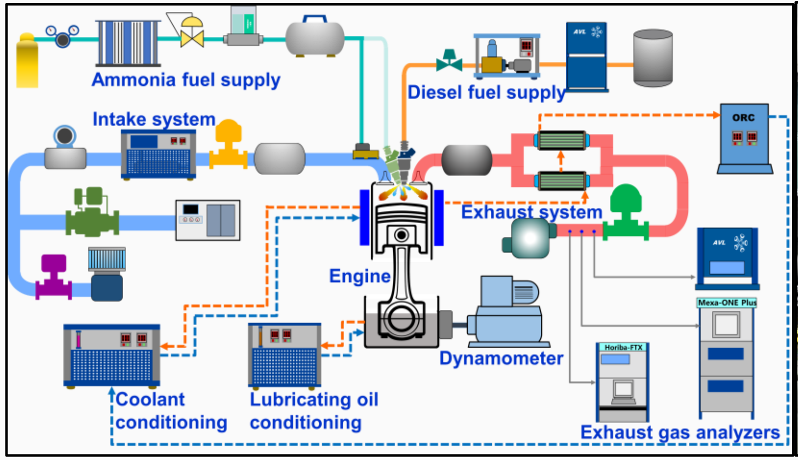
Human-computer interaction

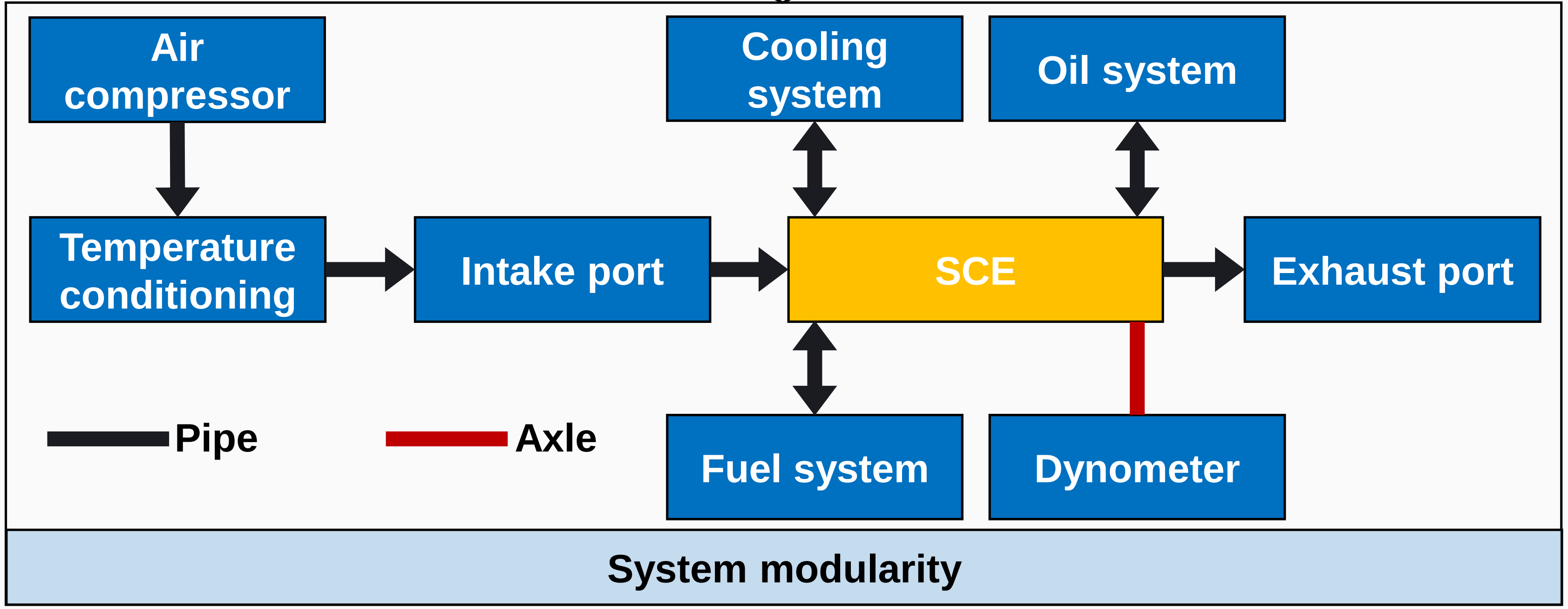
Engine performance and potential fault analysis

Application service

Digital twin database

SJTU SCE175 flex-fuel engine systems

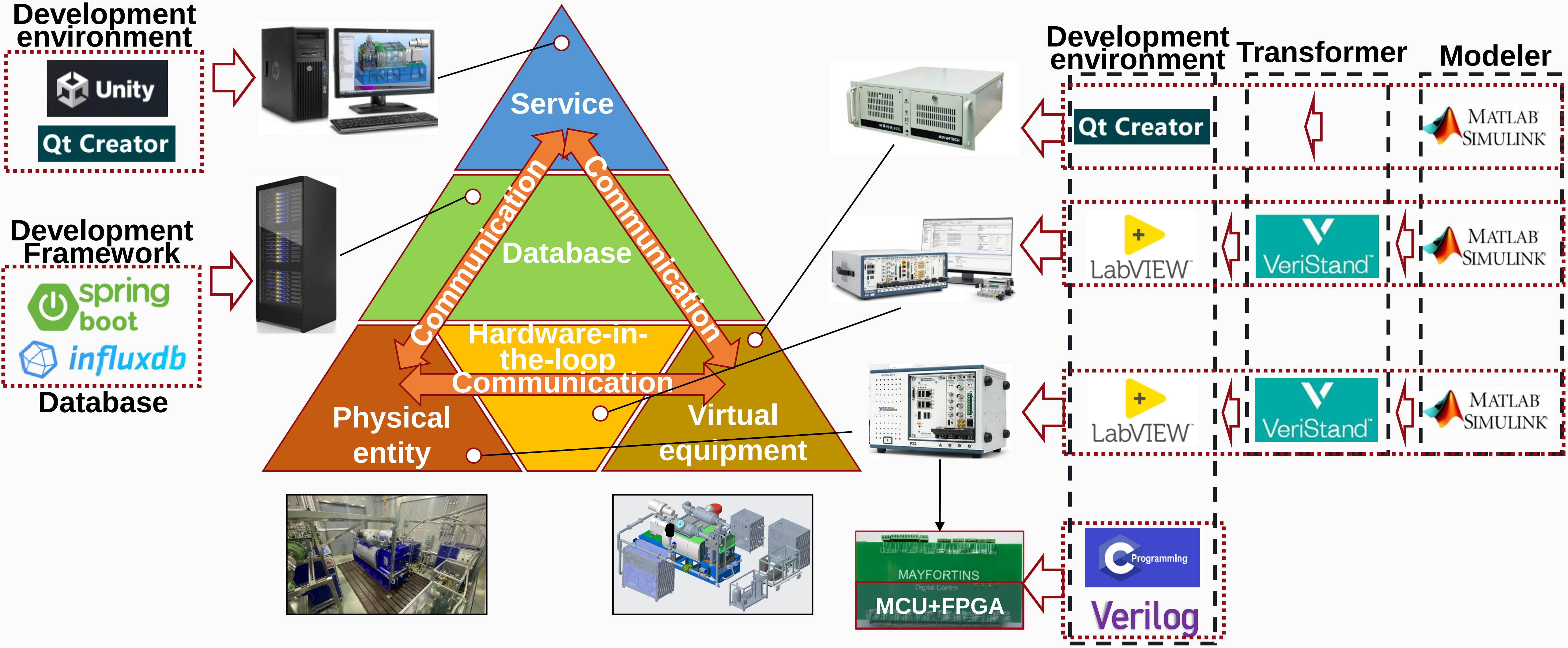




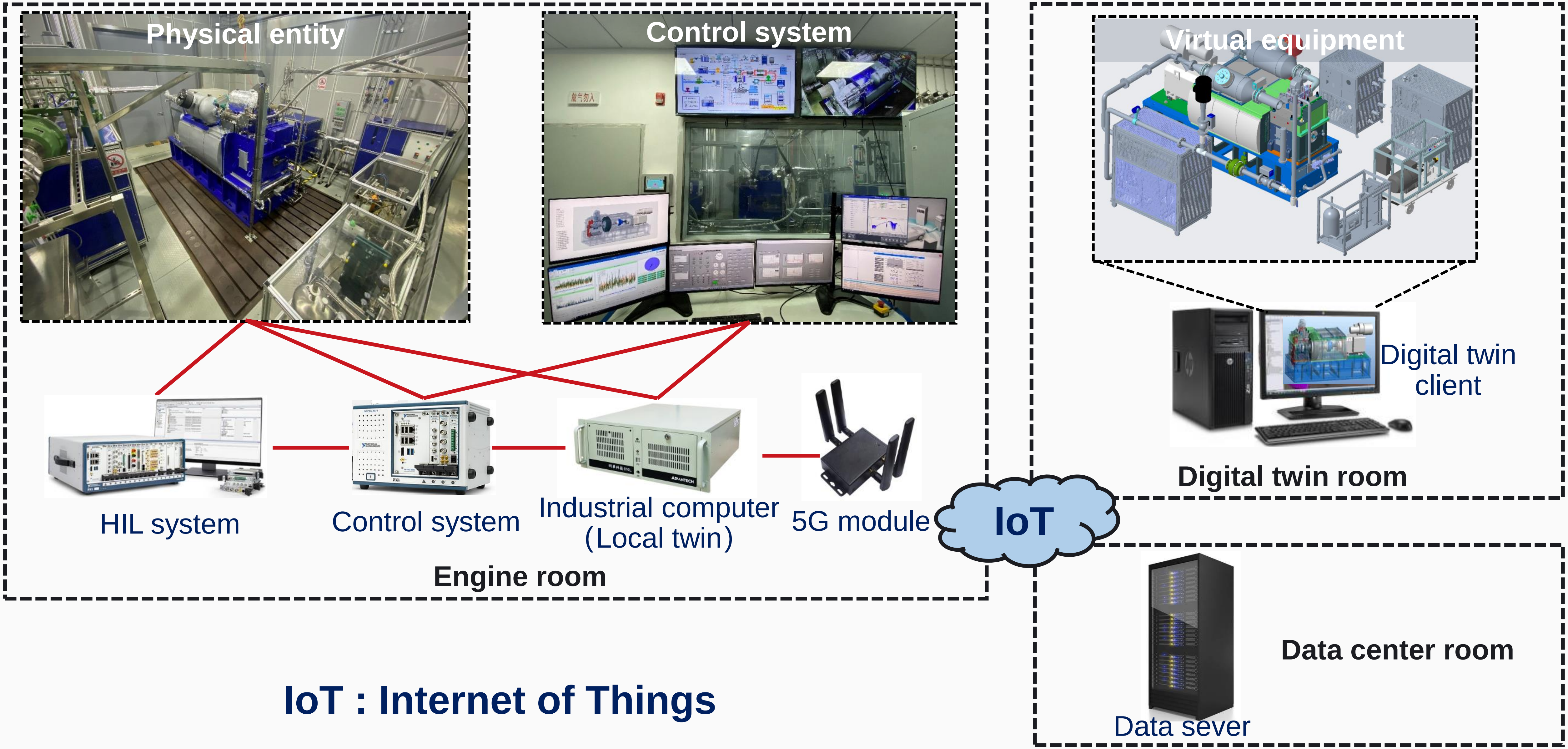
Specification	
Fuel	Flexible
Bore (mm)	175
Stroke (mm)	195
Comp. R(-)	15.6
Power (kW)	365
Speed (rpm)	2100
Max. IMEP(bar)	46.9

- Diesel / NG / Methanol / Ammonia /Hydrogen
- Simulated Turbocharging
- Regular / irregular exhaust emission measurement
- In-house R&D ECU
- Full instruments incl. pressure, temperature, vibration sensors

Digital twin of SJTU SCE175 engine system

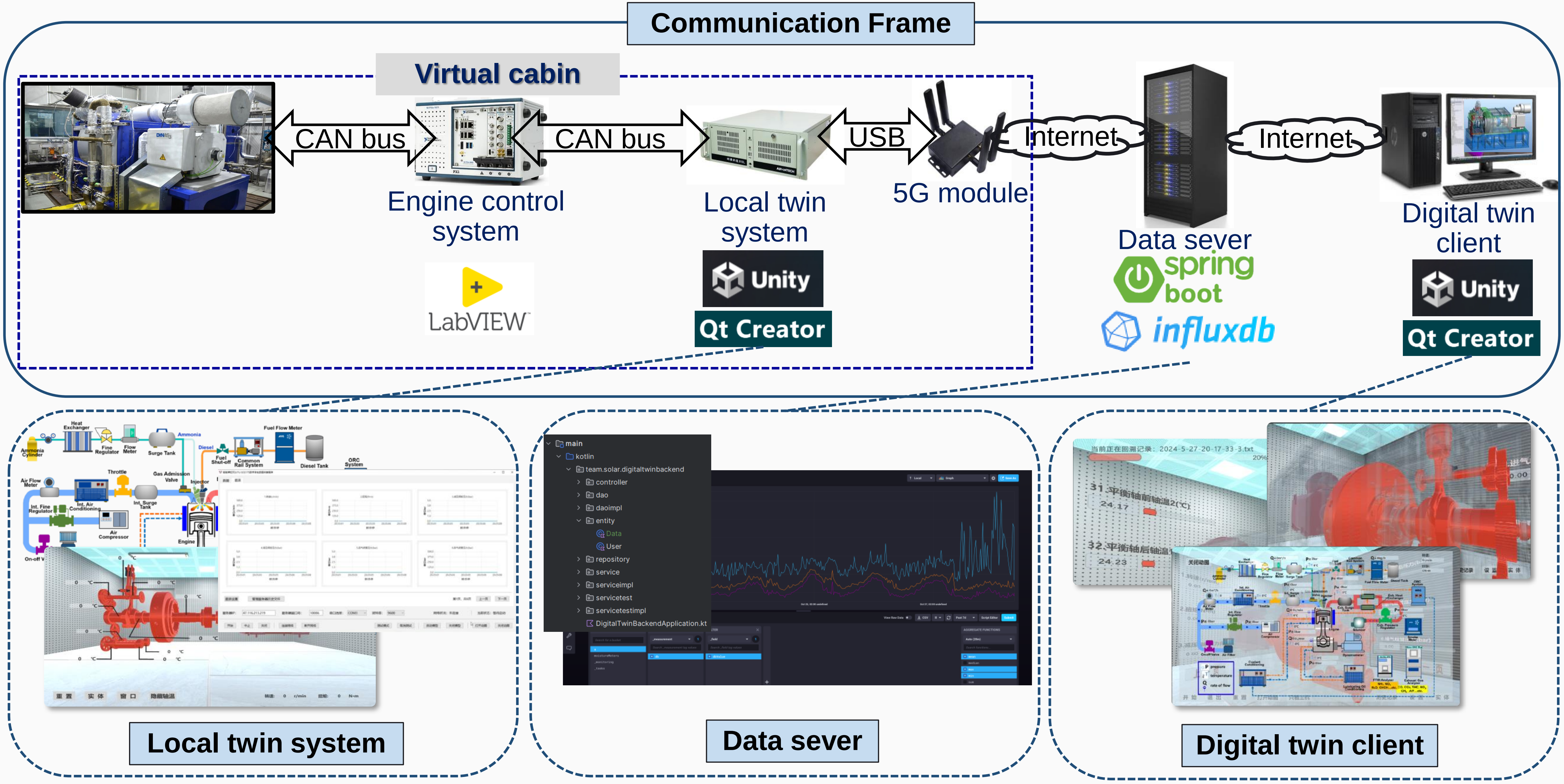


Digital twin of SJTU SCE175 engine system

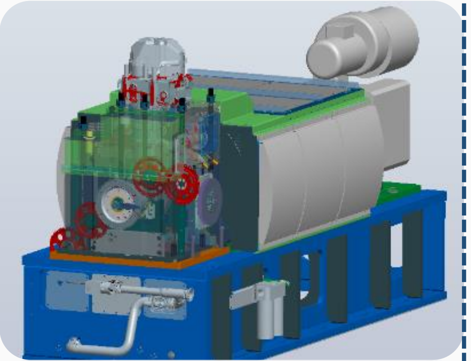


IoT : Internet of Things

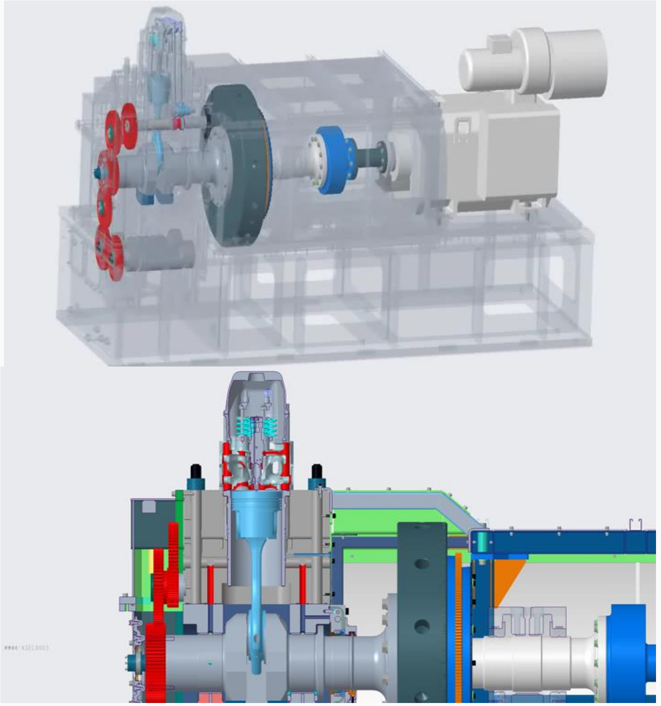
Digital twin of SJTU SCE175 engine system

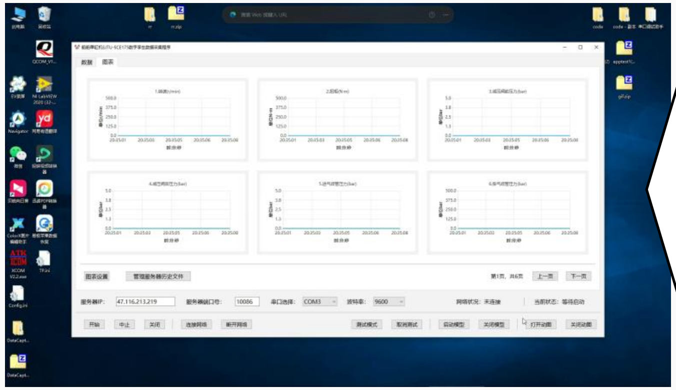


Digital twin of SJTU SCE175 engine system



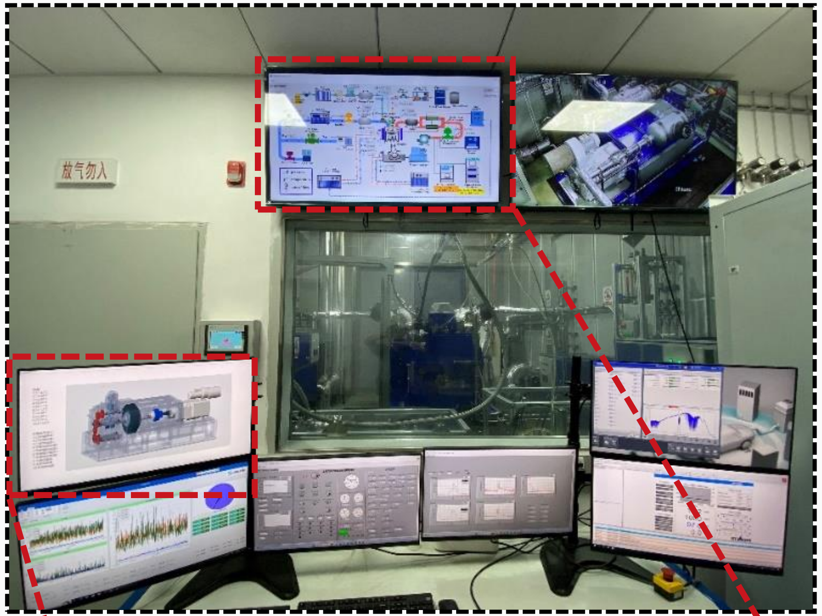
3D model

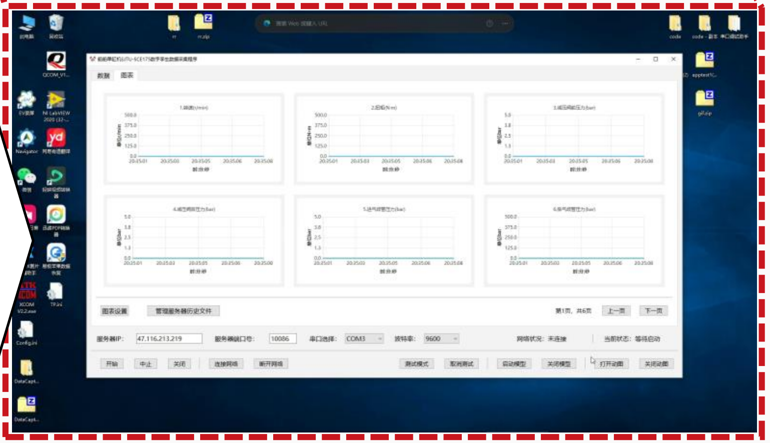




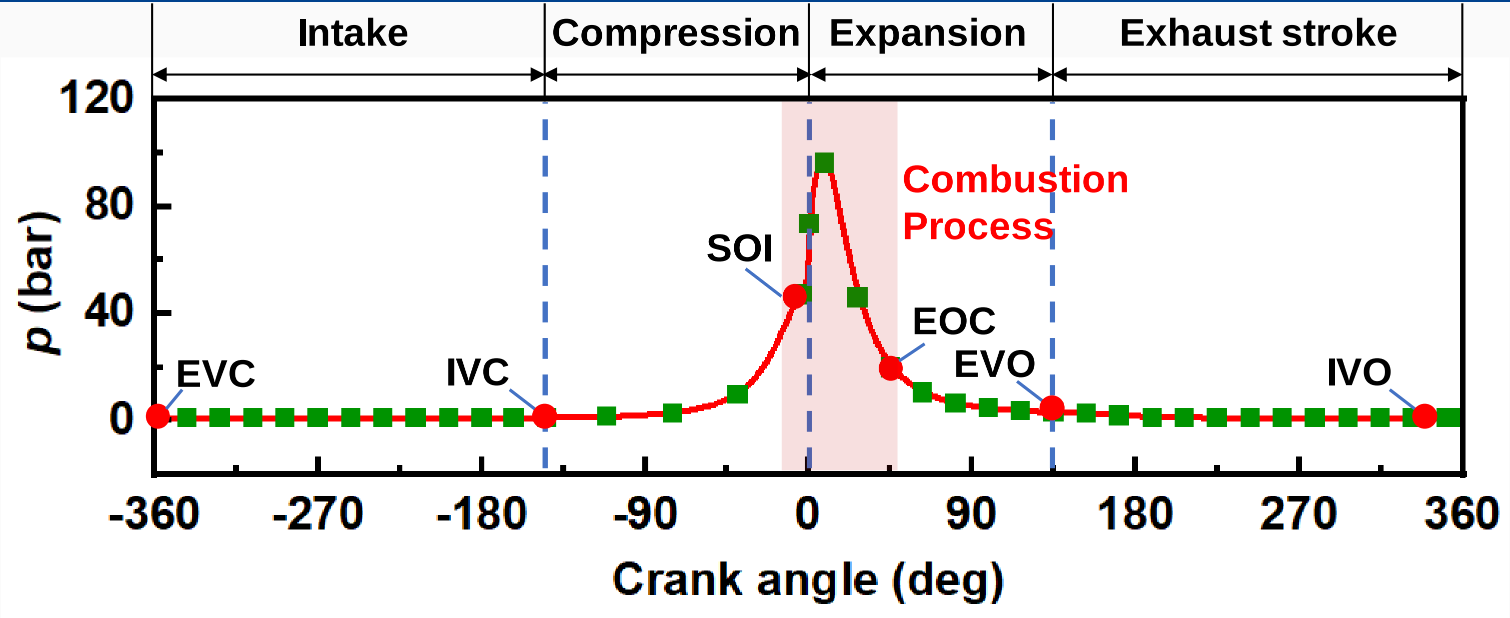
Real time

Pressure
Temperature
Vibration





Real-time model of in-cylinder pressure trace



Discretized variable time step model

$$\boldsymbol{IMEP} = \varphi \frac{\eta_{th} Q_{comb}}{V_{s,real}}$$

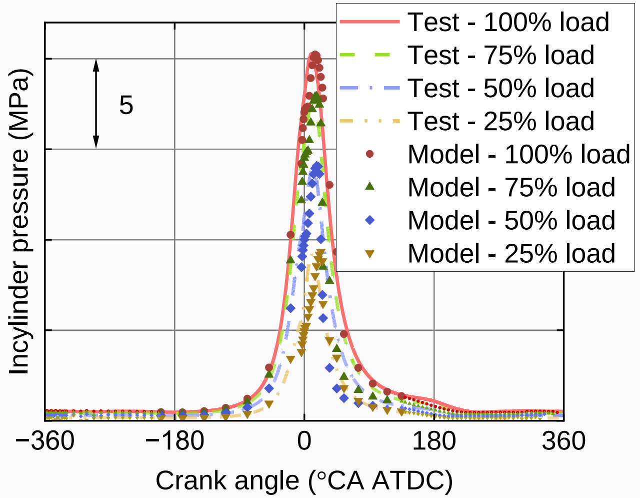
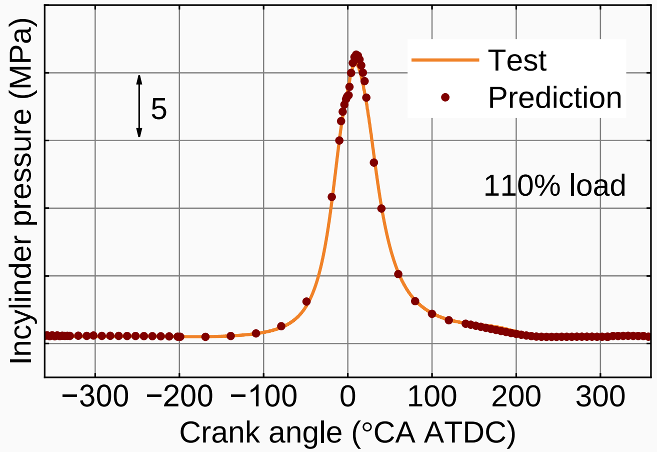
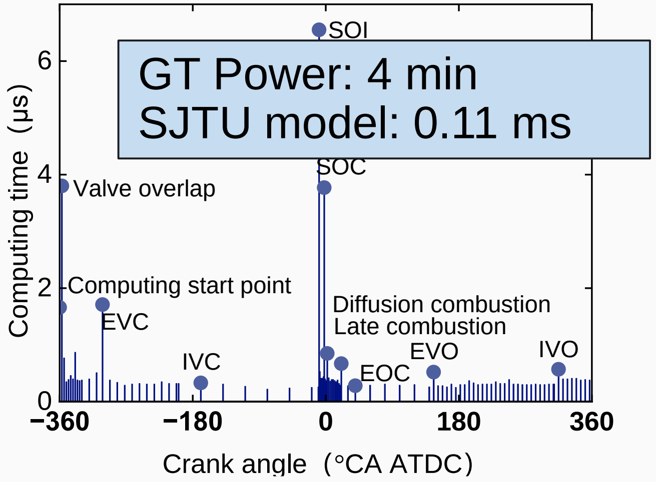
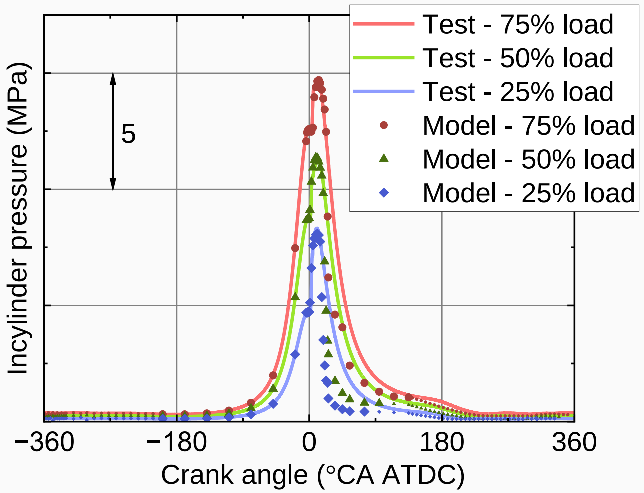
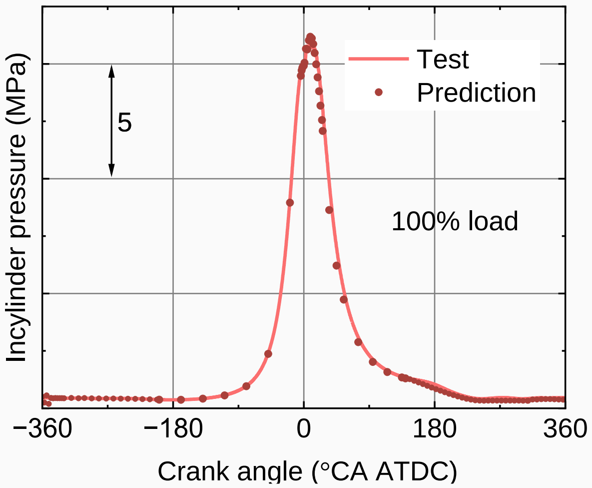
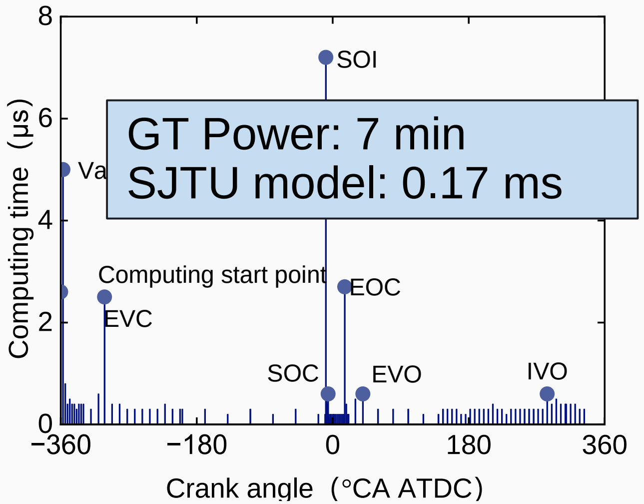
$$\eta_{th} = 1 - \frac{1}{\varepsilon_{real}{}^{\kappa-1}}$$

$$V_{s,real} = \frac{\varepsilon_{real} - 1}{\varepsilon_{real}} \frac{MRT_{IVC}}{P_{IVC}}$$

$$Q_{comb} = \frac{\eta_c H_u M_f}{1 + Y(\frac{1 + r_{EGR}}{1 - r_{EGR}})}$$

Exhaust + valve overlap	Intake stroke	Compression stroke	Expansion stroke
$P_i = P_{em}$ $T_i = T_{em}$ $M_{residual} = \frac{P_{em} V_{TDC}}{T_{em} R}$	$P_i = P_{im}$ $\quad T_i = \frac{P_{im} V_i}{M_i R}$ $T_{IVC} = T_{im}$ $M_{BDC} = M_{intake} + M_{residual}$ $M_{intake} = \frac{W_{ei}}{\frac{N}{2 \times 60}(1 - r_{EGR})}$ $M_i = M_{BDC} \sin^{1.5}(\theta_i / 2 \frac{\pi}{180})$	$P_i = P_{IVC}(\frac{V_{IVC}}{V_i})^{n_c}$ $T_i = T_{IVC}(\frac{V_{IVC}}{V_i})^{n_c - 1}$	$P_i = P_{EVO}(\frac{V_{EVO}}{V_i})^{n_e}$ $T_i = T_{EVO}(\frac{V_{EVO}}{V_i})^{n_e - 1}$ $P_{EVO} = P_{IVC} + \varphi \frac{\kappa - 1}{\varepsilon_{real}{}^{\kappa-1}} \frac{Q_{comb}}{V_{IVC}}$ $T_{EVO} = T_{IVC} + \varphi \frac{\kappa - 1}{\varepsilon_{real}{}^{\kappa-1}} \frac{Q_{comb}}{RM}$

Real-time model of in-cylinder pressure trace

	Calibration	Prediction	Computing performance
Diesel only			
Methanol/diesel dual fuel			

For a four-stroke engine run at 1000 rpm, 120 ms for one cycle, 0.16 ms for one crank angle!

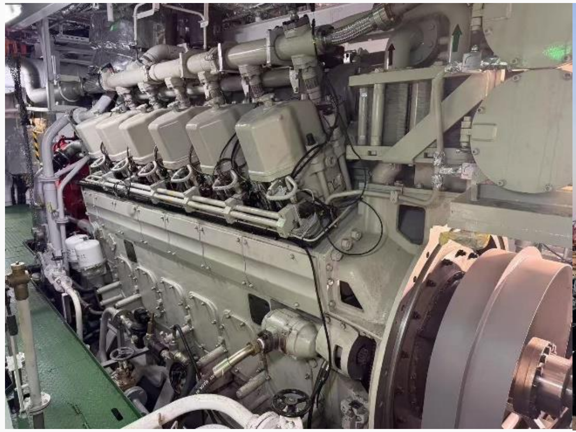
Summary and prospective

Summary

- The HIL technology is imported into the digital twin to form a six-dimension digital twin framework, solving the verification issue of the digital twin modeling for complex equipment.
- The application methods of the six-dimension and the corresponding the hardware and software platforms are described in details with an example of SJTU-SCE175.

Prospective

- Intelligent operations such as fault diagnosis, risk management and predictive maintenance of marine engine systems will be further developed based on the digital twin technology.
- Digital twins for the marine engines will be further developed and applied to real ship operations, ex. the ammonia powered tugboat.

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