Enabling Factors in the Development of Dynamic Digital Twins

GLOBAL PRODUCT DATA INTEROPERABILITY SUMMIT 2019

Multi-Physics Meta-Models

James Crist
Senior Application Engineer
EnginSoft

EnginSoft at a Glance

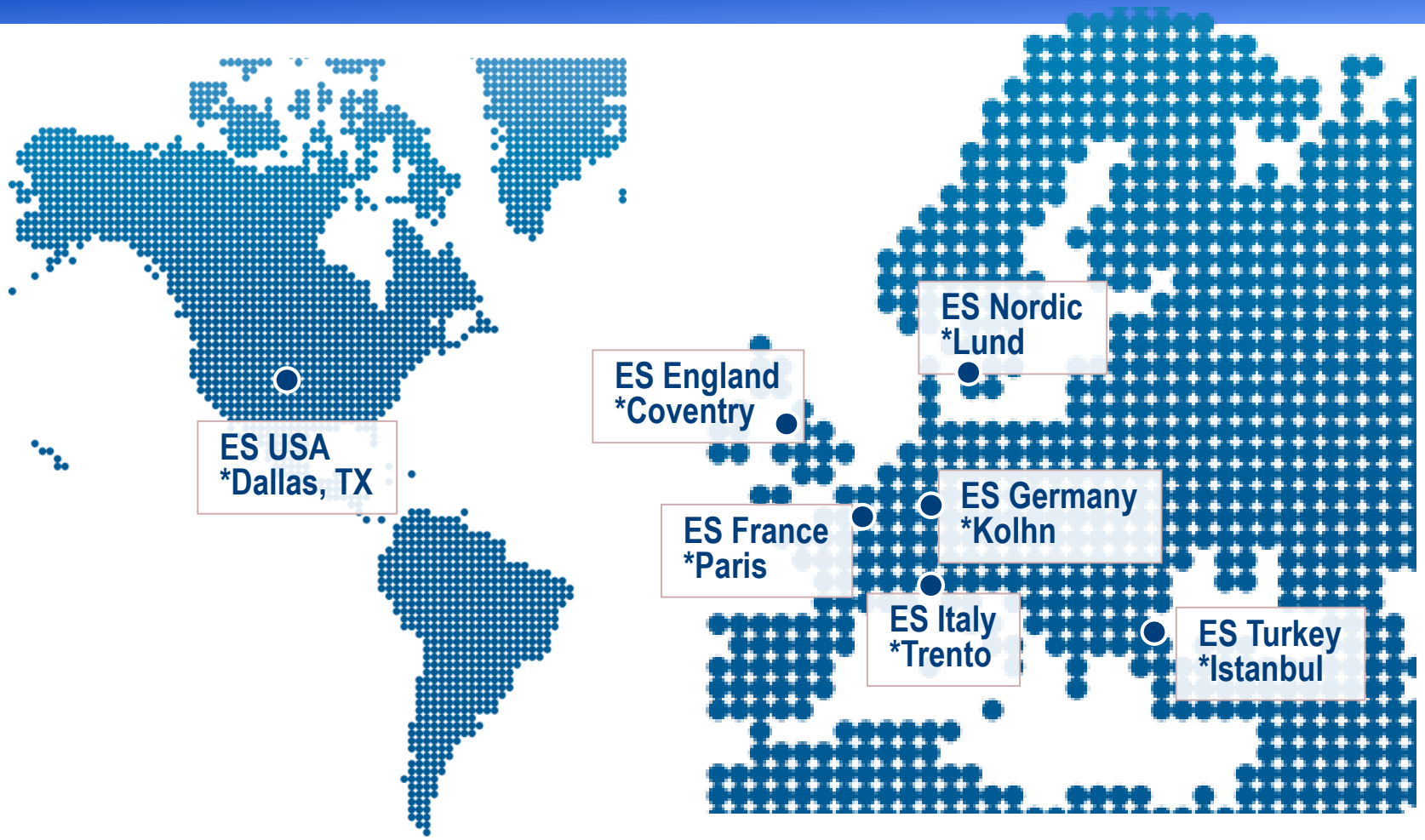
- **EnginSoft is a premier consulting firm in the field of Simulation Based Engineering Science (SBES)**
- **Multi-national company, with more than 200 experts in Virtual Prototyping and Optimization**
- **Deliver commercial & customized solutions featuring best-in-class CAE software, advanced training and technical support**
- **30 years history and relationships worldwide**

www.caeconference.com

Vicenza Convention Centre (Italy)
2019, October, 28-29

Global Presence

Global Product Data Interoperability Summit | **2019**



EnginSoft's DNA: Different by Choice

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- **Engineering Consulting**
- **CAE Software Solutions**
- **Customized Training**
- **Funded Research (*)**

(*) EnginSoft is a research center for numerical methods in engineering acknowledged by the Italian Ministry of Education, Universities and Research

Our skills

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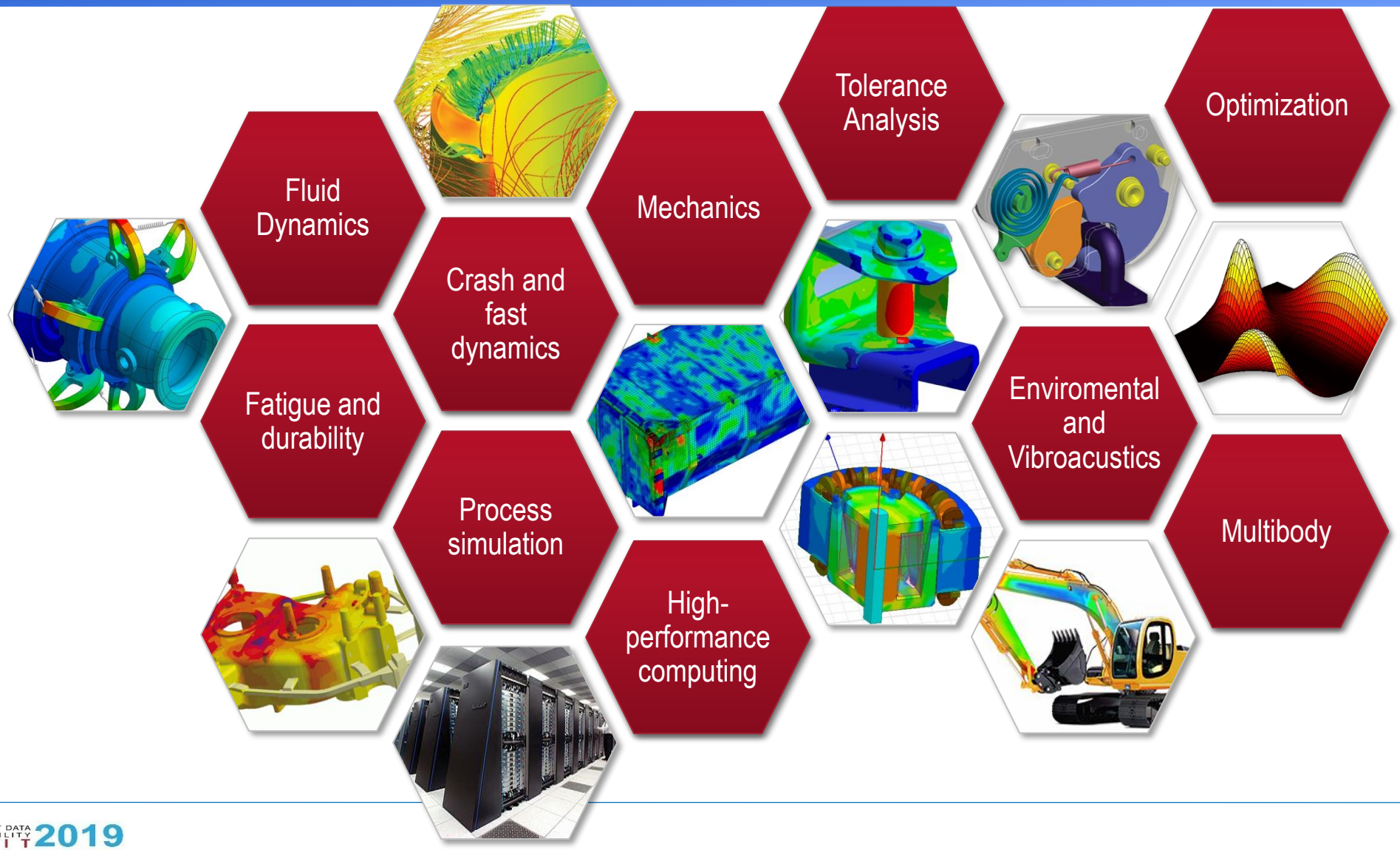

The technologies

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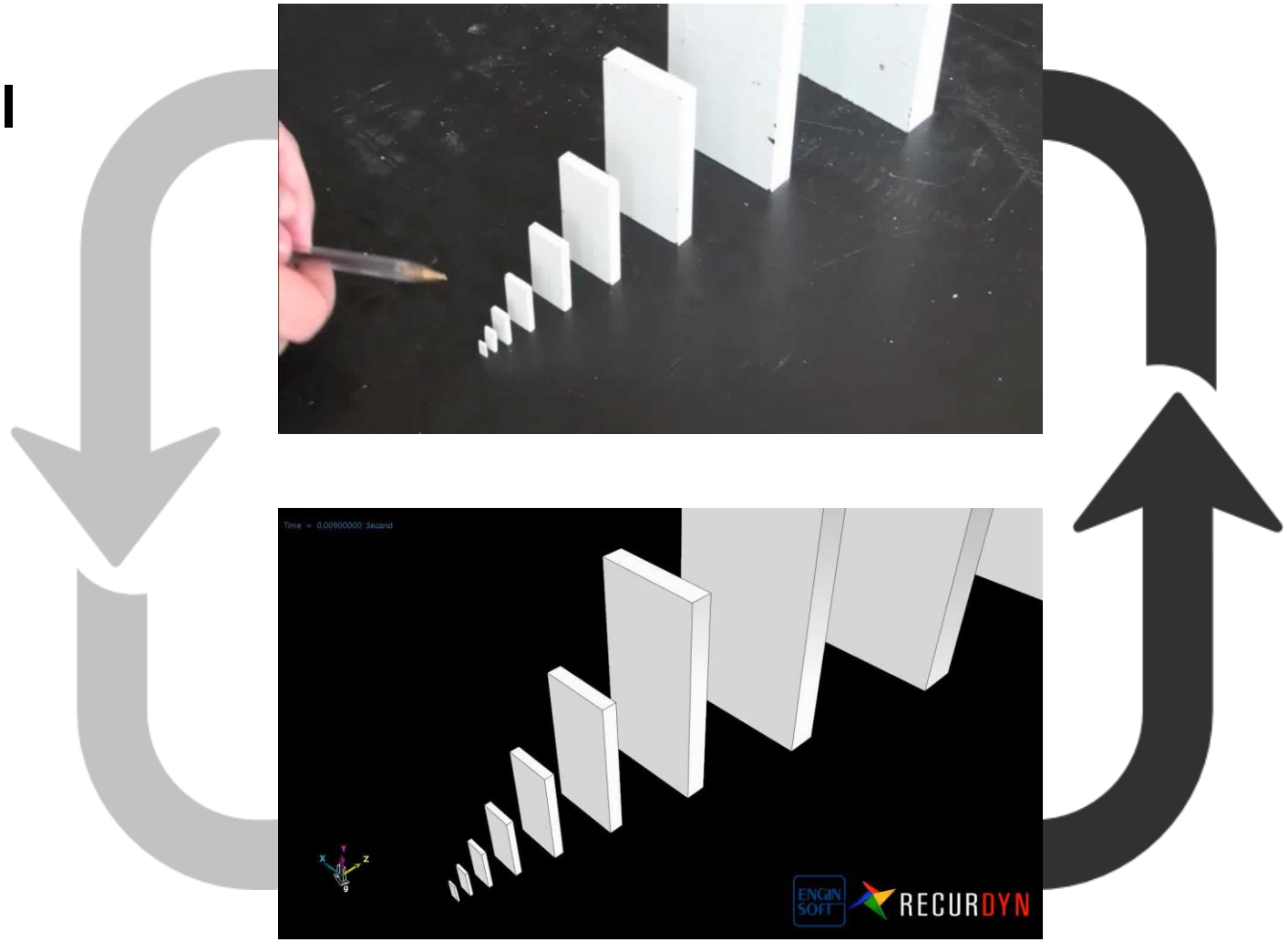
ANSYS
modeFRONTIER
MAGMA
SIMSOLID simulation reinvented
FORGE NxT 1.0
RECURDYN SOLUTIONS 4 ENGINEERS
ESAComp
LS-DYNA
Sigmetrix
FLOWNEX SIMULATION ENVIRONMENT
newmerical TECHNOLOGIES INT.
Total Materia

Agenda

- **Dynamic Digital Twin**
- **Meta Model or Surrogate Model**
- **Complexity and Reliability**
- **Development of Meta Models**
- **Calibration of Meta Models**
- **Take Home Message**



> ***With an estimated 21 billion connected sensors and endpoints by 2020, digital twins will exist for billions of things in the near future. Potentially billions of dollars of savings in maintenance repair and operation (MRO) and optimized IoT asset performance are on the table.***

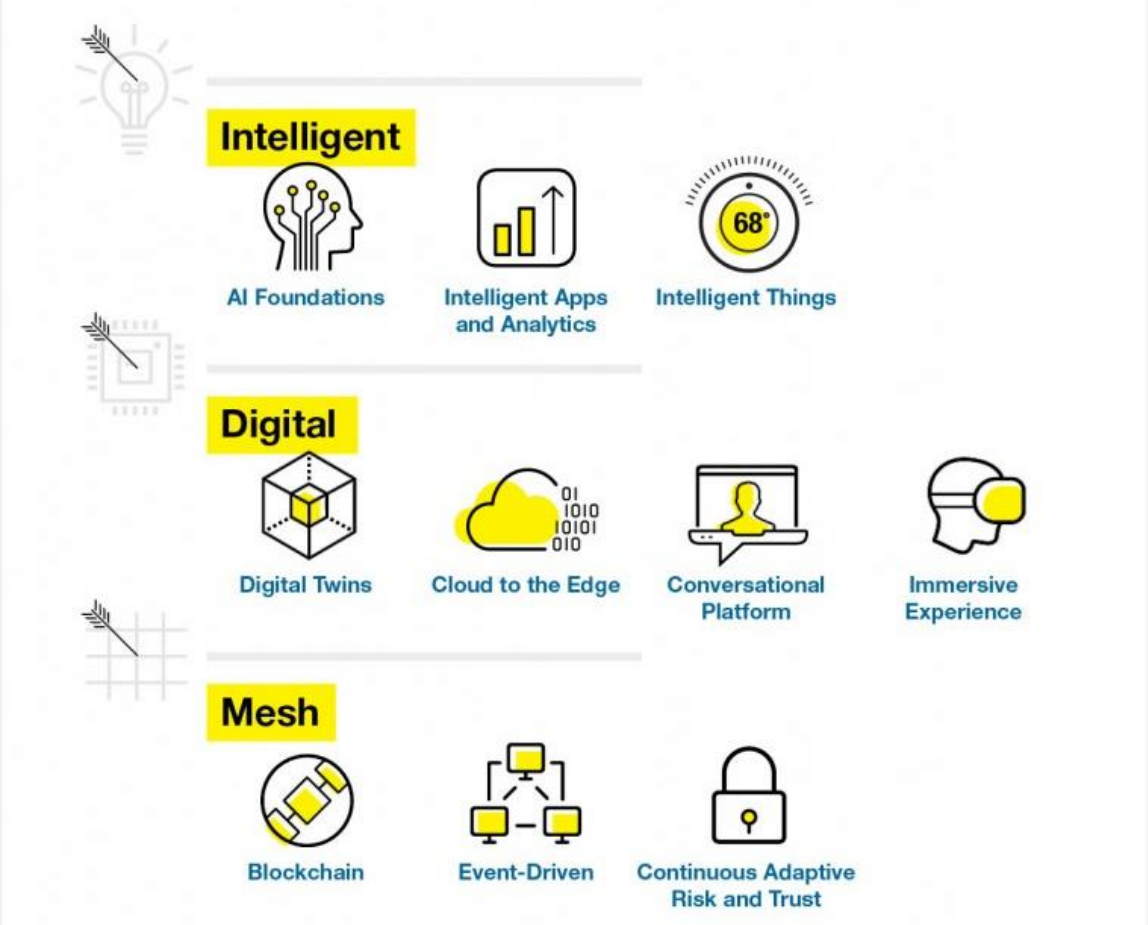
David Cearley, VP of Gartner

Is it a hot topic?

Digital Twin

- **Digital representations of a "real-world" entity, system, process**
  - **<u>Mathematical models</u>**
- **In the context of IoT (Industry 4.0) they are linked to real-world objects**
  - **return the state of the counterparts**
  - **respond instantaneously to changes**
  - **improve / predict operations**

Top 10 Strategic Tech Trends 2018
(gartner.com/SmarterWithGartner)



Digital Twins In CAE Industry

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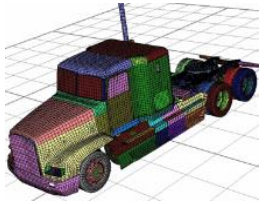
1960 → 1975 → 2019

Digital Mockup

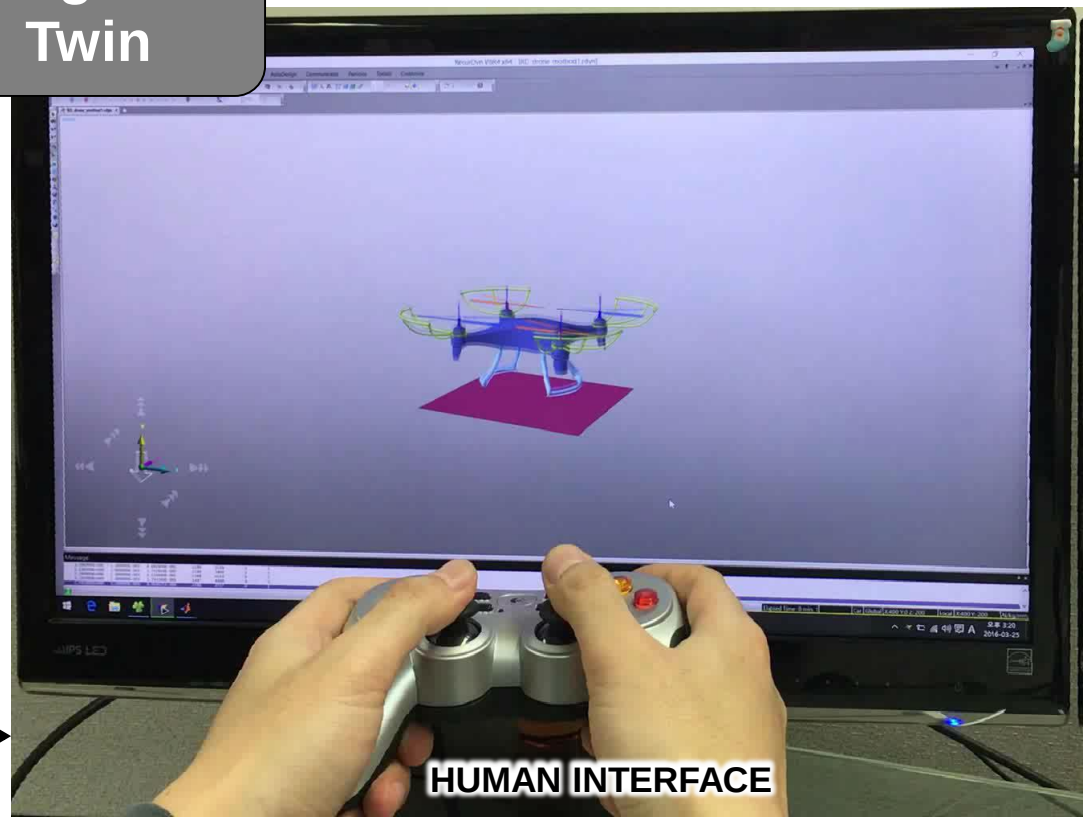
Virtual Prototype



Digital Twin

ON LINE SENSOR DATA

- **CAMERA**
- **ACCELEROMETER**
- **GPS**
- **GYROS**
- **...**



Digital Twin Development Steps

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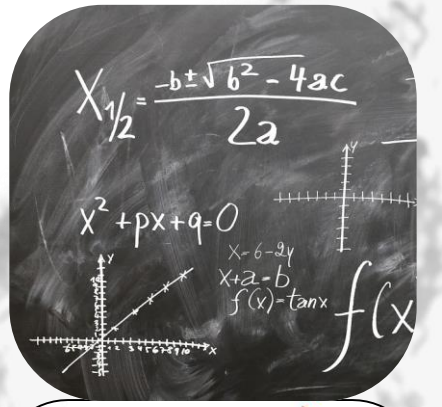
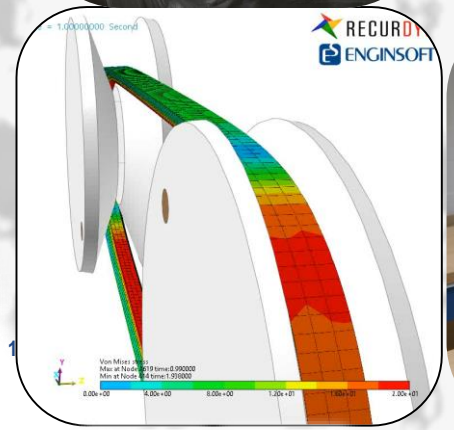
THEORY



KNOWLEDGE



SIMULATION

DATA

CAPTURE

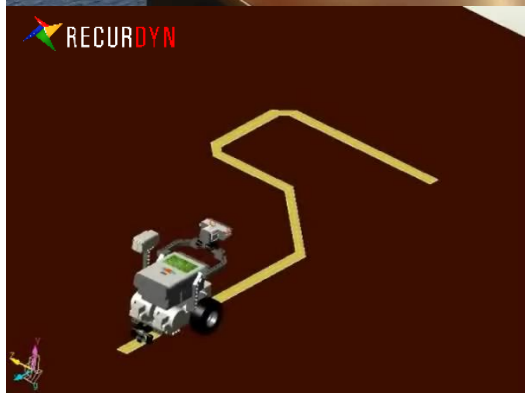
UNDERSTAND I/O

CREATE
VALIDATE
TRANSLATE

SUPPORT MODEL

"model" is an abstract representation of the selected phenomenon.

USE



Digital Twins as Part of a Digital Ecosystem

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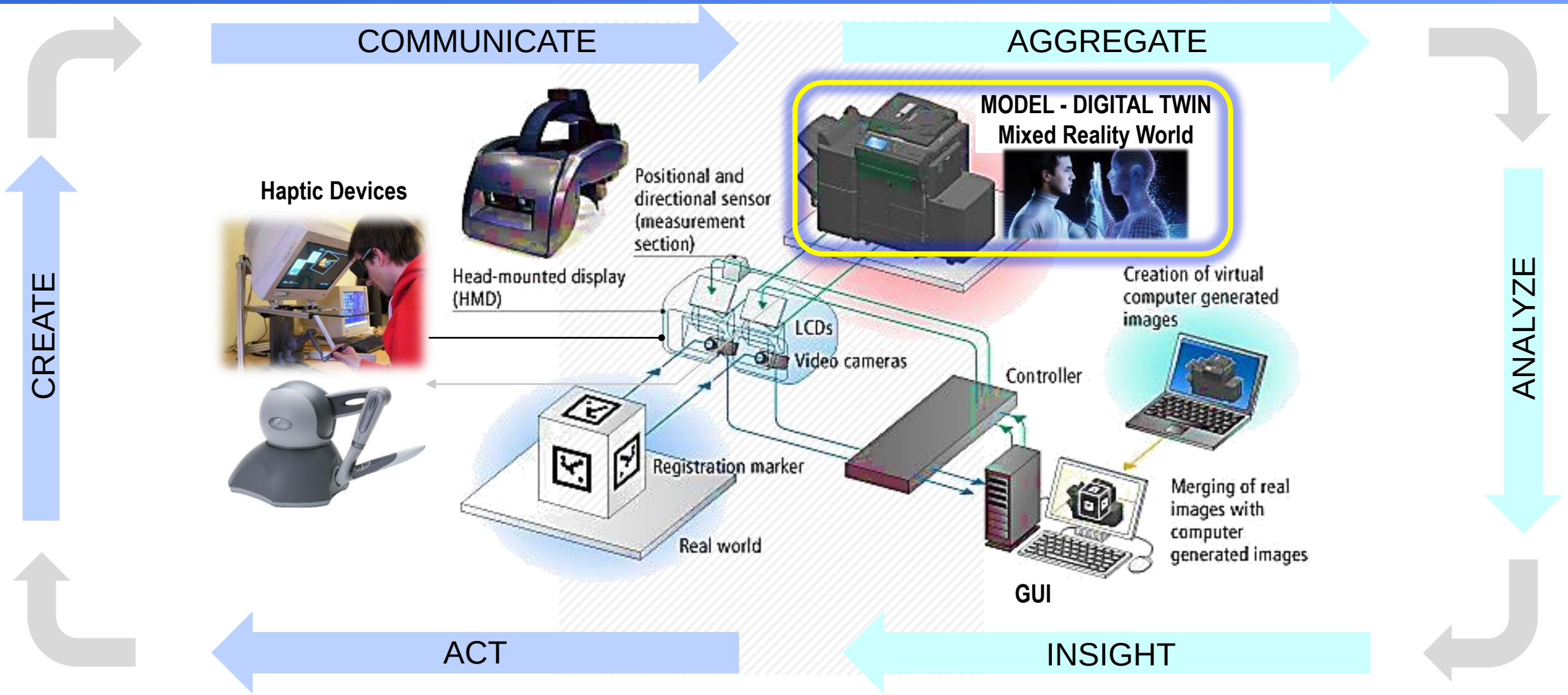
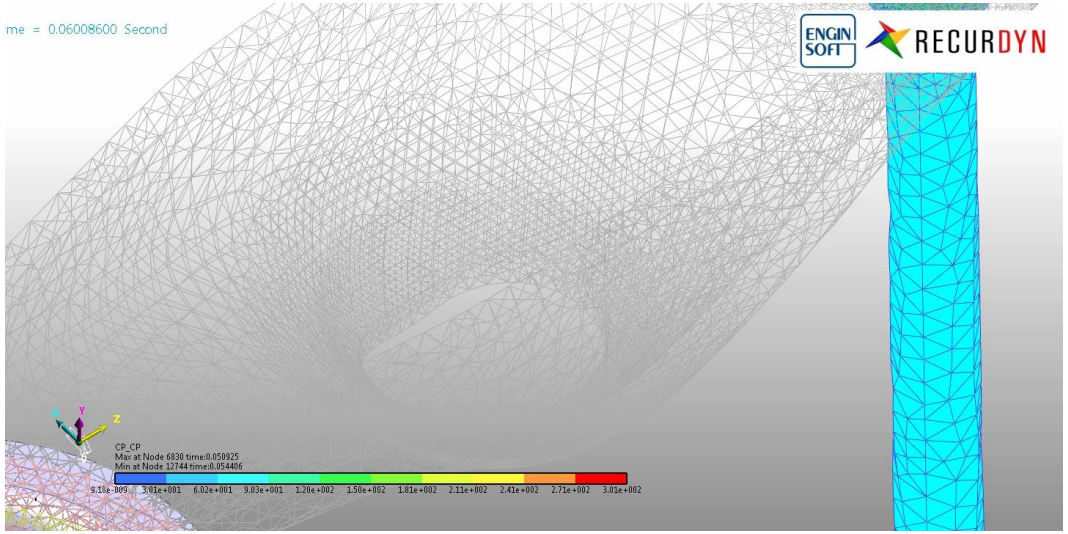
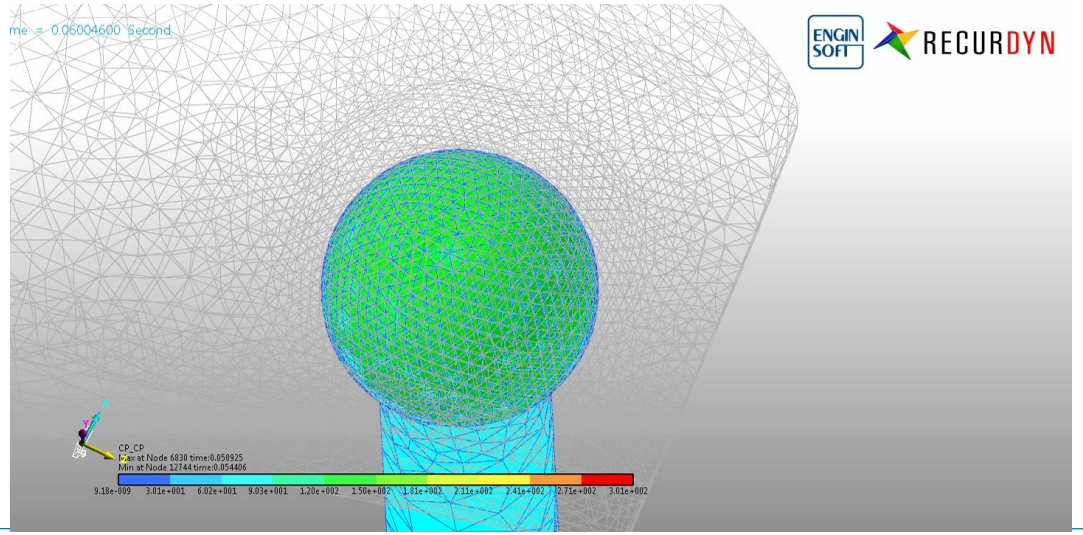


Digital Twin General Specifications

- **Reliability**
  - **leverage engineering knowledge**
  - **introduce machine learning**
- **Velocity**
  - **computational power, data storage, infrastructure**
  - **develop & optimize kernel models**
  - **adjust the optimal level of detail**
- **Standardization**
  - **highest possible value and best chance of success**





Wealth of Information vs Velocity

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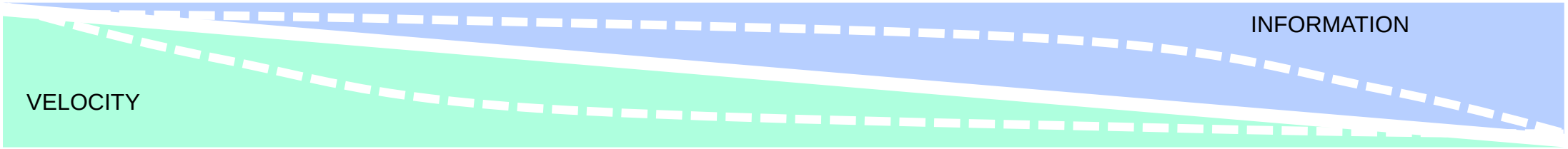
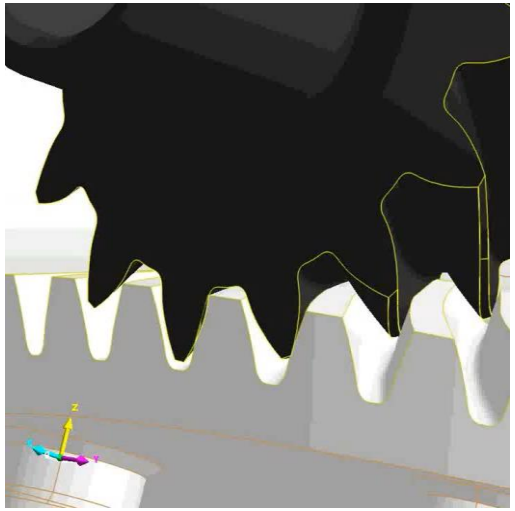
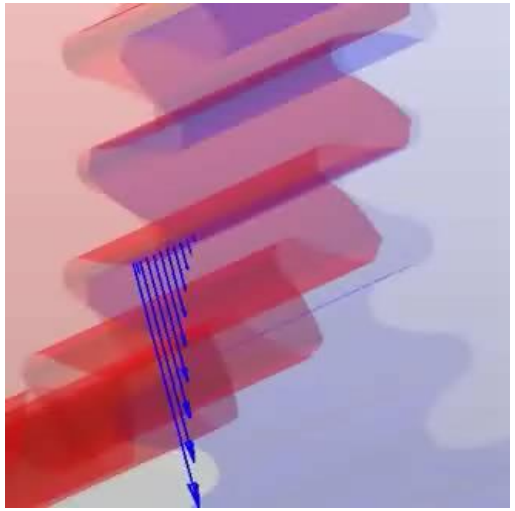


MODEL

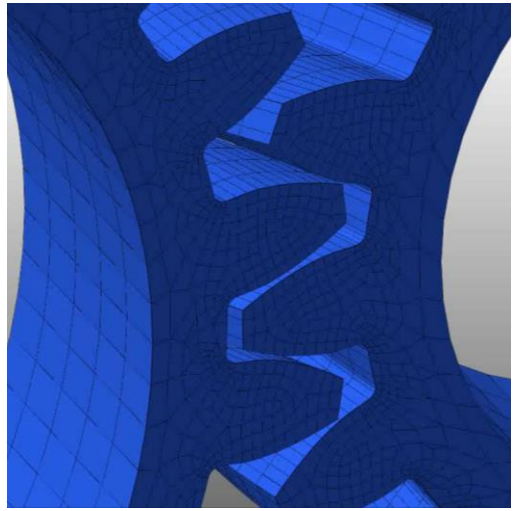
IDEAL MBD



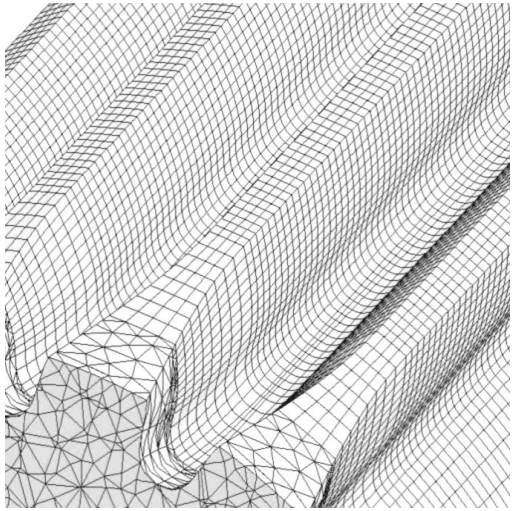
FAIR MBD



MFBD



FE



OUTPUTS

Ideal Kinematics

Real Kinematics
Loads

Real Kinematics
Loads
Rough Structural

Real Kinematics
Loads
Fine Structural

Complexity vs Reliability

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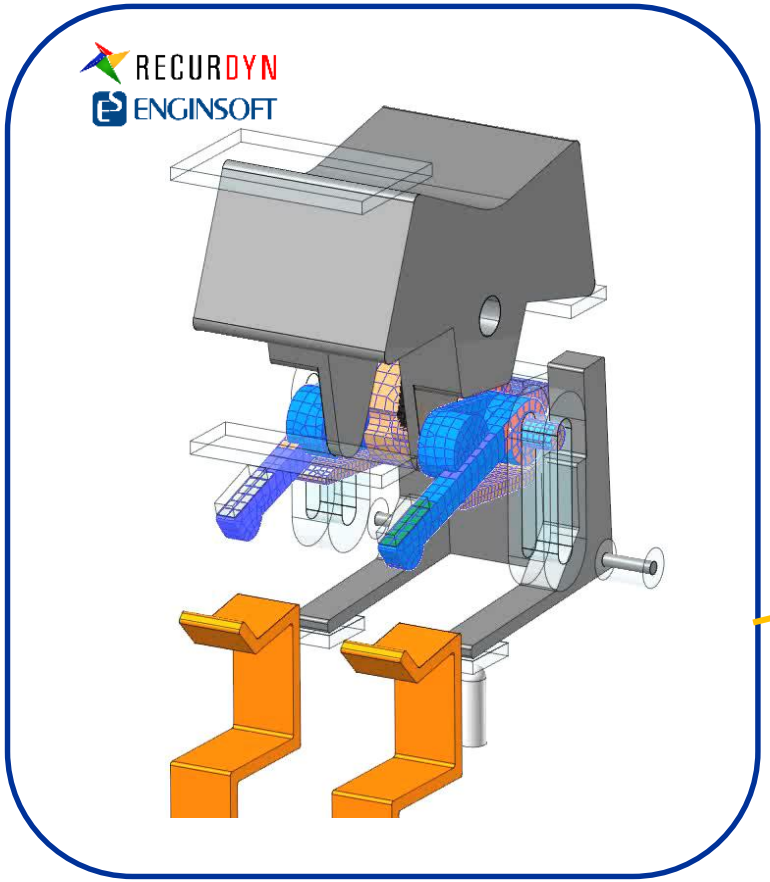
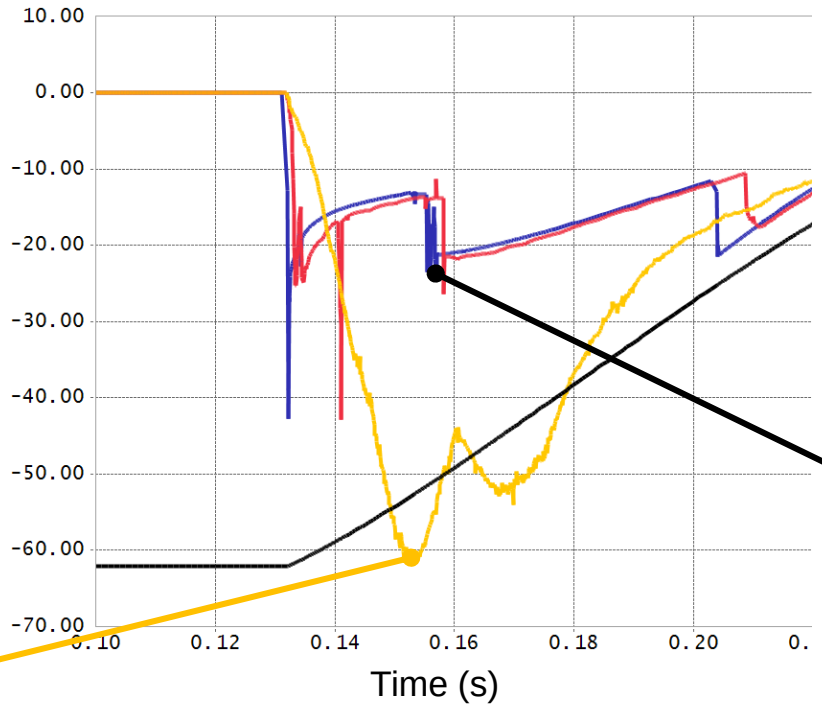
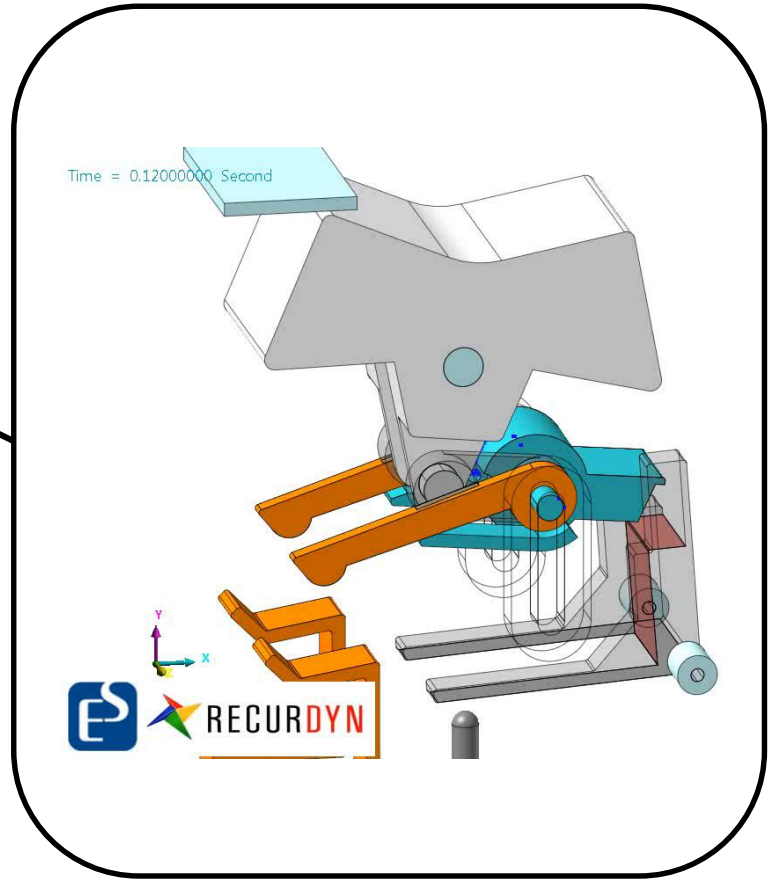
Match Experiments



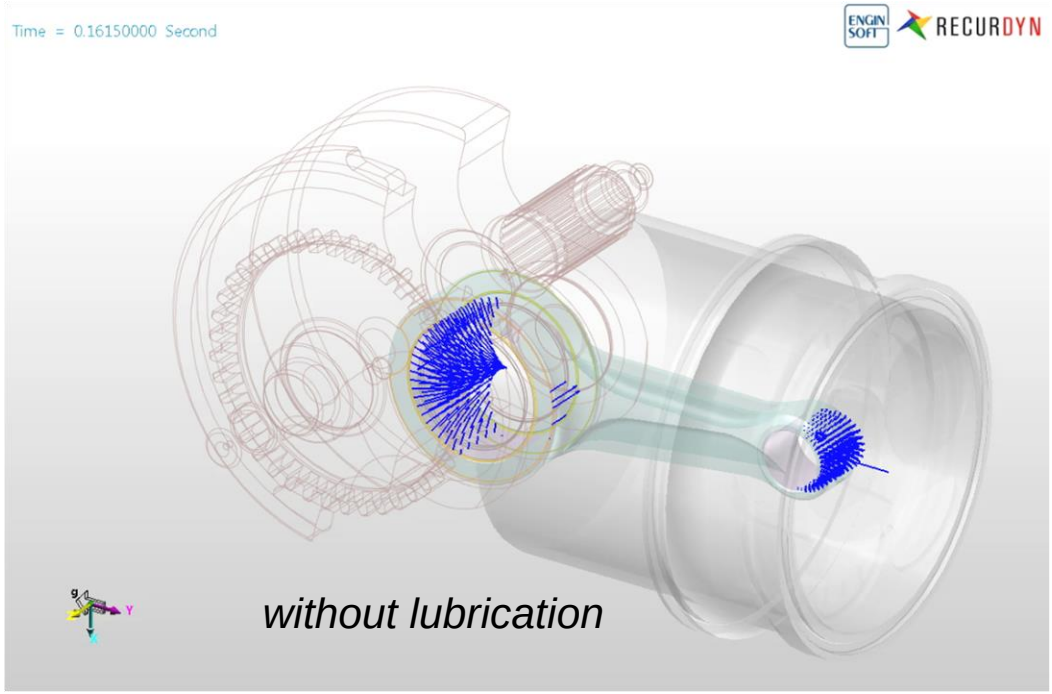
Button Force (N)

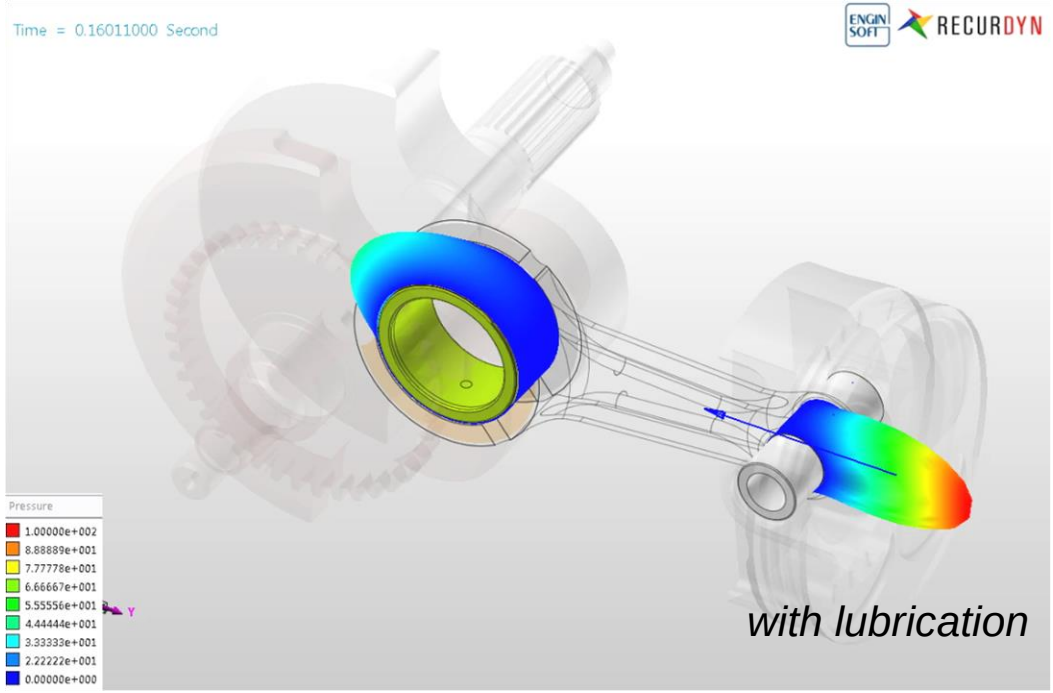


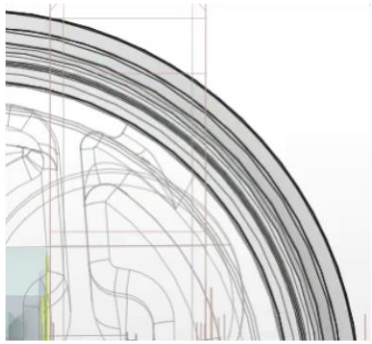
Under estimate



Digital Twin Purposes Drive the Design of Support Model





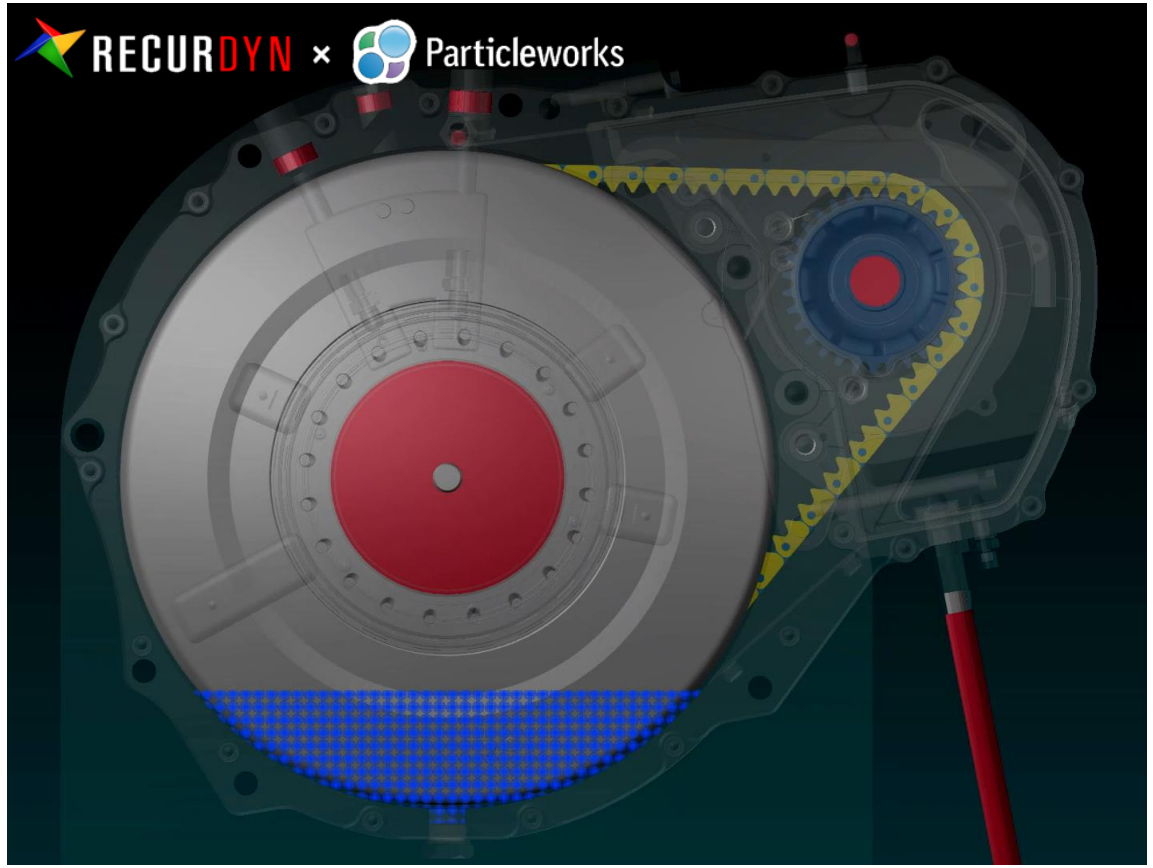


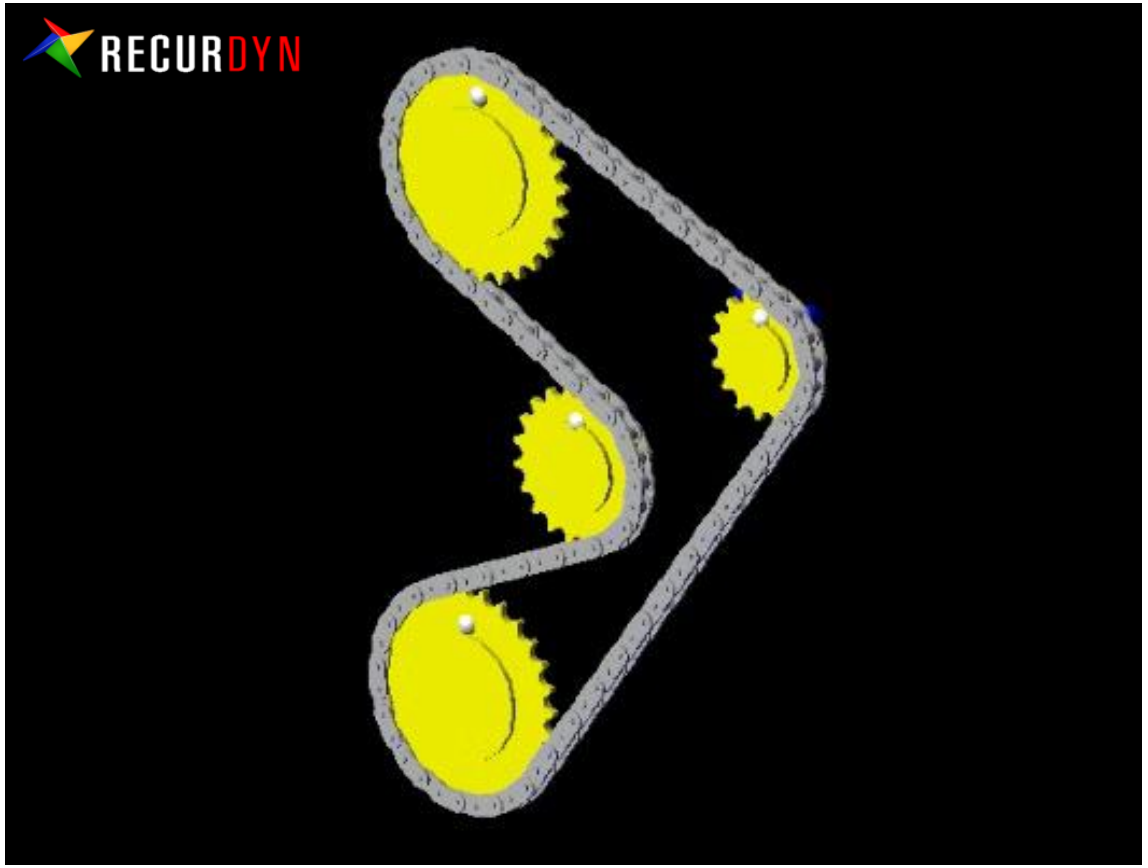
Digital Twin of an Engine (e.g. queried by the ECU)
Goal: correlate the chamber pressure with piston side motion

What to consider in the support digital model?

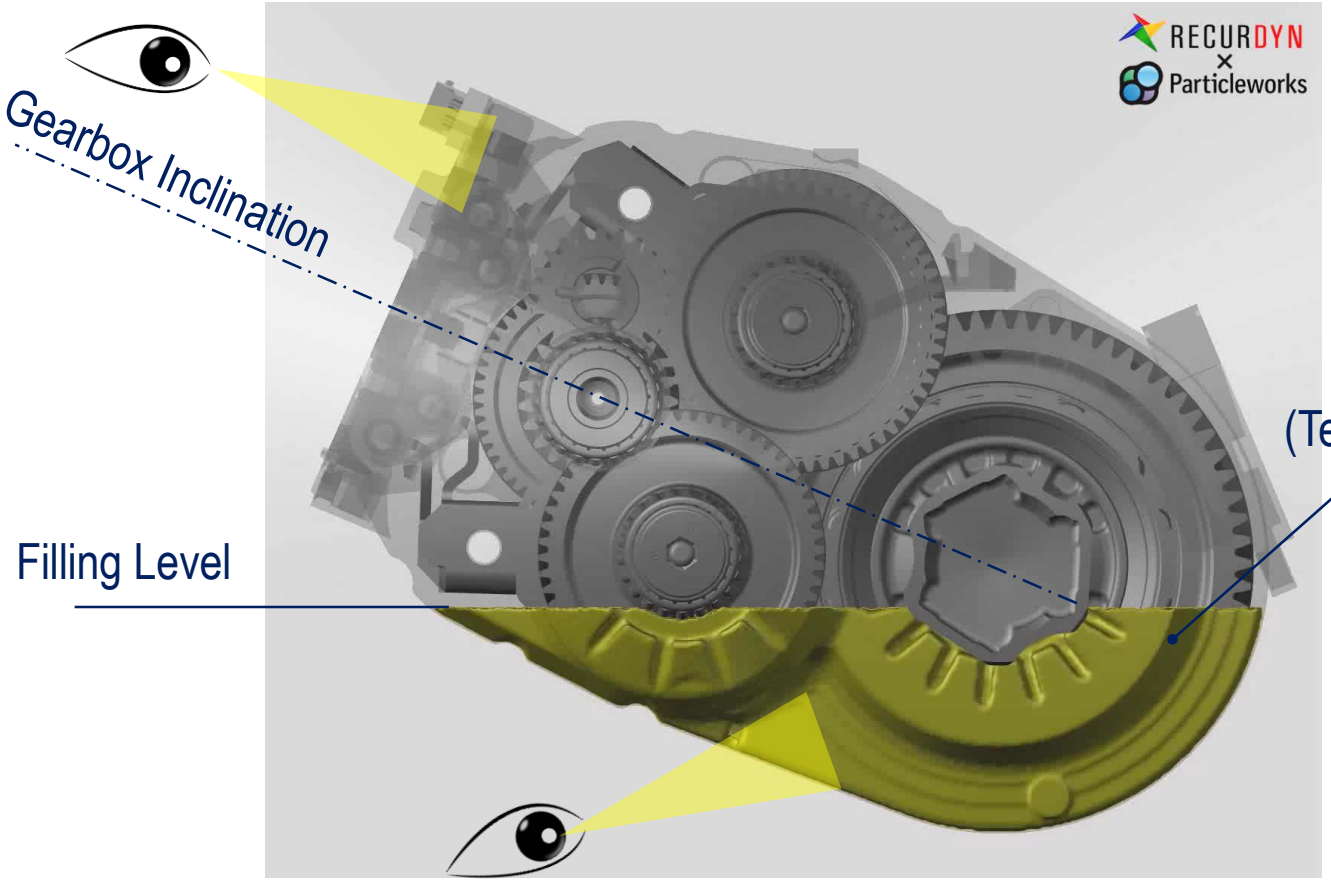
Digital Twin Purposes Drive the Design of Support Model

Link-To-Link clearance? Teeth chamfers / fillets? Lubrication or not? Motion irregularities?

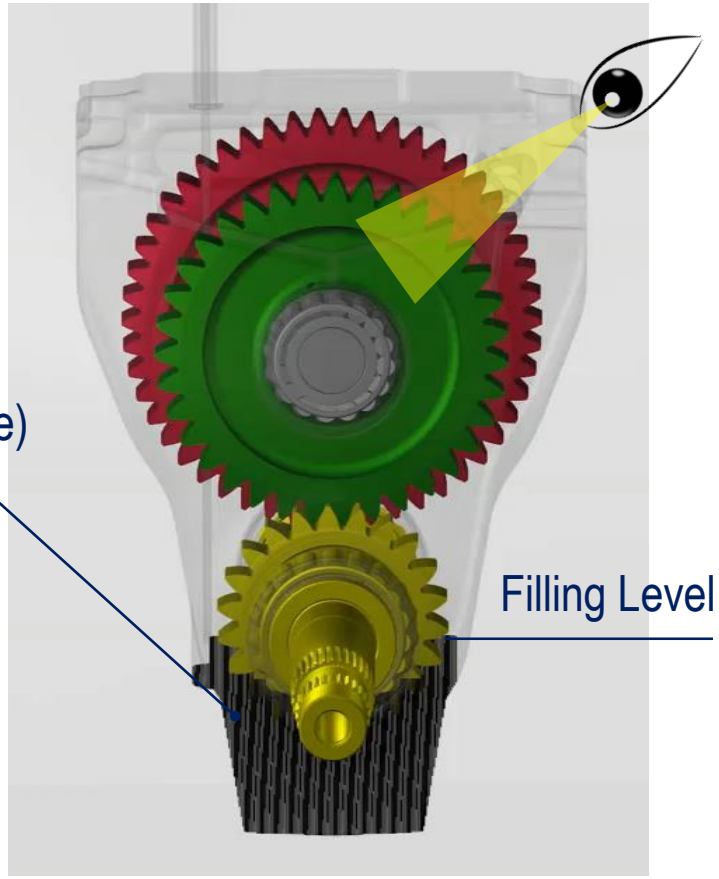




Digital Twin Purposes Drive the Design of Support Model

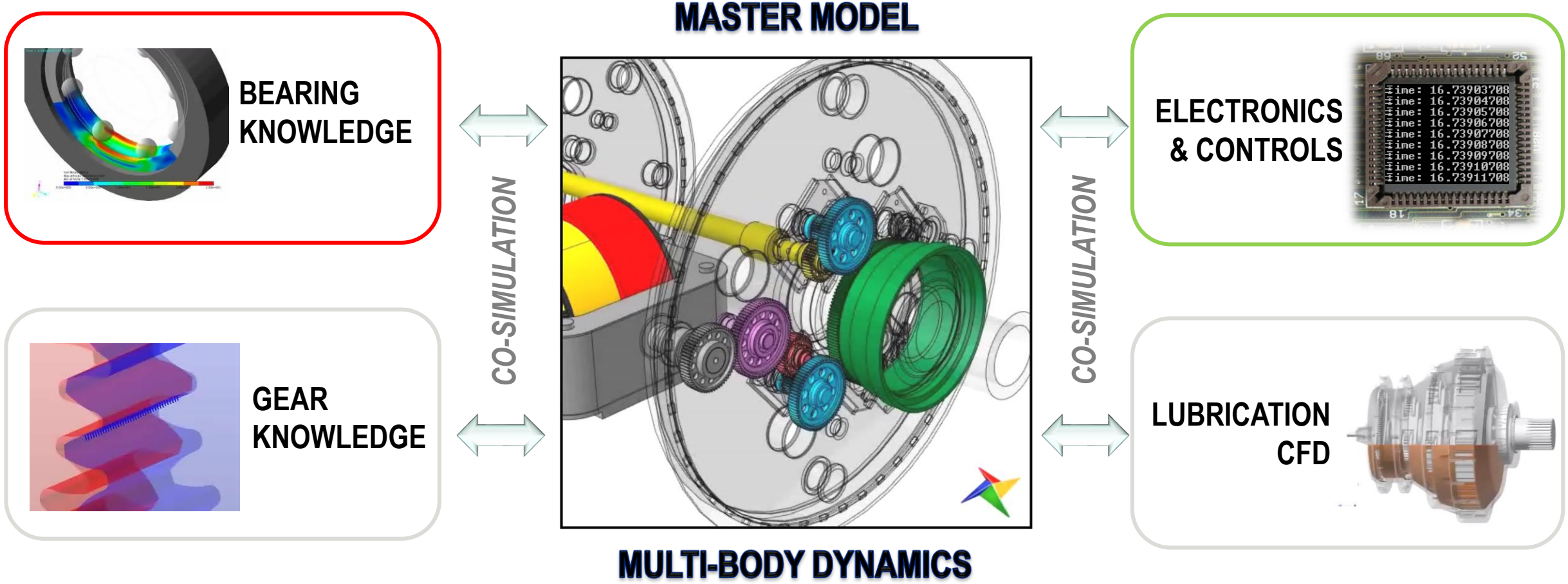


Lubricant
Viscosity
(Temperature)



Is lubrication always guaranteed?

Support Models for Digital Twins are not “Out-Of-The-Box”

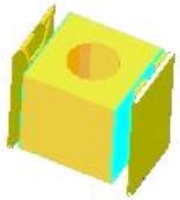


MBD is a powerful and complete approach, but… **now way to run in real time!**

Meta or Surrogate Model or Response Surface Model

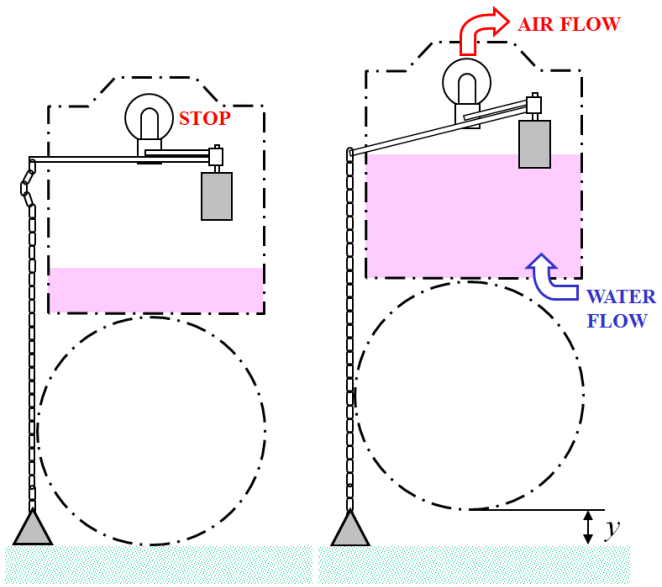
- **Model that approximates a more complex and higher order model**
  - **return close-to outputs for same inputs**
  - **for dynamic models could be an algebraic or differential model**
  - **<u>developed on experience basis</u>**
    (i.e. fitting N-dimensional data set)
  - **<u>developed on theory basis</u>**
    (i.e. mathematical equivalence)
- **Necessary when the support model is too computationally expensive**
  - **large non-linear MBD models**
  - **any combination of MBD, FEA, Control, Analytics, and CFD**

RECURDYN

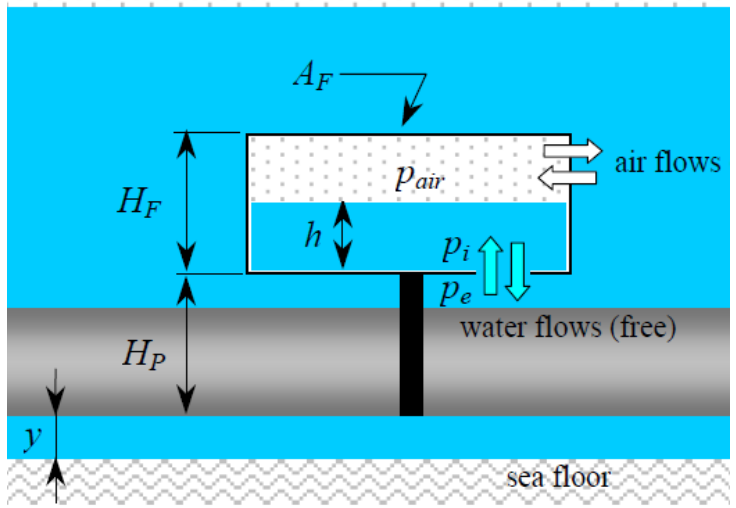


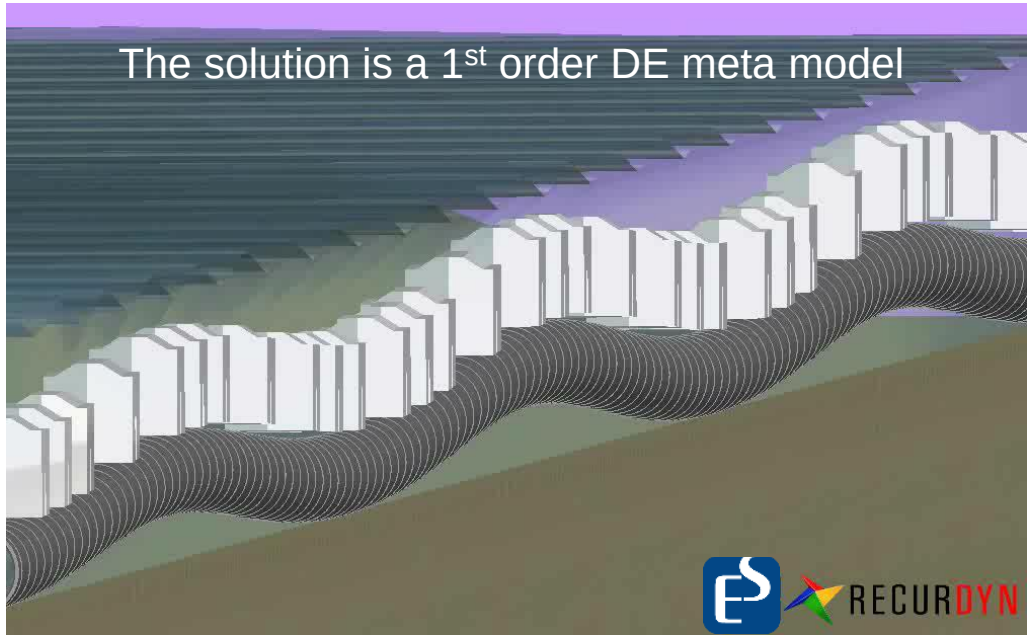
(no gravity tests need to be virtual)

Theory-Based Support Model & Meta Model



2nd order / non-linear DE per floater

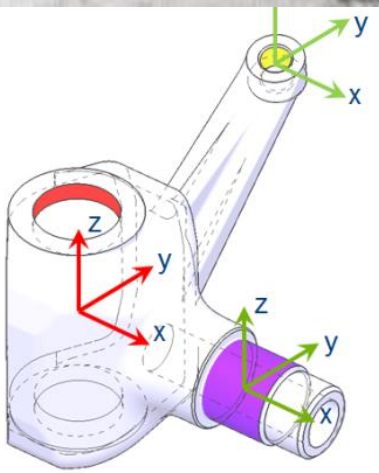


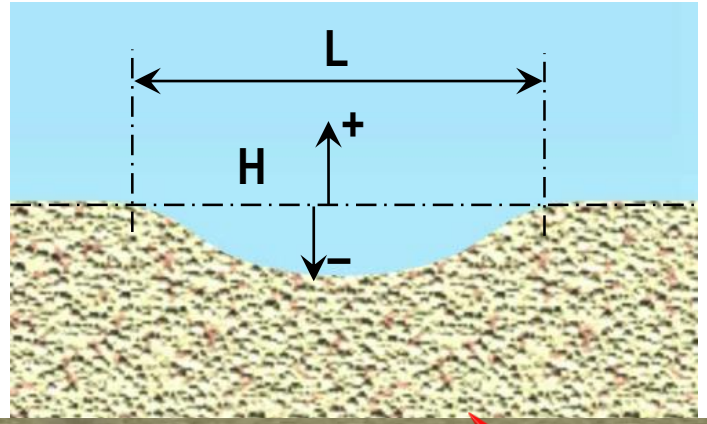


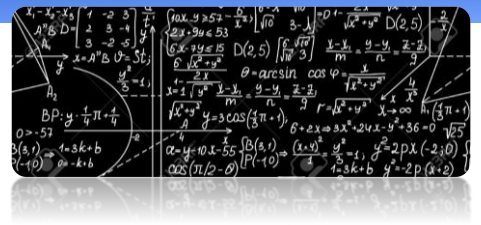
COMPLETE DIFFERENTIAL MODEL

$$\tau \frac{dp_{dyn}}{dt} + p_{dyn} = \overline{p}_{dyn}$$

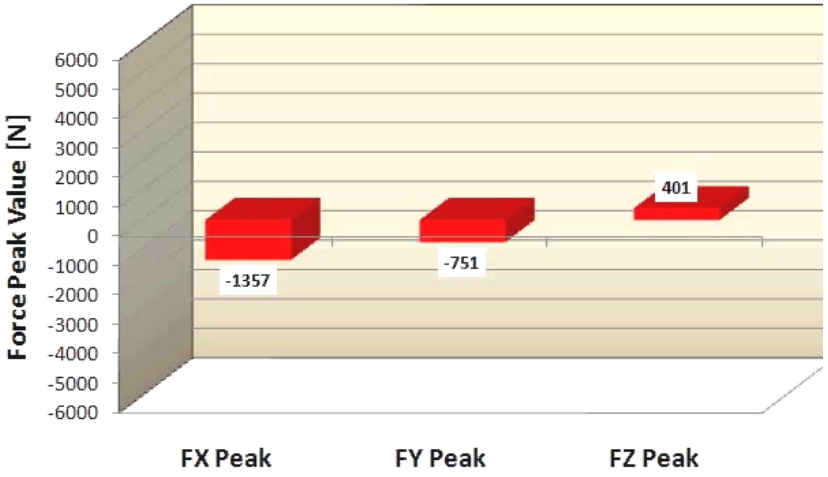
Simulation/Data-Based Support Model & Meta Model







Height	0.000 m	0 mm
Length	0.800 m	800 mm
Speed	1.300 m/s	4.68 km/h



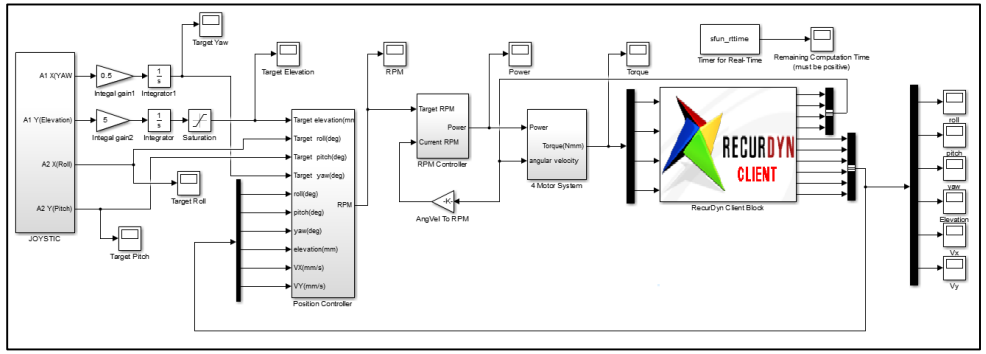
The solution is an algebraic meta model

Instant Response!

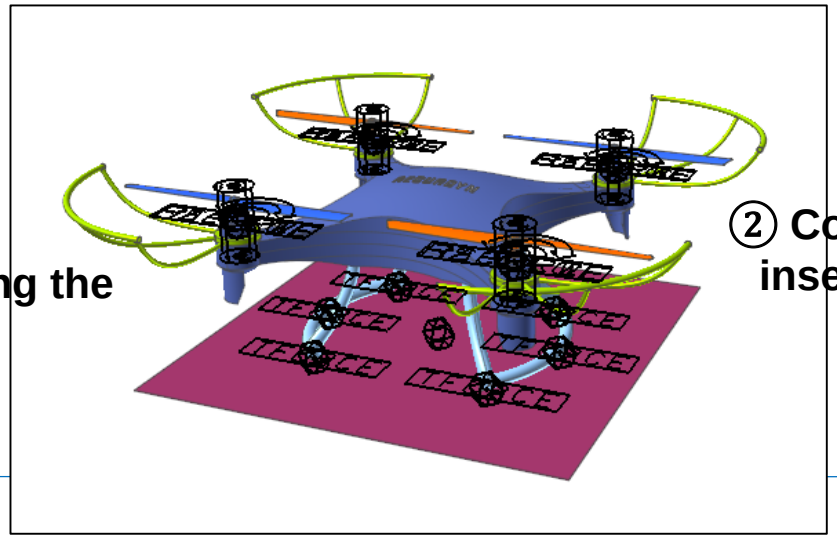
Introduction

◆ Workflow

① User command the desired location



② Controller output torque is inserted to dynamic model



③ Returns RPM, position .etc and waiting the newly command

Propeller thrust & drag force calculation

◆ Method 1 (Experimental model)

- Calculate the force using Ct, Cp graph which is from experiment in steady-state
- Appropriate for small-size propeller model

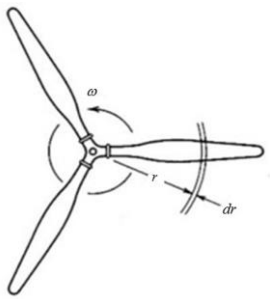
$$J = \frac{V}{nD} \quad C_T = \frac{T}{\rho n^2 D^4} \quad C_P = \frac{P}{\rho n^3 D^5} \quad \eta = J\frac{C_T}{C_P}$$

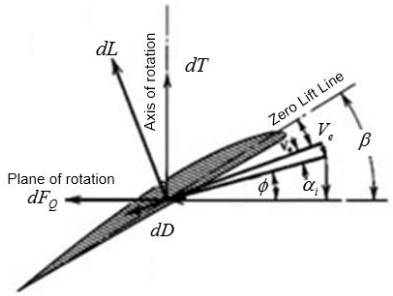
T : trust
P : power
C_T : coefficient of power
C_P : coefficient of thrust
n : RPS
ρ : density

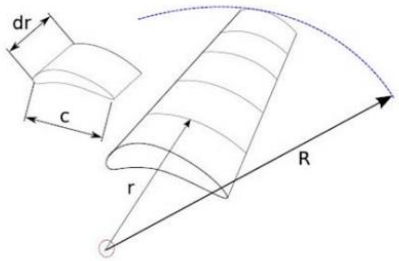
McCormick, B.W., "Aerodynamics, Aeronautics, and Flight Mechanics," Wiley, Second Edition, 1995.

◆ Method 2 (Blade Element Model, BEM)

- Propeller thrust and torque are computed by integrating the equations of the elemental thrust and torque from root to tip of the blade
- Appropriate for large propeller model
- If user doesn't have experimental data







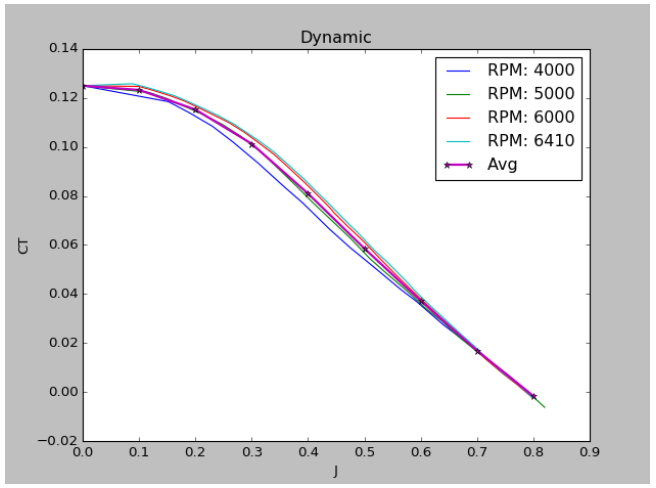
Experimental method

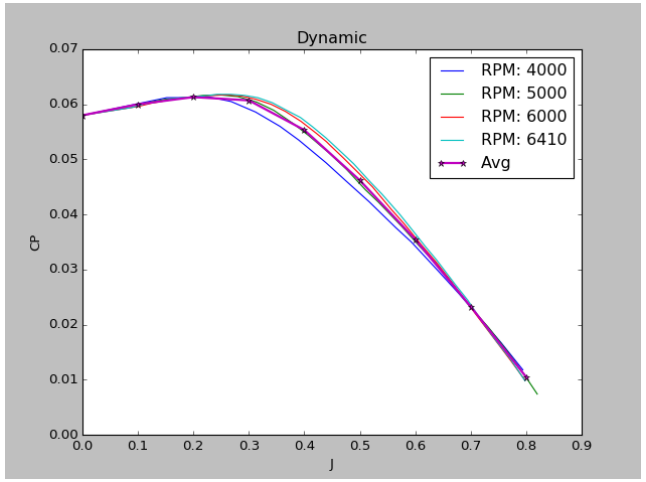
◆ Approach

Super-Nylon propellers

Master Airscrew Electric

- **Super-Nylon propellers 9x6 in dynamic state**



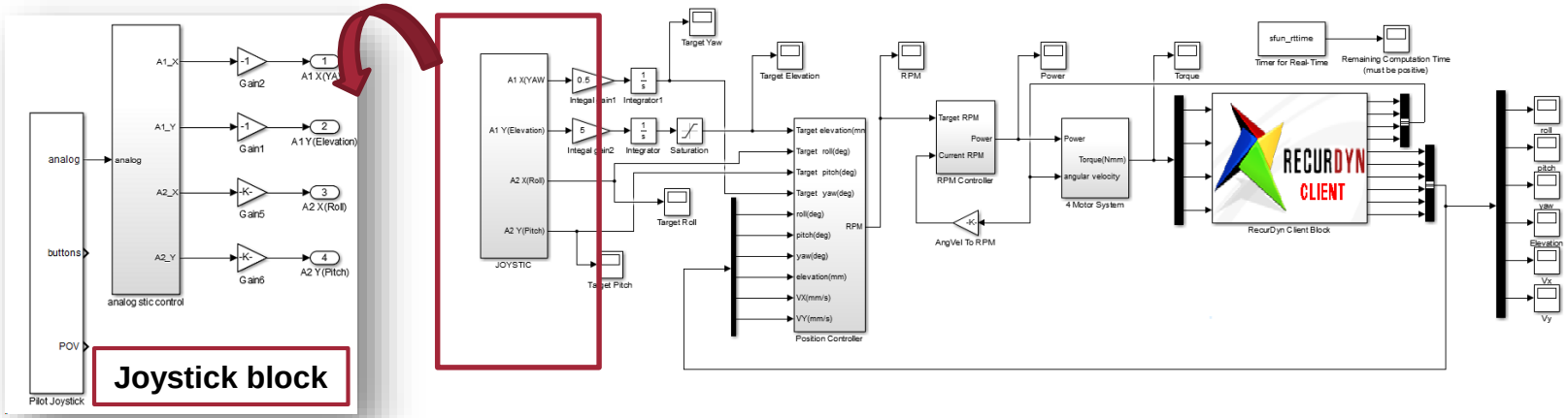


- Variation at each RPM is negligible → Can be represented in 1 graph
- **Since the model size is small and experiment data also have, RD construct the model using method1**

Control model

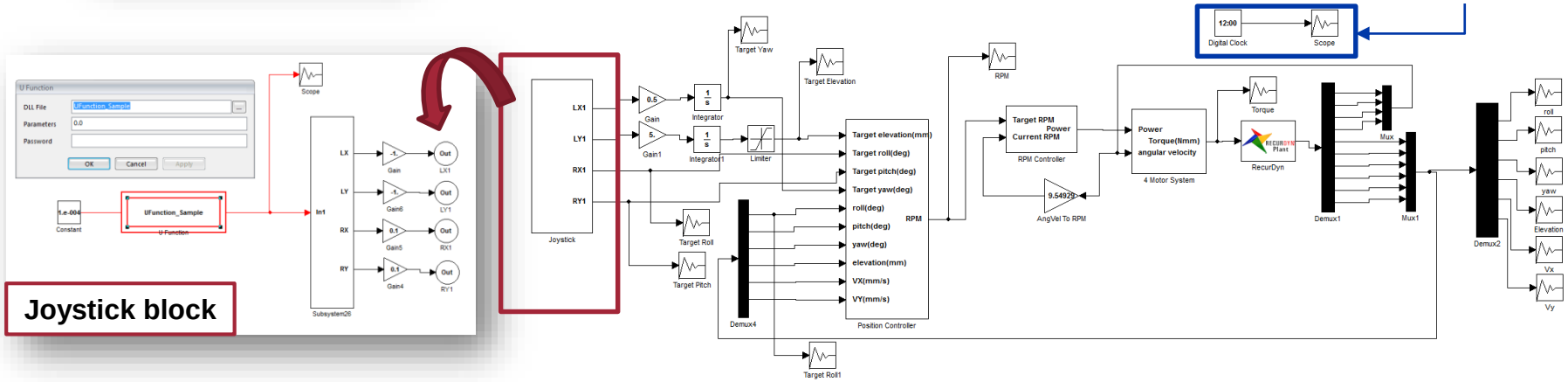
◆ Simulink

- Necessary Simulink toolkit : Aerospace blockset

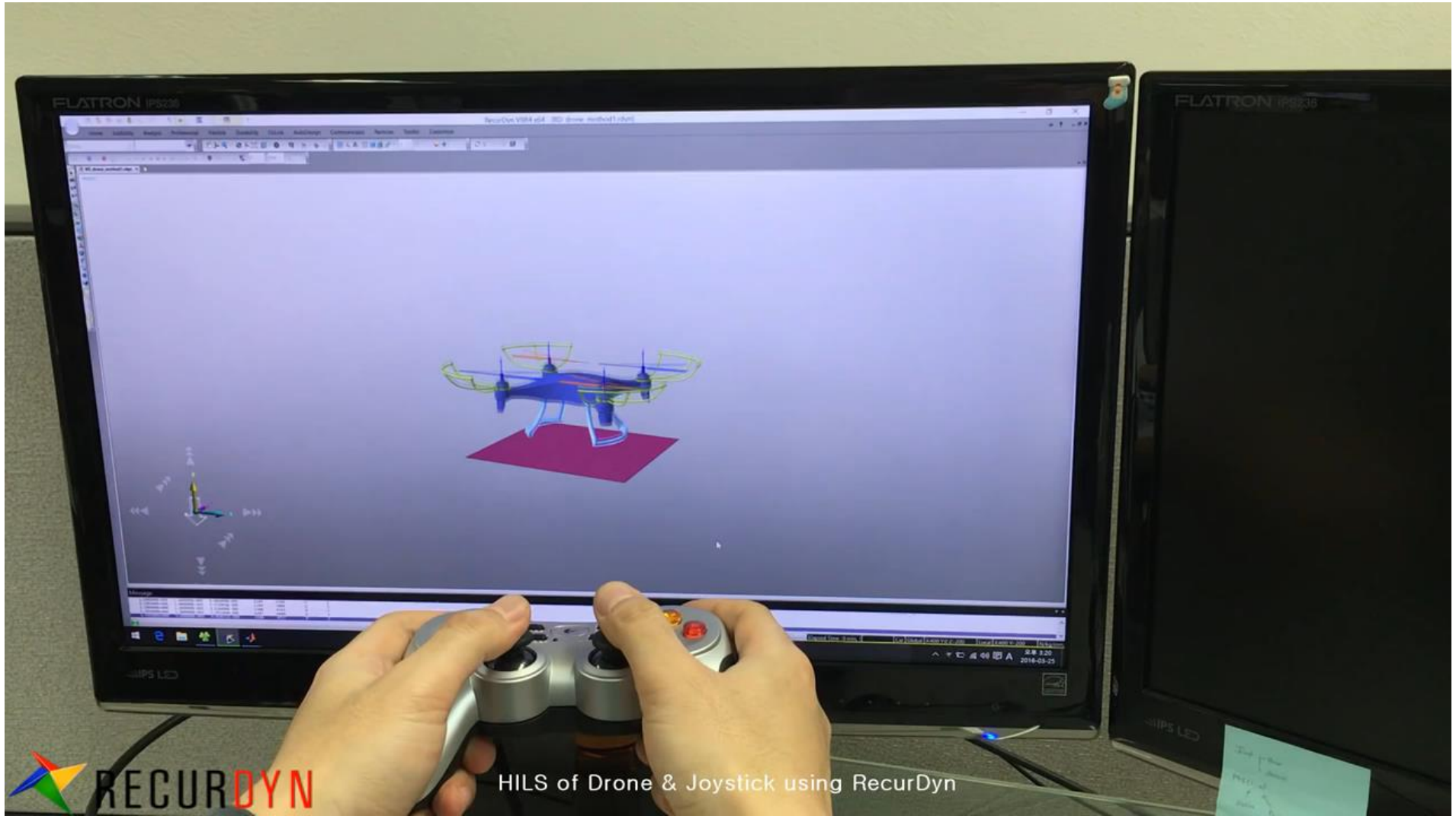


◆ CoLink

Real-time block



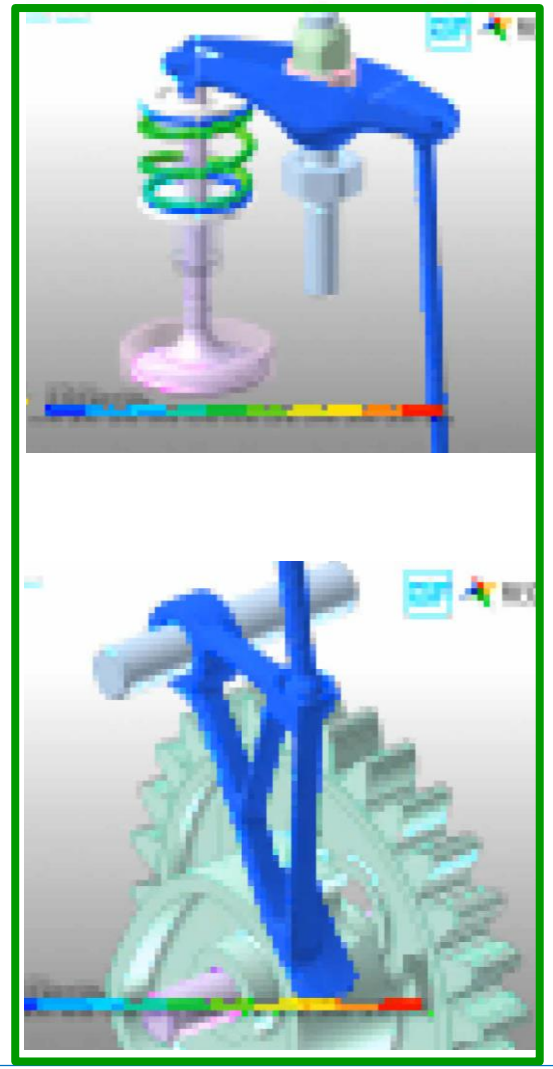
Demo video



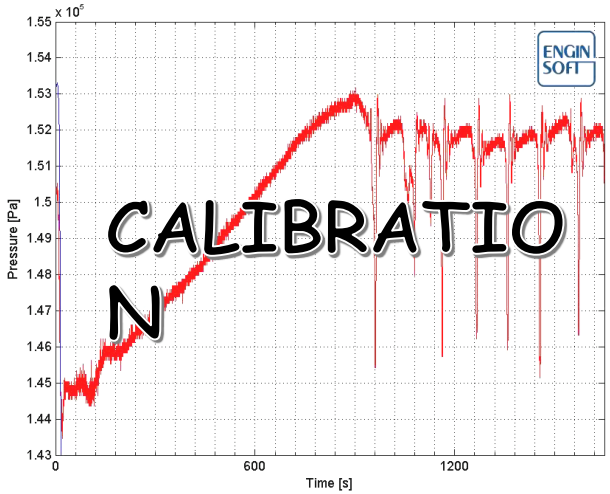
Surrogate Model (Digital Twin) Generation & Calibration

- **Learn from data (measured / simulated)**
  - **need large database to properly map the N-dimensional world**
- **Generate (fast) mathematical models**
  - **parametric physics-related models**
  - **parametric advanced interpolation methods**
- **Calibrate the mathematical models**
  - **tune the parameters to achieve good matching with initial database**
- **Calibration is an iterative process**
  - **number of virtual runs grow with N of parameters and N of objectives**
- **A well calibrated meta-model is reliable with restrictions**
  - **for the set of I/O considered upfront**
  - **for boundary conditions set upfront**

Calibration is the Link between Support Model and Meta Model

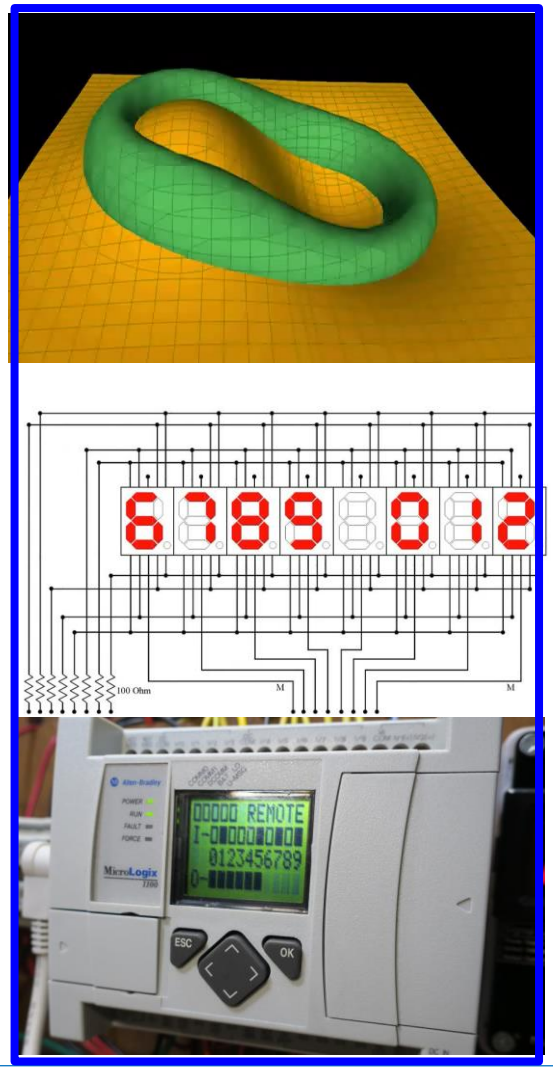


Heavy / CPU-demanding MFBD Model



must return same outputs for same inputs

Surrogate / Real-Time Math Model (DT)



Get the Reliable Meta Model (Digital Twin Engine)

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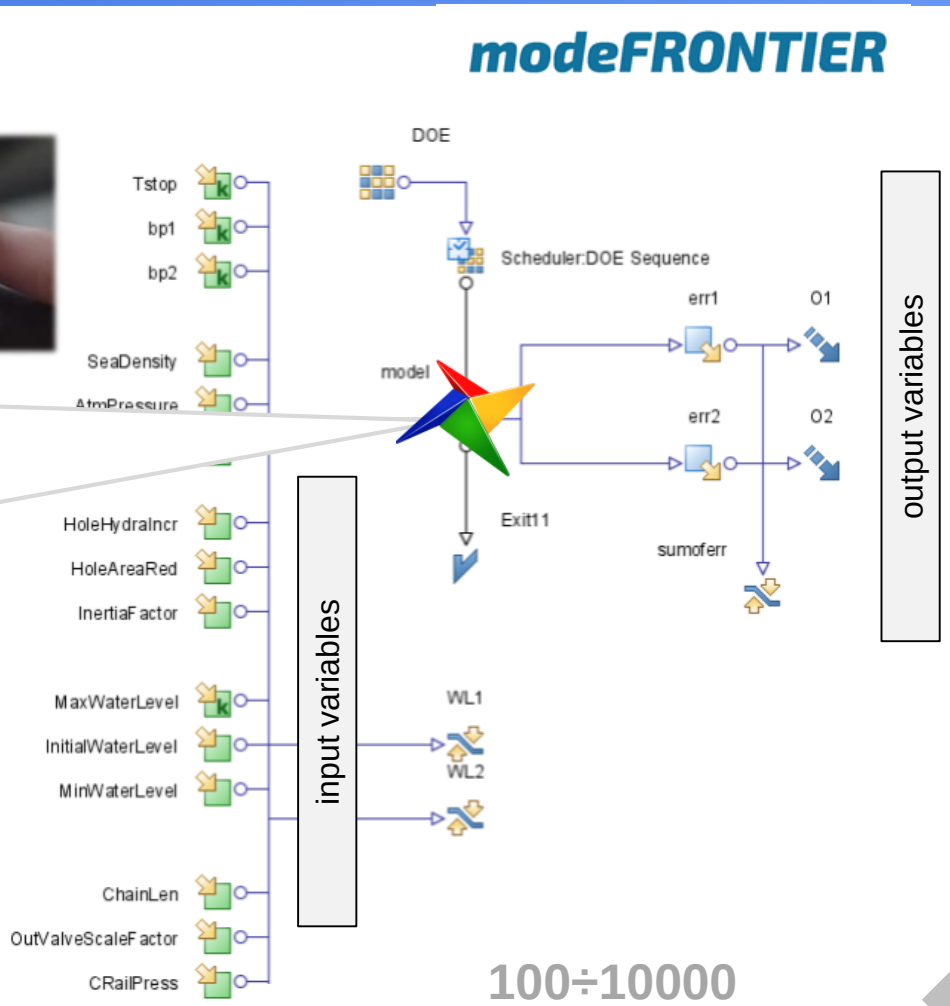
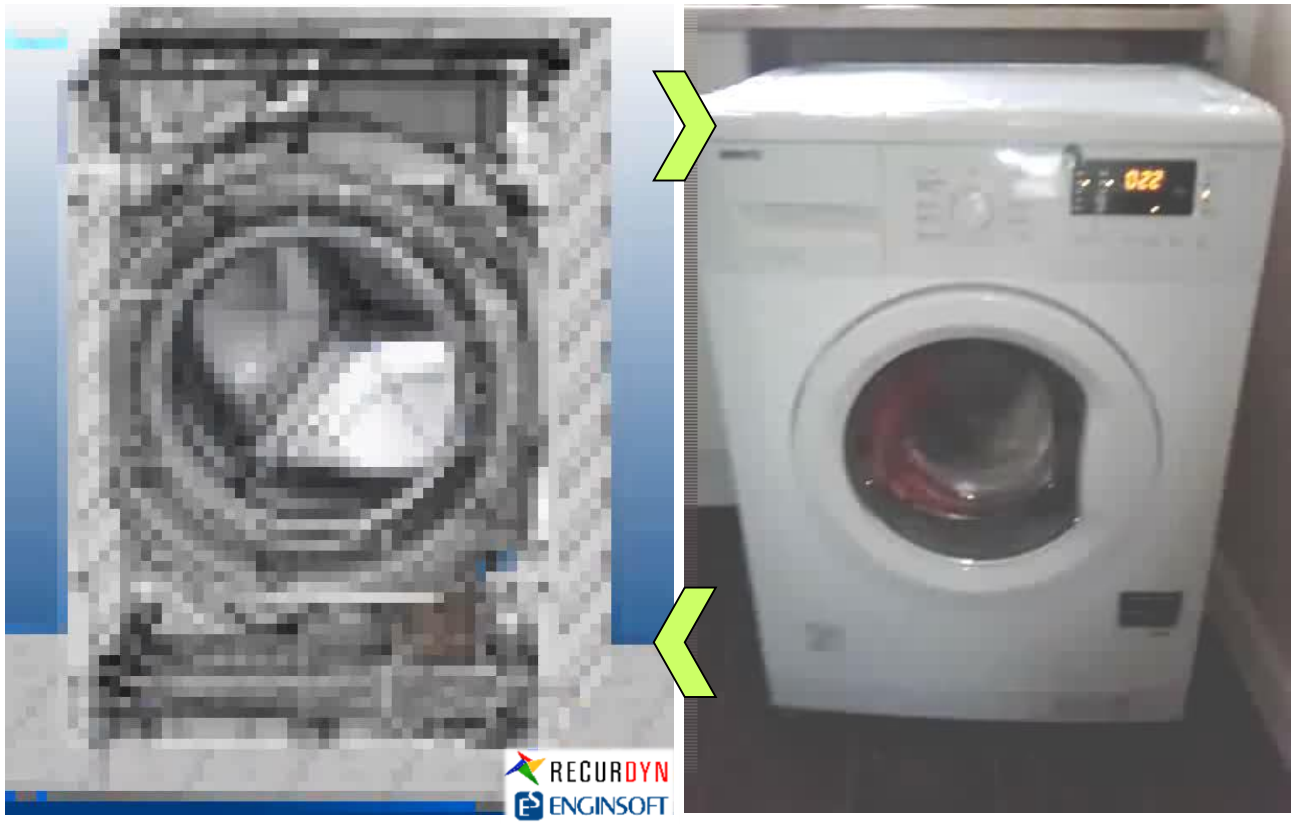
- query database
- generate meta-model
- run meta-model
- compare outputs
- adjust parameters
- reduce differences



100÷10000
ITERATIONS

Multi-Dimensional Calibration is a Hard Challenge

- **Artificial intelligence explores the multi-dimensional domain looking for best matching (Pareto's frontier)**
- **By experience…**
  - **dynamic models are well captured only by theory-based models**
  - **manufacturing plant models can be well represented by abstract meta models**
  - **<u>quality of achievements strongly depends on the initial amount of data</u>**



Generation of Large Training Data in Acceptable Time

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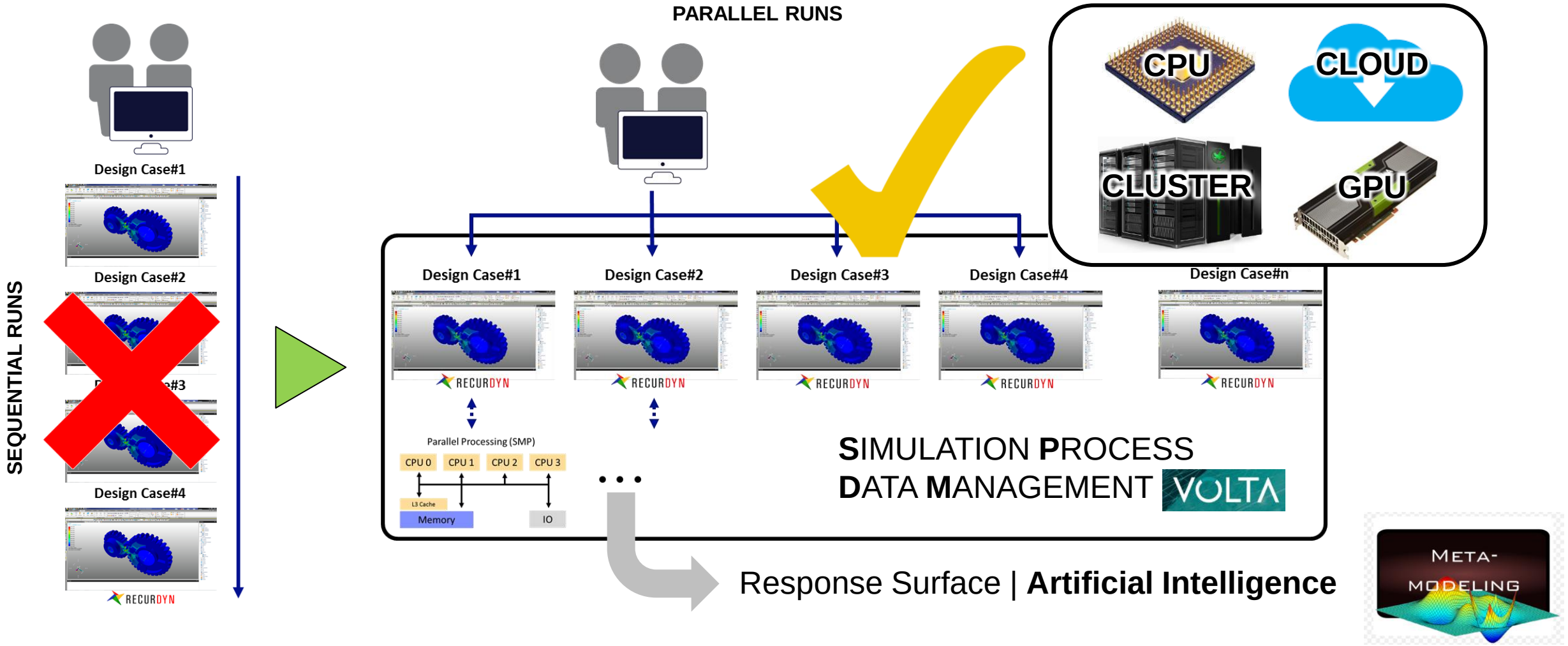

Take Home Messages

- **Meta-Modeling appears to be the only approach that opens the road to Digital Twins of Dynamic Type.**
  - **analytics is not a standard approach and requires high skills (not common)**
- **Dynamics is strongly non-linear, causing the need a huge amount of data to assure adequate level of reliability**
- **Development of Dynamic Digital Twins is an expensive process**
  - **need many physical experiments (laboratory and prototypes)**
  - **need many simulations (large calculation power and software)**
- **Simulation is still the cheapest approach to generate data for Digital Twin development**
  - **cost of SW and HW constantly decreases**

Thank you!

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