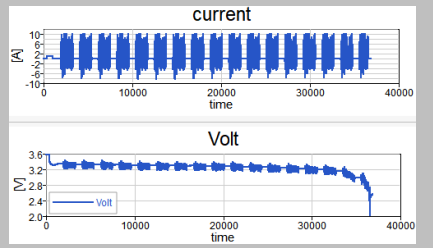
ALTAIR

ALTAIR ROMAI: 利用AI和经典系统理论生成ROM

romAI 目的

数据

	A	B	C	D	E	F	G	H	I
1	time	Xref_mm	Yref_mm	X_mm	Y_mm	X_dot	Y_dot	TX_deg	TY_deg
2	0	0	0	0.1478	2.29719	0.002035	-5.00691	-0.13154	-0.75129
3	0.005	0	0	0.14781	2.272156	0.001635	-4.02188	-0.1229	-0.64688
4	0.01	0	0	0.147817	2.256972	0.000992	-2.43939	-0.11618	-0.66437
5	0.015	0	0	0.14782	2.247762	0.000601	-1.47957	-0.11099	-0.7383
6	0.02	0	0	0.147823	2.242176	0.000365	-0.8974	-0.107	-0.83284
7	0.025	0	0	0.147824	2.238788	0.000221	-0.5443	-0.10394	-0.92927
8	0.03	0	0	0.147825	2.236733	0.000134	-3.46057	-0.10162	-1.01857
9	0.035	0	0	0.147825	2.204182	6.809494	-9.0794	-0.09988	-0.74168
10	0.04	0	0	0.21592	2.145939	18.91092	-2.3765	-0.98042	-0.34267

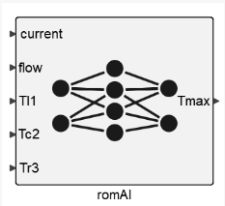


动态系统模型

$$u(t) \rightarrow \begin{cases} \dot{x} = f(x(t), u(t), \theta) \\ y = g(x(t), u(t), \theta) \end{cases} \rightarrow y(t)$$

数字孪生· ROM · 监测

IoT　RT simulator　Control
Optimization

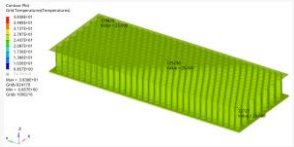


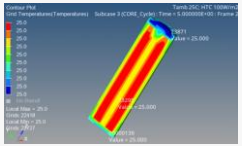
NATIVE

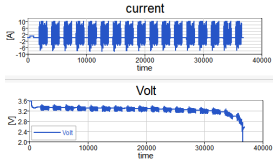
SUPPORTED STD

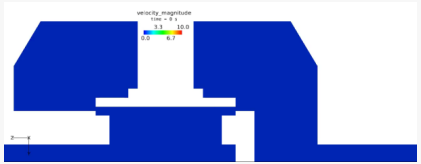
ALTAIR

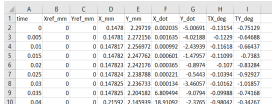
romAI 应用

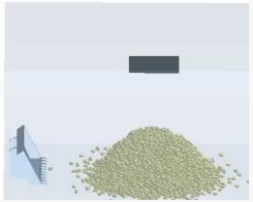




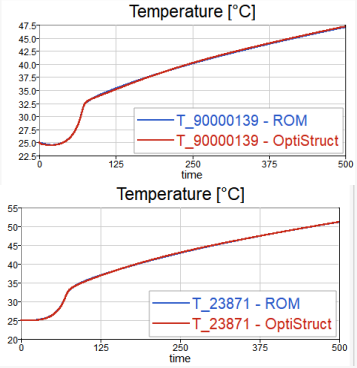




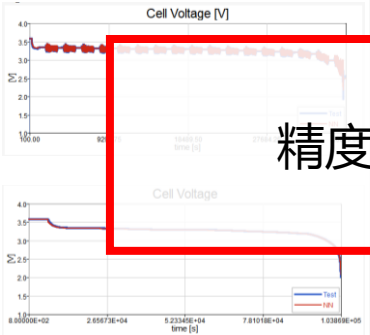




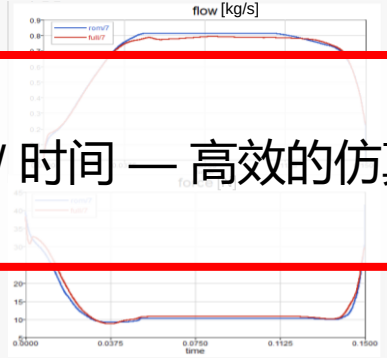
热学



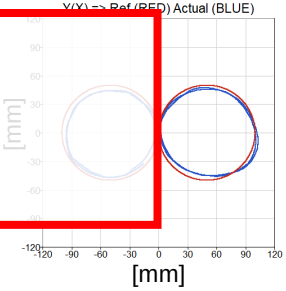
电学



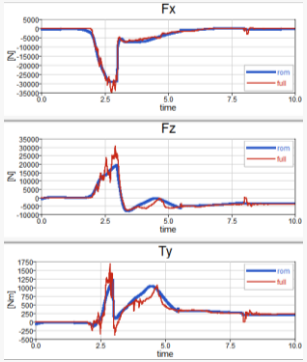
流体



机械



离散元



精度 / 时间 — 高效的仿真

ALTAIR

romAI 目的

数据

	A	B	C	D	E	F	G	H	I
1	time	Xref_mm	Yref_mm	X_mm	Y_mm	X_dot	Y_dot	TX_deg	TY_deg
2	0	0	0	0.1478	2.29719	0.002035	-5.00691	-0.13154	-0.75129
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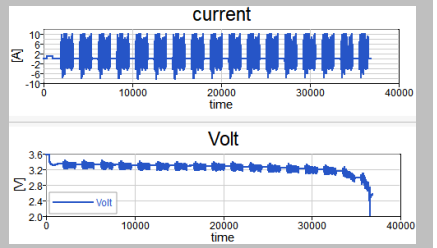
9	0.035	0	0	0.147825	2.204182	6.809494	-9.0794	-0.09988	-0.74168
10	0.04	0	0	0.21592	2.145939	18.91092	-2.3765	-0.98042	-0.34267



动态系统模型

$u(t)$

$$\begin{cases} \dot{x} = f(x(t), u(t), \theta) \\ y = g(x(t), u(t), \theta) \end{cases}$$

$y(t)$

数字孪生 · ROM · 监测

IoT　RT simulator　Control
Optimization

NATIVE

SUPPORTED STD

ALTAIR

romAI: 基于数据生成的动态系统模型

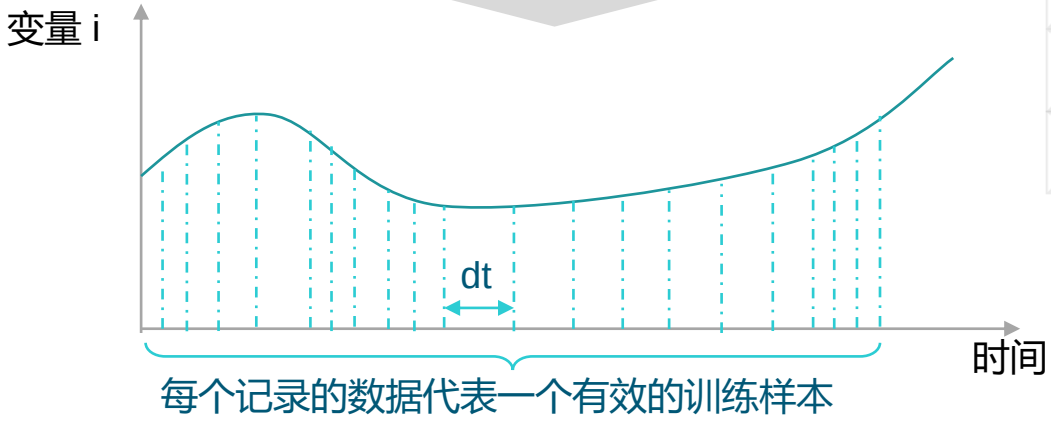
- 少量的仿真/测试
- 不受时间离散化影响
- 集成用户的专业经验
- 满足模型的泛化属性

romAI: 数据

数据 → Learning romAI → 动态系统模型

仿真

测试



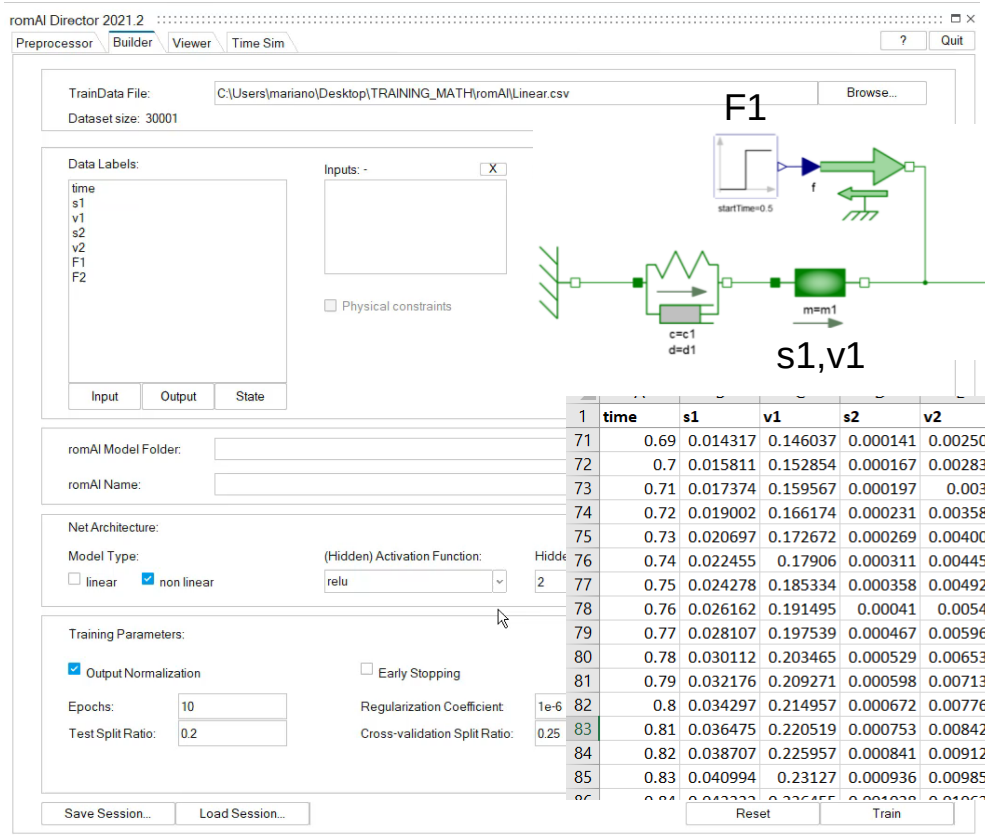
每个记录的数据代表一个有效的训练样本

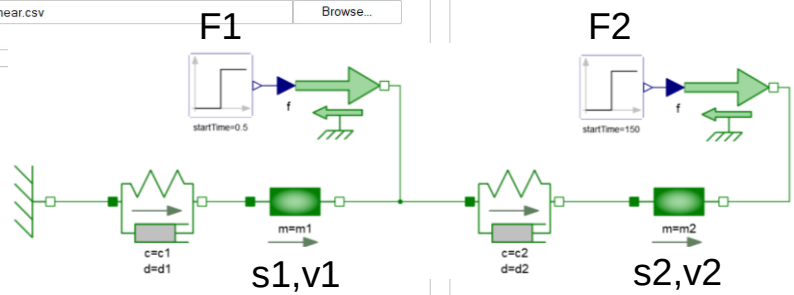
少量的仿真/测试	✓
不受时间离散化影响	✓
集成用户的专业经验	
满足模型的泛化属性	

ALTAIR

romAI: 训练（学习）

数据 → Learning → romAI → 动态系统模型





	time	s1	v1	s2	v2	F1	F2
71	0.69	0.014317	0.146037	0.000141	0.002504	1	0
72	0.7	0.015811	0.152854	0.000167	0.002839	1	0
73	0.71	0.017374	0.159567	0.000197	0.0032	1	0
74	0.72	0.019002	0.166174	0.000231	0.003589	1	0
75	0.73	0.020697	0.172672	0.000269	0.004005	1	0
76	0.74	0.022455	0.17906	0.000311	0.004451	1	0
77	0.75	0.024278	0.185334	0.000358	0.004925	1	0
78	0.76	0.026162	0.191495	0.00041	0.00543	1	0
79	0.77	0.028107	0.197539	0.000467	0.005966	1	0
80	0.78	0.030112	0.203465	0.000529	0.006533	1	0
81	0.79	0.032176	0.209271	0.000598	0.007132	1	0
82	0.8	0.034297	0.214957	0.000672	0.007763	1	0
83	0.81	0.036475	0.220519	0.000753	0.008428	1	0
84	0.82	0.038707	0.225957	0.000841	0.009126	1	0
85	0.83	0.040994	0.23127	0.000936	0.009859	1	0

的仿真/测试 ✓

时间离散化影响 ✓

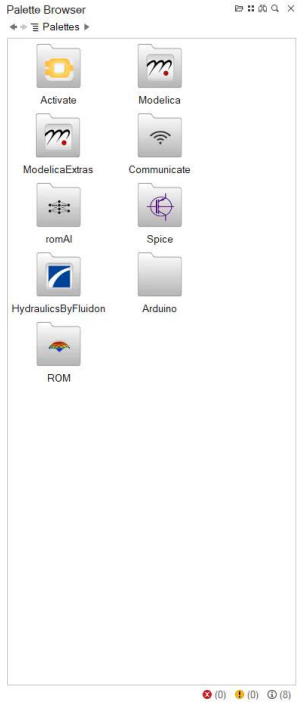
用户的专业经验 ✓

模型的泛化属性

ALTAIR

romAI: 动态系统

数据 → Learning (romAI) → 动态系统模型



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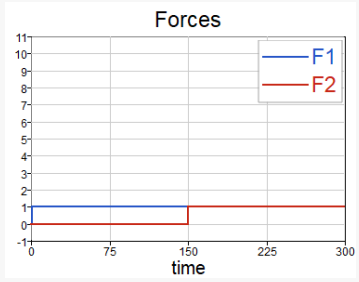
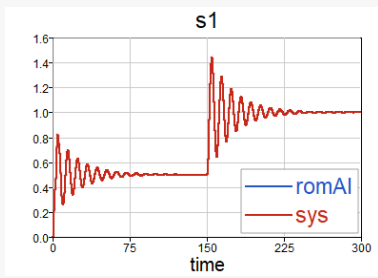
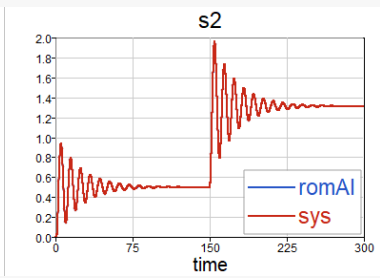
romAI: 动态系统

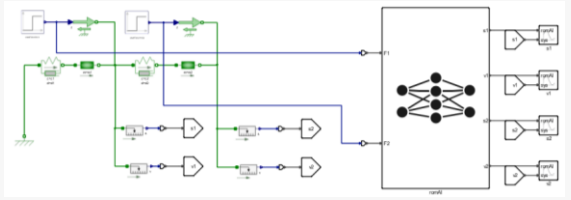
数据 → Learning romAI → 动态系统模型

TRAINING SET

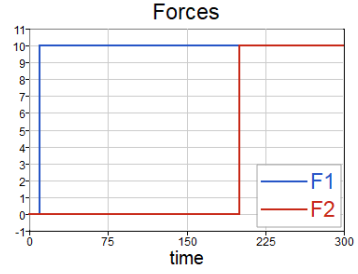


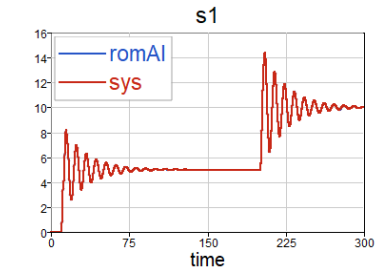


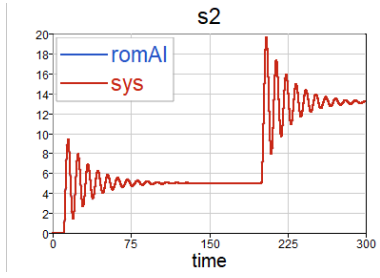


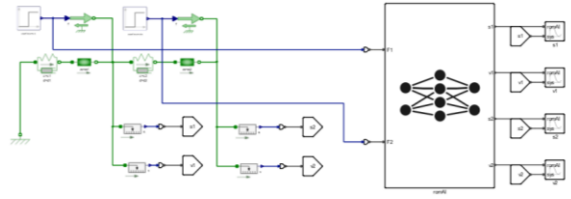


TEST 1

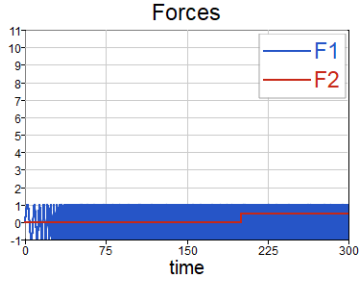


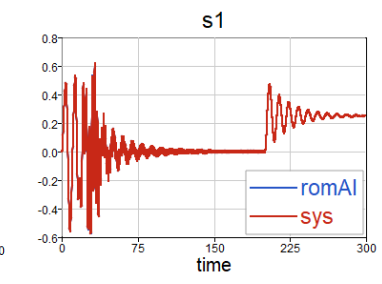


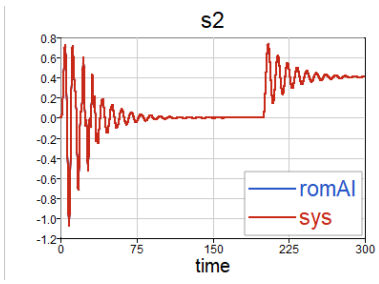


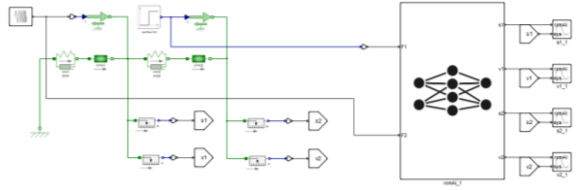


TEST 2





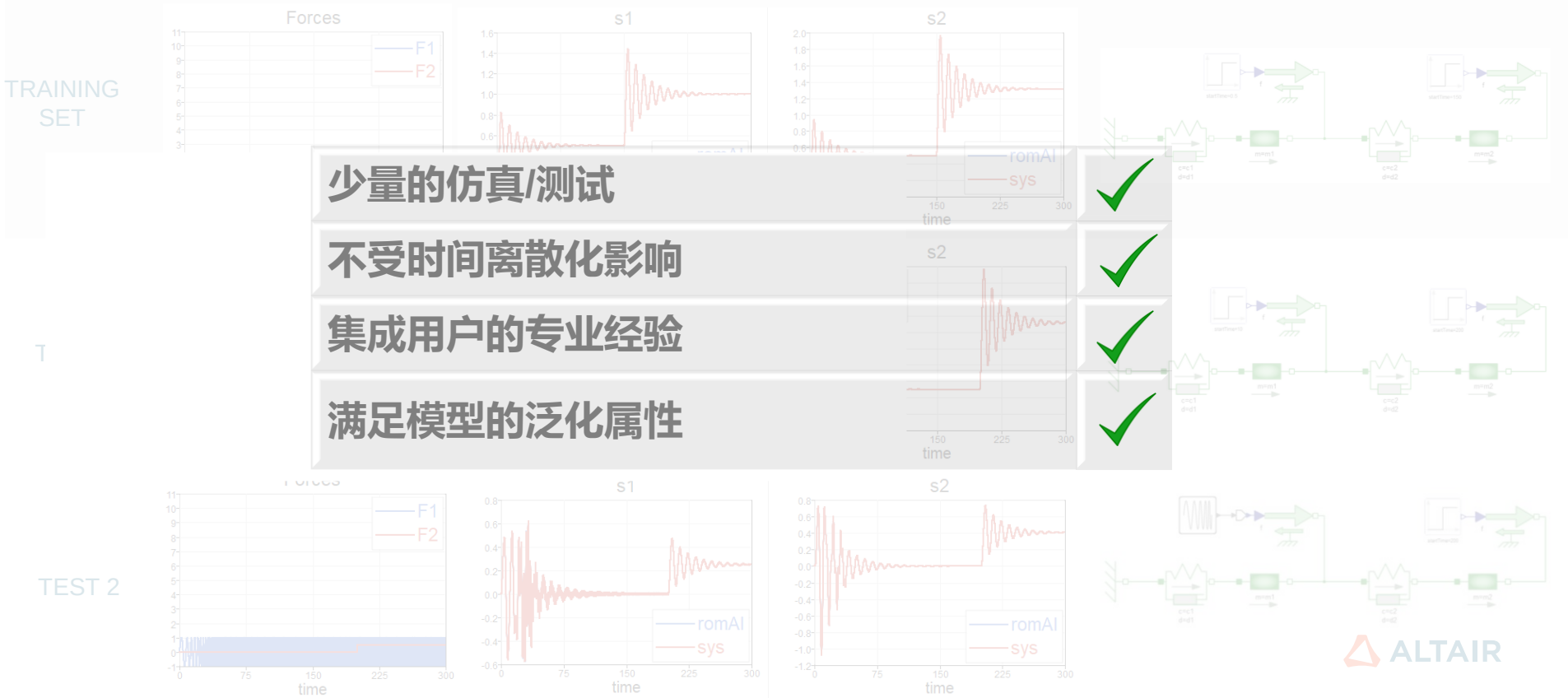




ALTAIR

romAI: 动态系统

数据 → Learning romAI → 动态系统模型



- 少量的仿真/测试 ✓
- 不受时间离散化影响 ✓
- 集成用户的专业经验 ✓
- 满足模型的泛化属性 ✓

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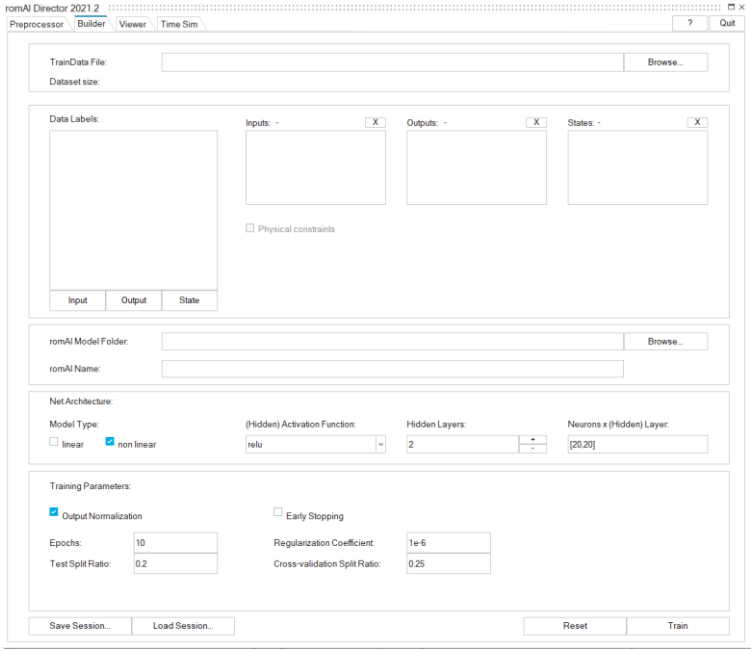
romAI

COMPOSE AND ACTIVATE

ALTAIR

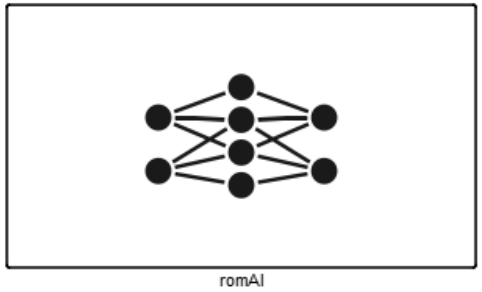
romAI tools

romAI Director



用于训练数据生成ROM

romAI block



用于时域系统仿真
(使用ROM)

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romAI: Activate/Compose

	romAI Director (*)	romAI block (*)
Compose 	✓	✗
Activate 	✓	✓

(* 需要在 Activate 、 Compose中安装 romAI library)

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romAI 应用

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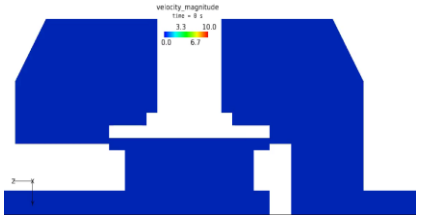
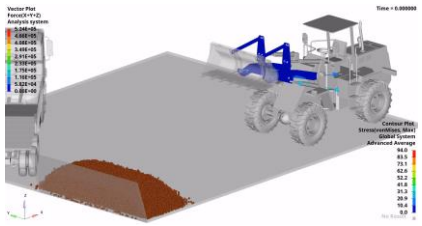
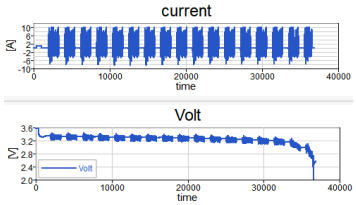
Simulation





Real system



Reduced-Order Model

System Identification

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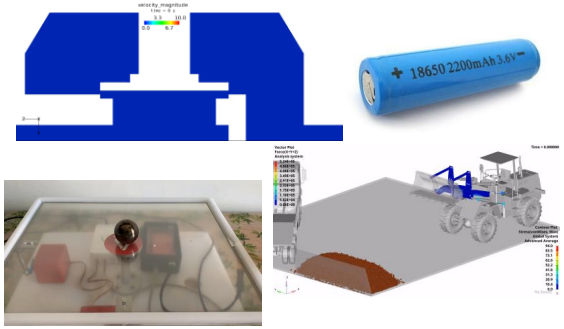
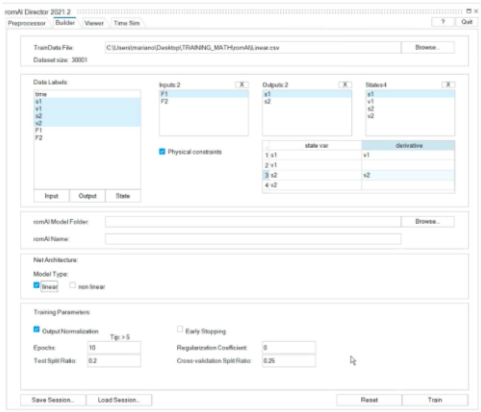
romAI 使用流程（ROM生成及应用）

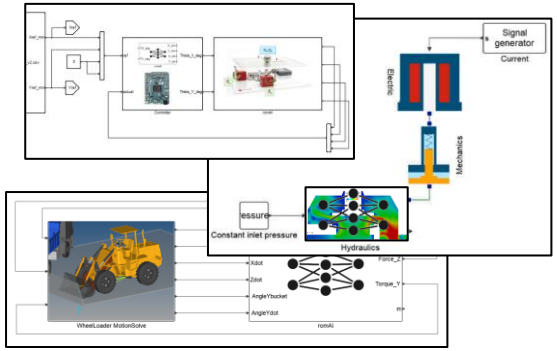
仿真或测试



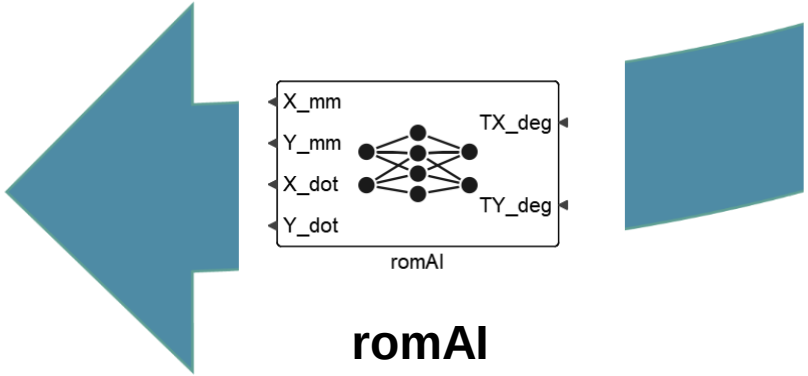
训练数据

机器学习

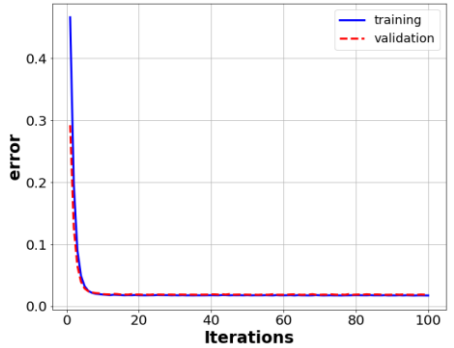




系统仿真

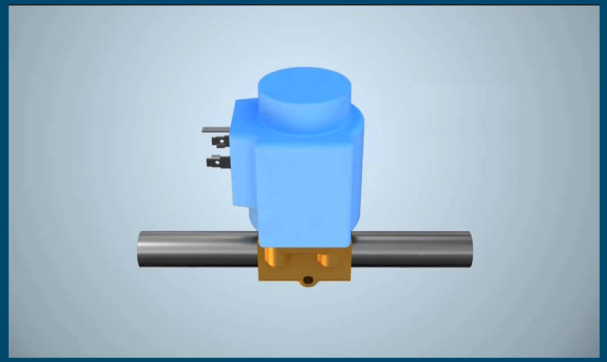


romAI



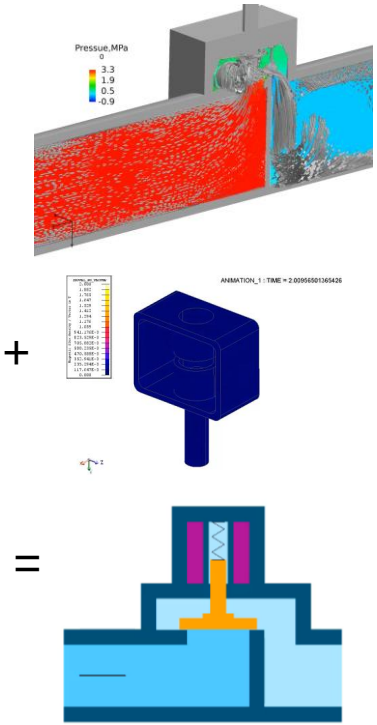
电磁阀
(SOLENOID VALVE)

如何在保证精度的前提下减少仿真时间?



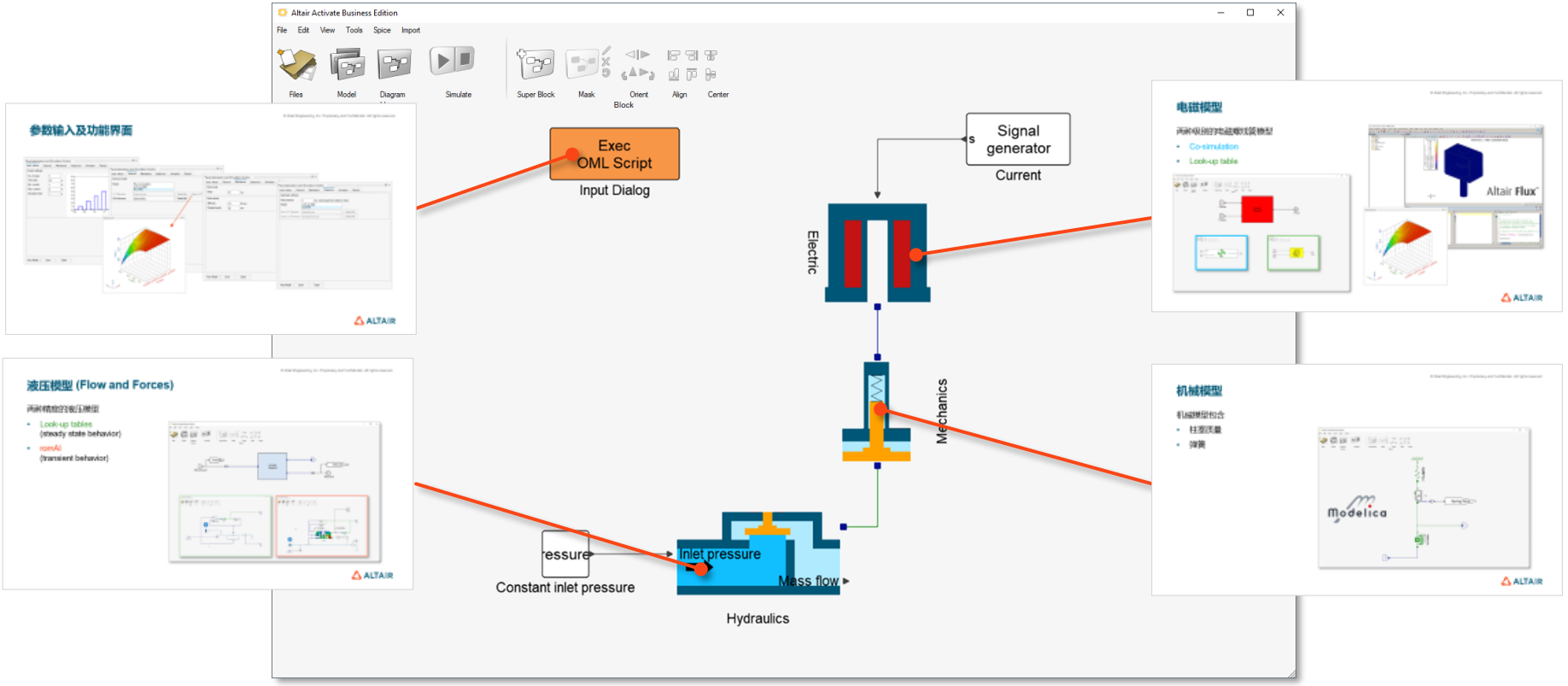
co-simulation

ALTAIR



ALTAIR

电磁阀系统分析模型



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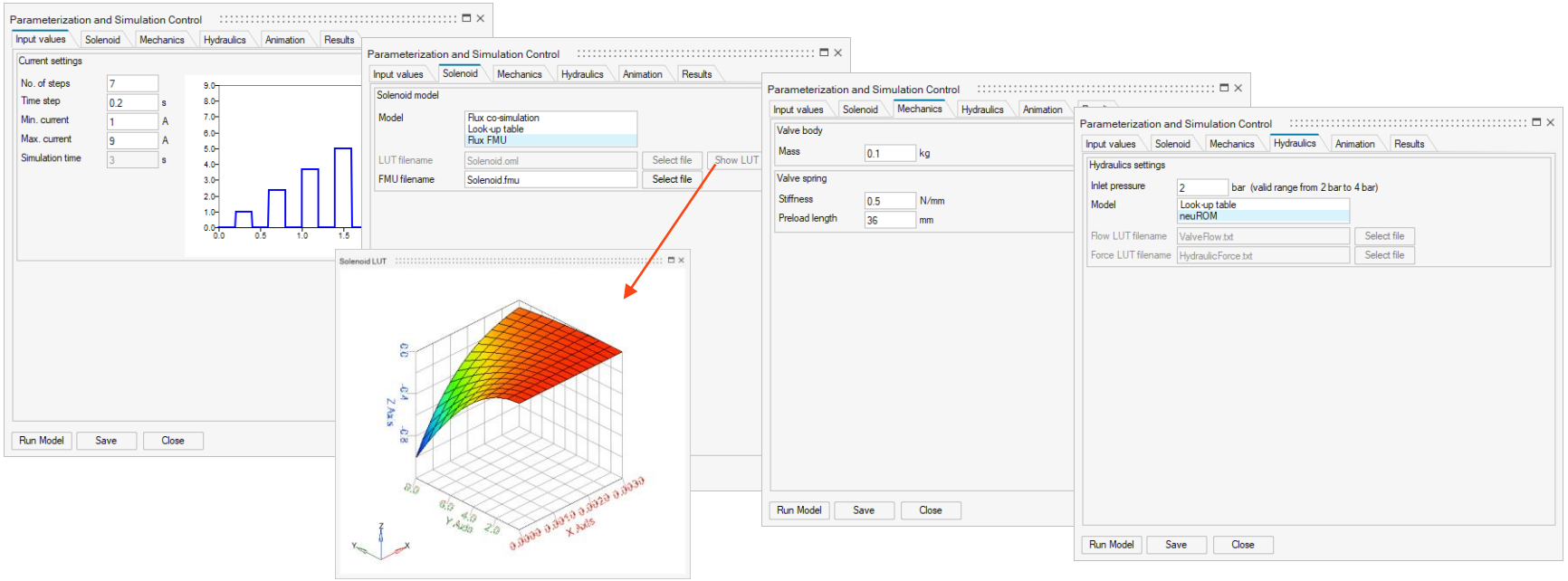
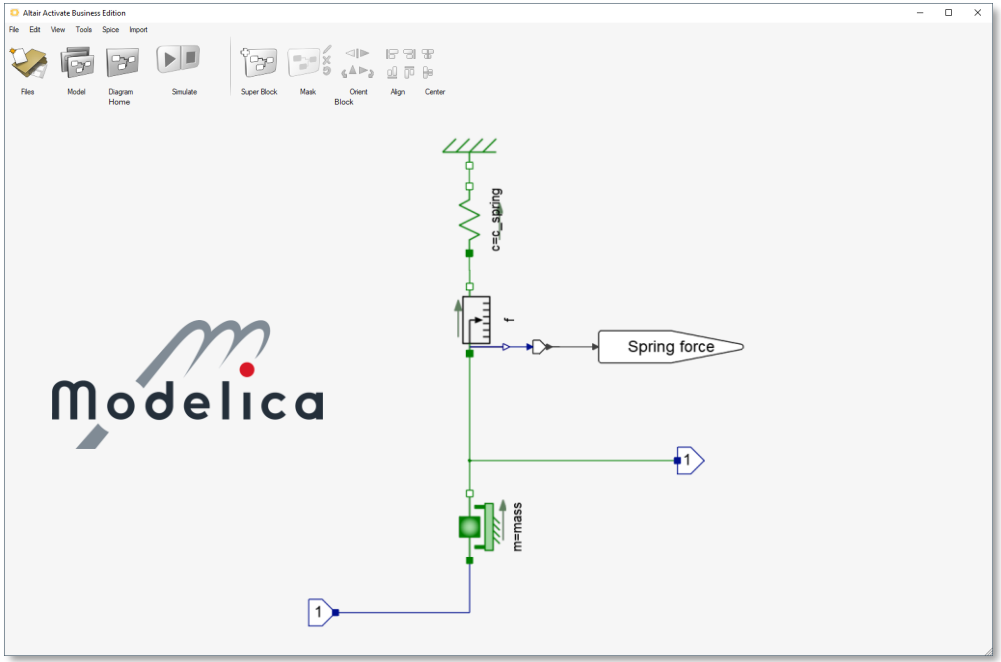
参数输入及功能界面



机械模型

机械模型包含

- 柱塞质量
- 弹簧

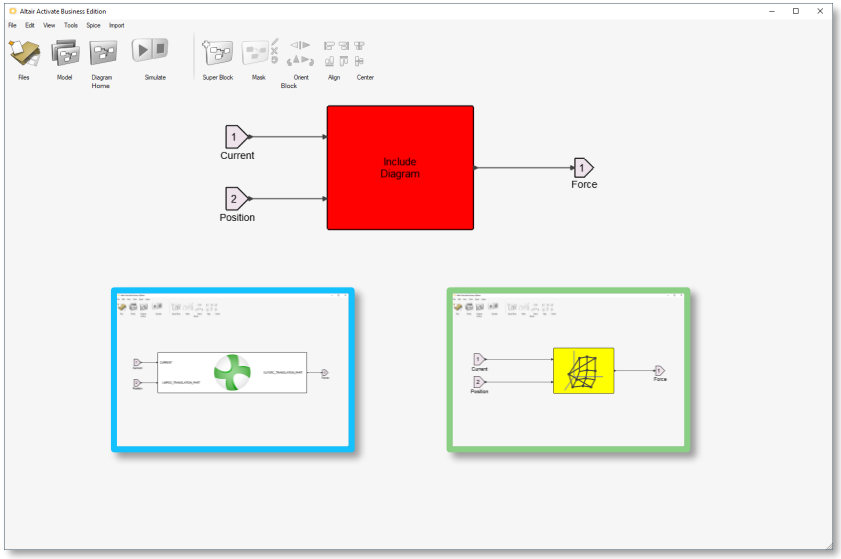


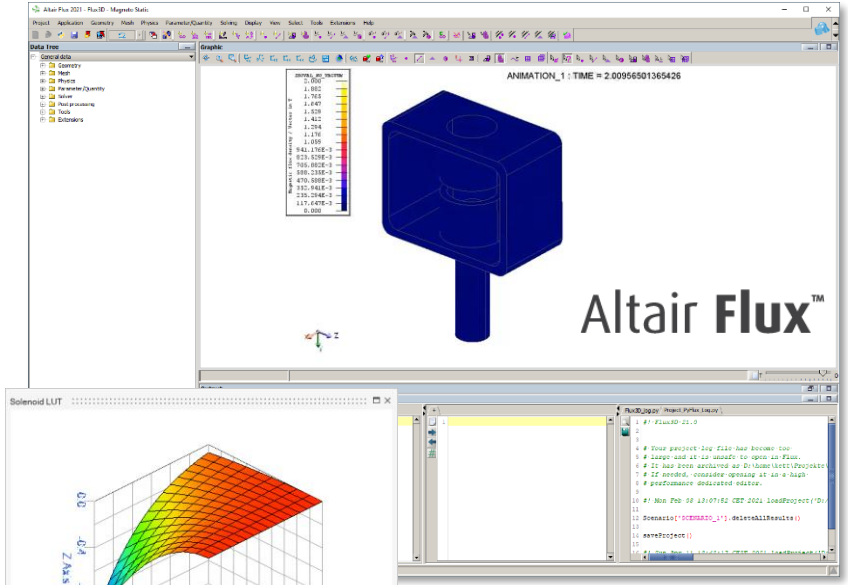
ALTAIR

电磁模型

两种级别的电磁螺线管模型

- Co-simulation
- Look-up table





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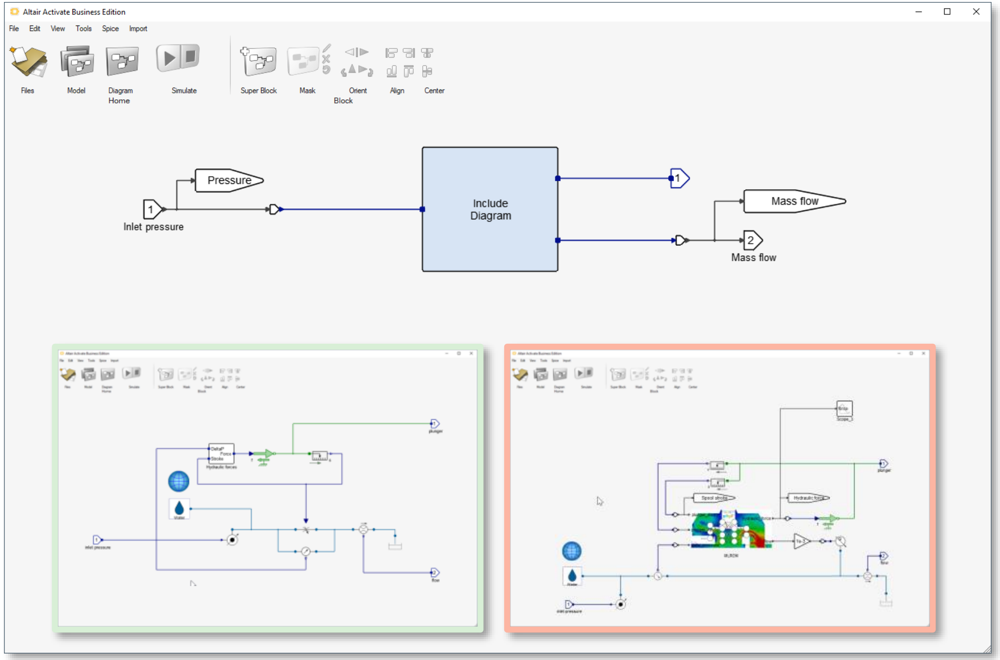
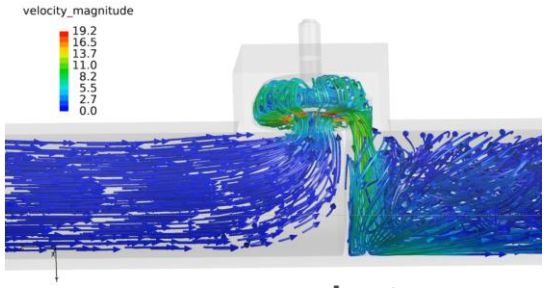
液压模型 (Flow and Forces)

两种精度的液压模型

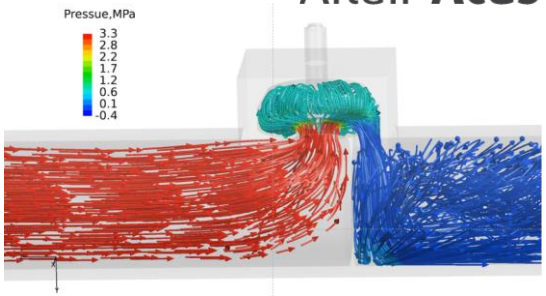
- Look-up tables
  (steady state behavior)
- romAI
  (transient behavior)

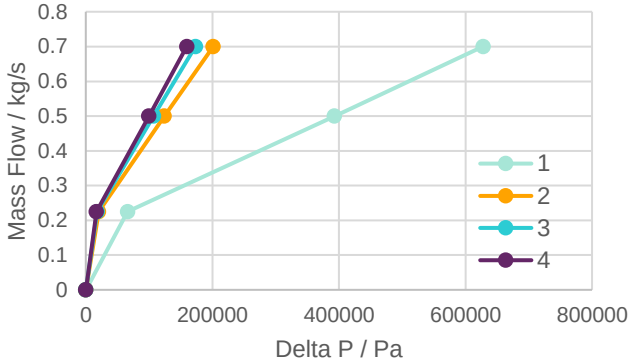


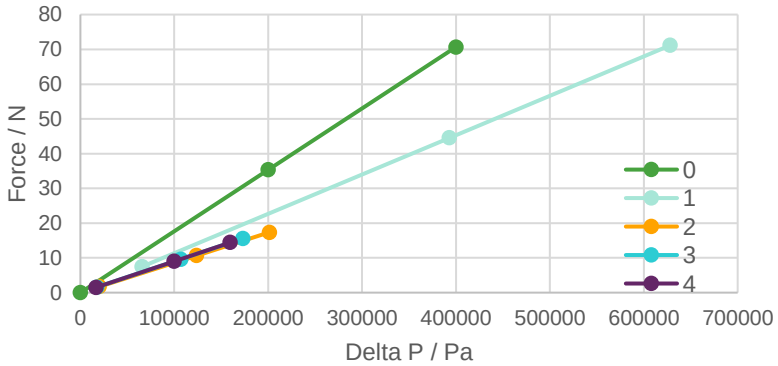
LUT Model – Flow and Force



Altair **AcuSolve**™







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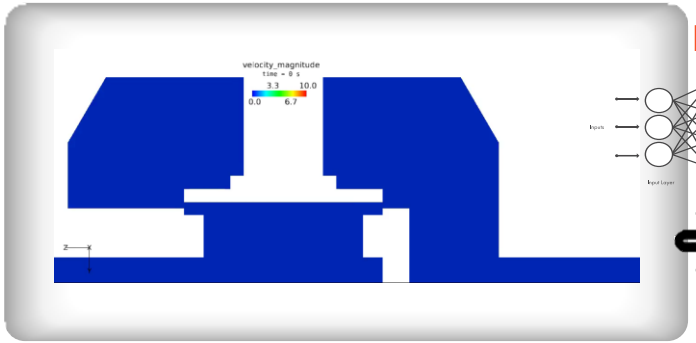
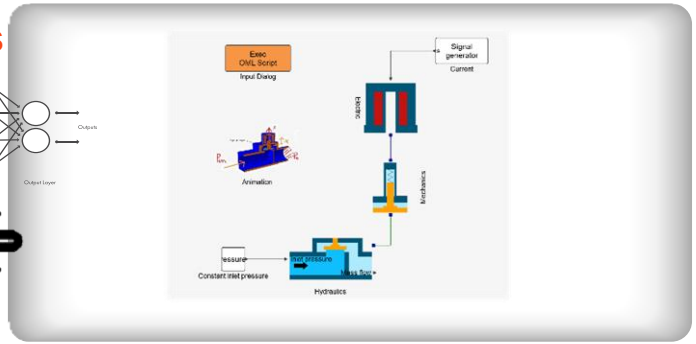
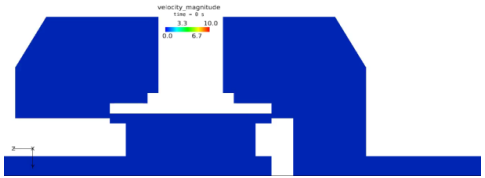
romAI – Best of Both Worlds

3D World	1D World
	
Accurate Focus on components, subsystems	Fast Focus on system performance

romAI – Generation and Usage

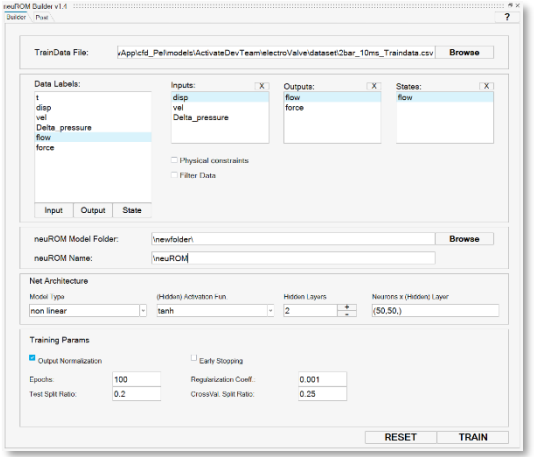
3D analysis

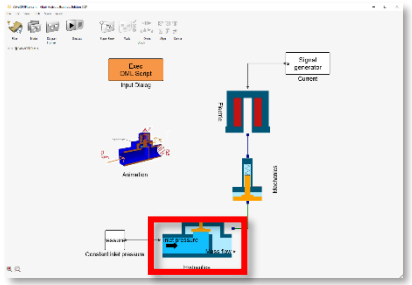


Training data

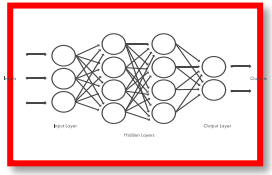
$$\begin{bmatrix} x(t_i) \\ v(t_i) \\ \Delta p\ (t_i) \\ Q(t_i) \\ F(t_i) \end{bmatrix}$$

Machine learning



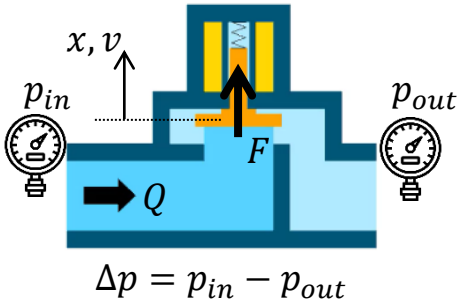


System simulation



romAI

romAI – CFD 问题描述



INPUTS:

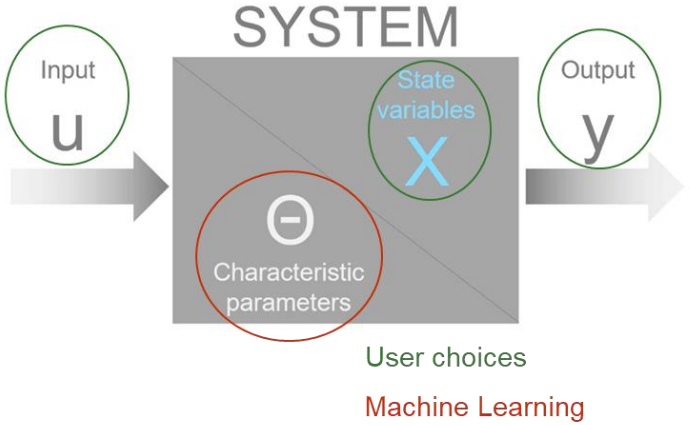
Plunger 位移 x
Plunger 速度 v
压力差 Δp

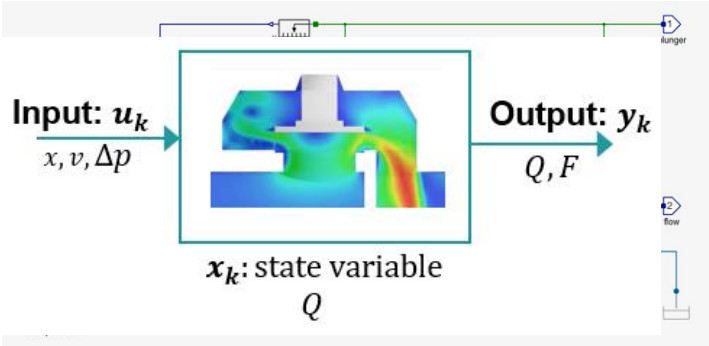
STATE VARIABLE:

流量 Q

OUTPUTS:

流量 Q
液压力 F





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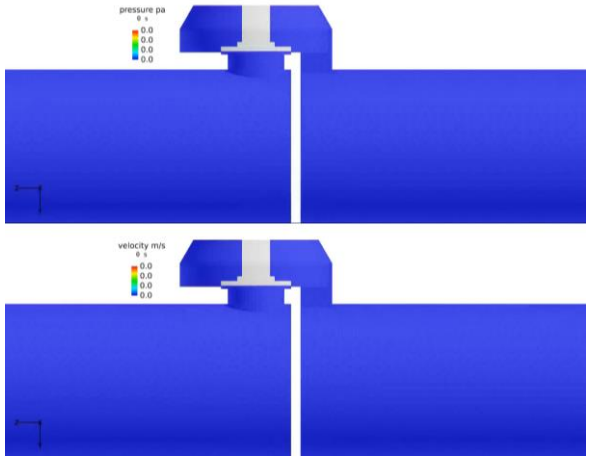
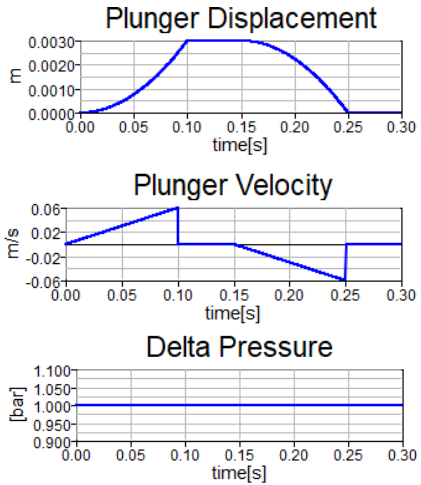
romAI – 从 CFD 仿真获得数据

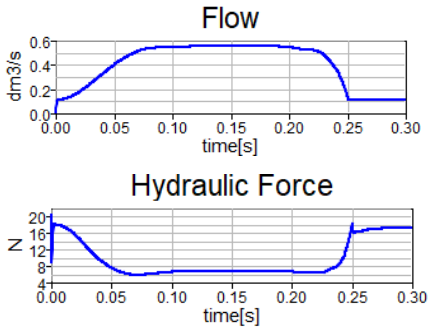
训练数据通过采用CFD瞬态仿真4中不同工况获得 （~ 1700数据点）：

pInlet	2 bar, 4 bar
Opening time	10 ms, 100 ms

Example: results @ 2 bar inlet pressure and 100 ms opening time

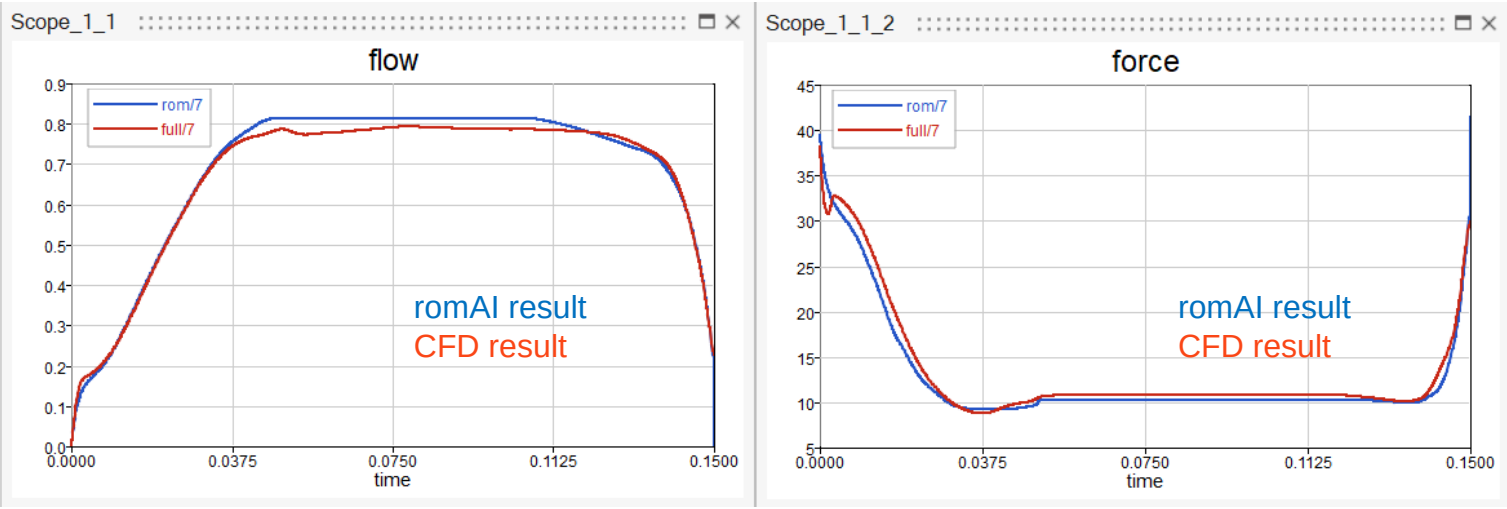






romAI – CFD 仿真结果 vs romAI

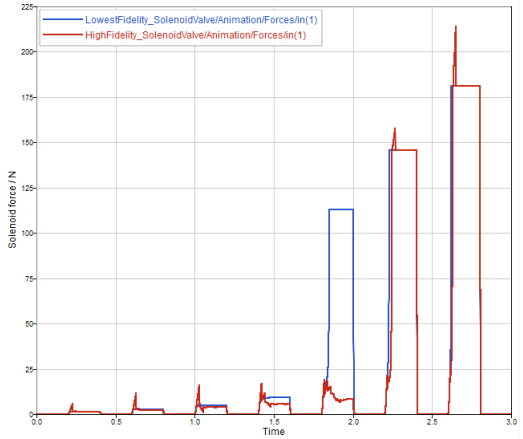
Test dataset @ 3 bar inlet pressure and 50 ms opening time.



两种模型系统仿真结果对比

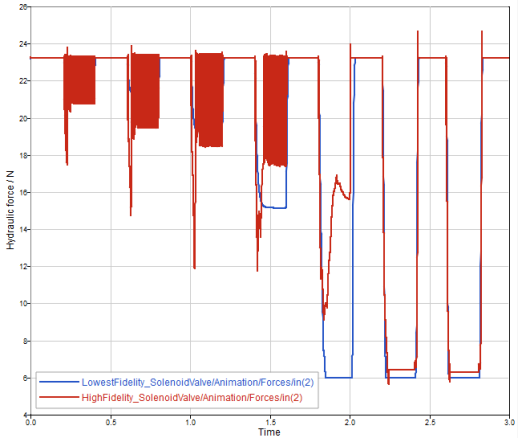
LUT vs. romAI

Solenoid force

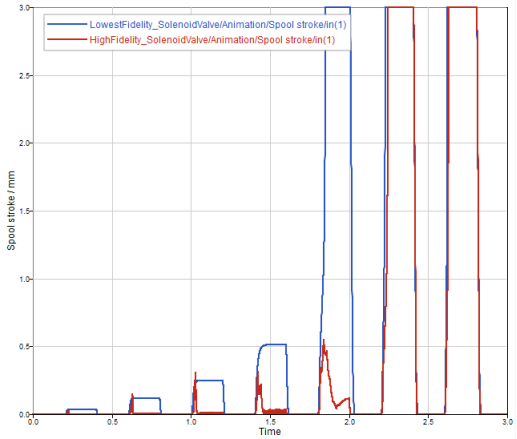


Hydraulic force

Lowest fidelity model Highest fidelity model



Spool stroke



romAI 模型能够反映更多的系统动态行为，如力和行程结果的过冲。

Oscillation in hydraulic force is caused by missing CFD data for closed valve and simplification in transition to small openings.

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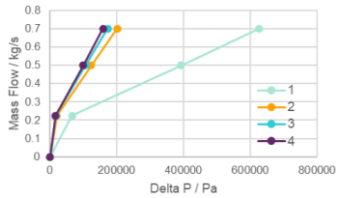
在瞬态和稳态状态下都保持较好的精度

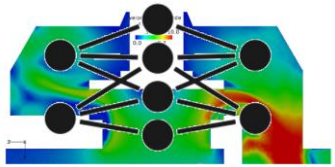
STEADY STATE

TRANSIENT

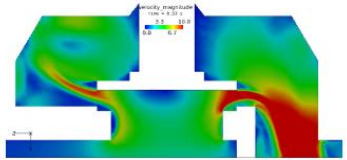
ACCURACY



look-up table

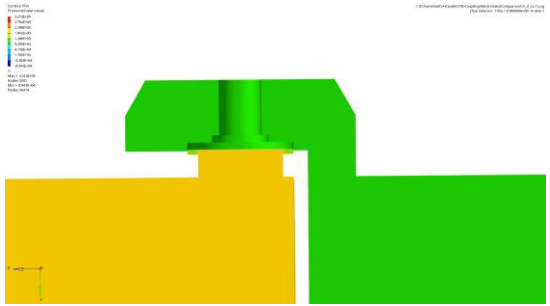


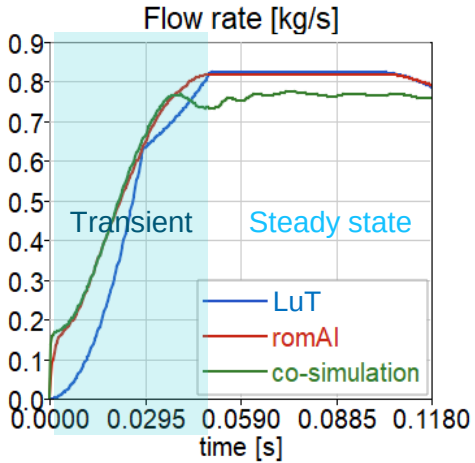
romAI

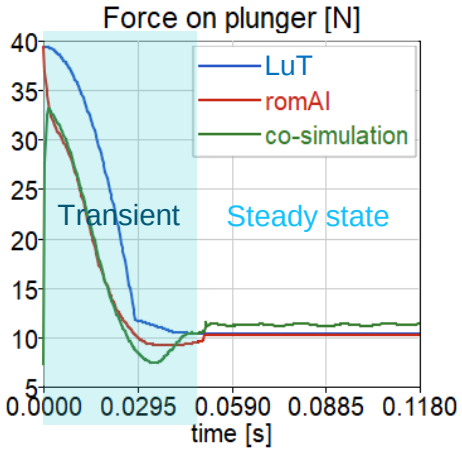


co-simulation

valve opening







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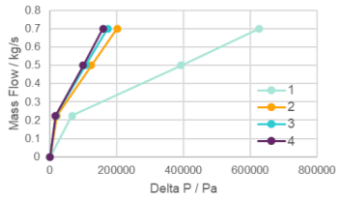
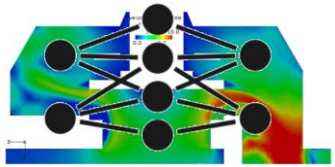
高效的兼容实时运行（Real-time）的降阶模型

STEADY STATE

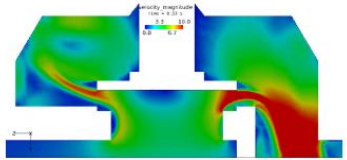
TRANSIENT



look-up table



romAI



co-simulation

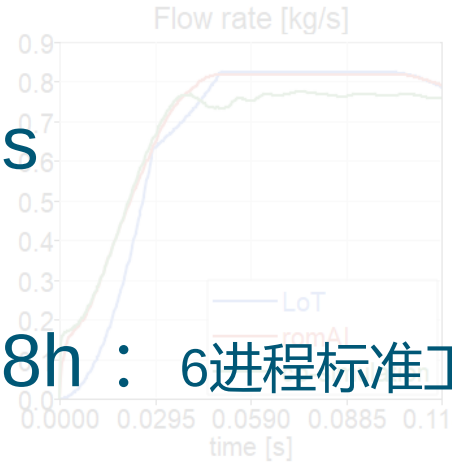
ACCURACY

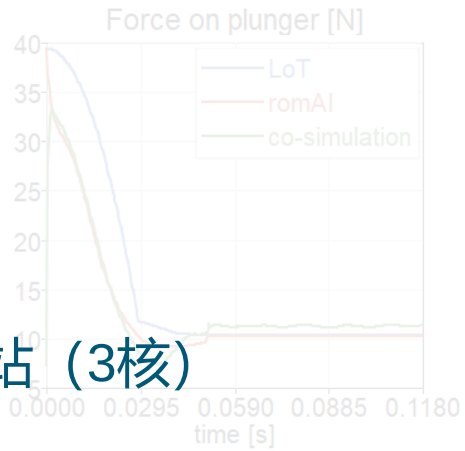
仿真时间

valve opening

<1s

<1s





~18h： 6进程标准工作站（3核）

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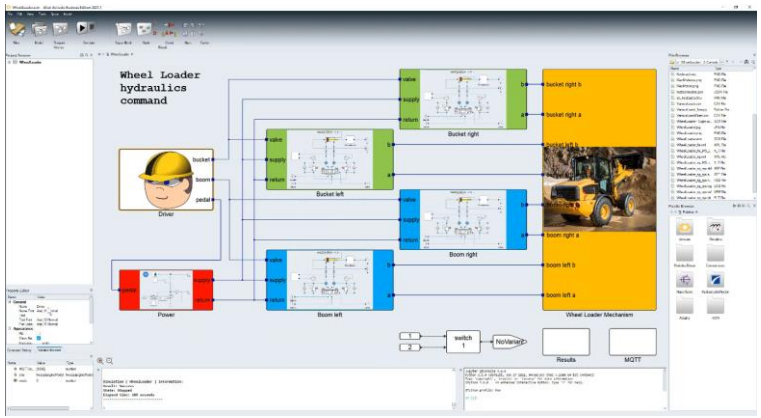
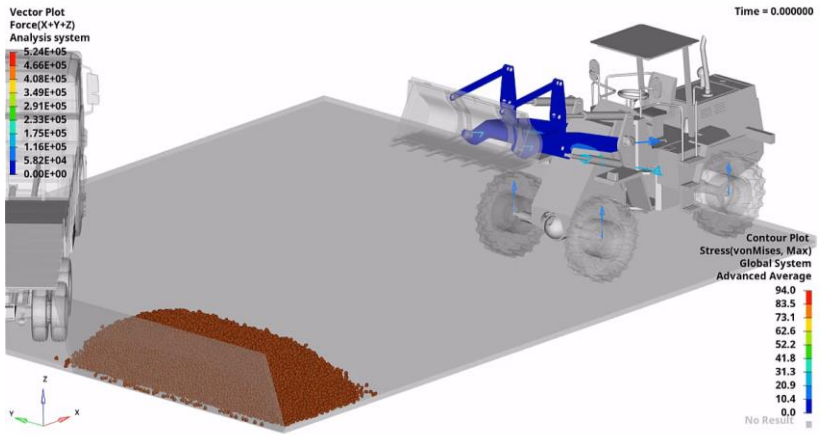
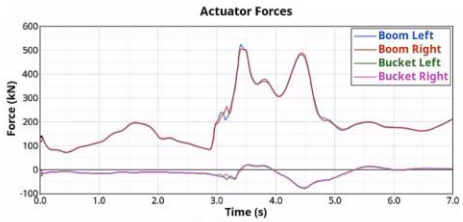
轮式装载机
(WHEEL LOADER)

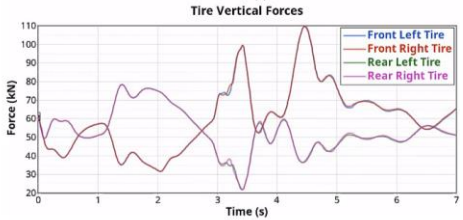
系统集成



- 控制系统
- 液压执行机构
- 包含柔性组件的多体
- 散装物料







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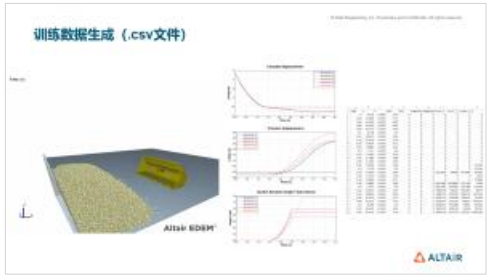
是否希望在保持精度的前提下减少仿真时间?

Wheel loader: 保持精度的前提下减少仿真时间

数据生成

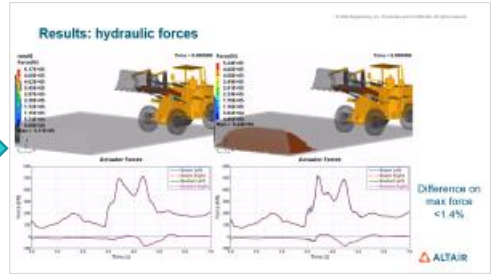


30 min

ROM 生成 & 验证

8h

结果评估



15min

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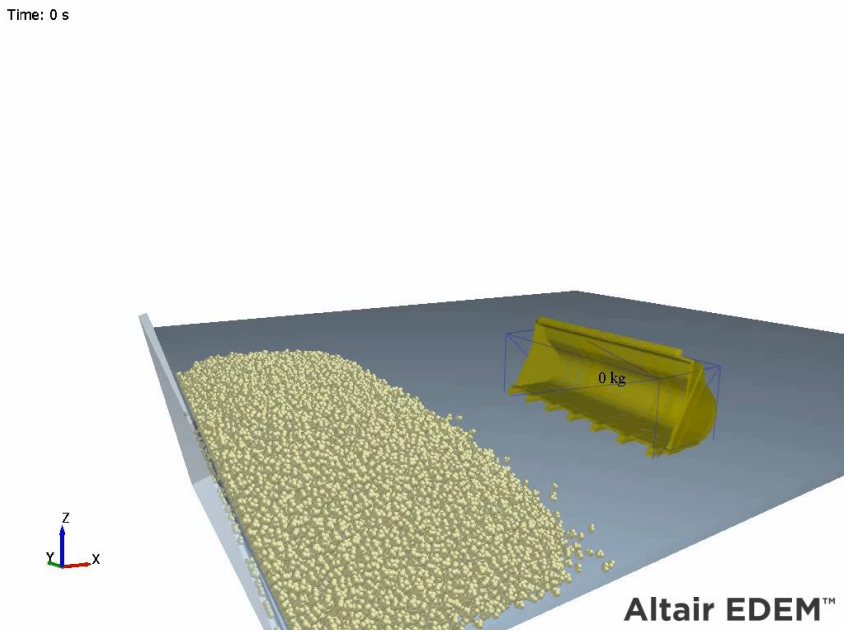
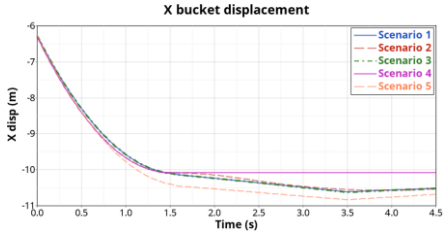
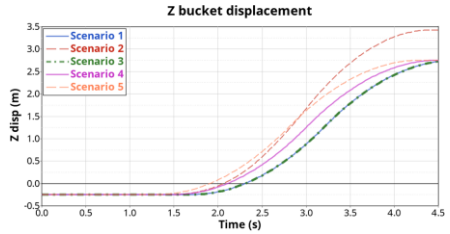
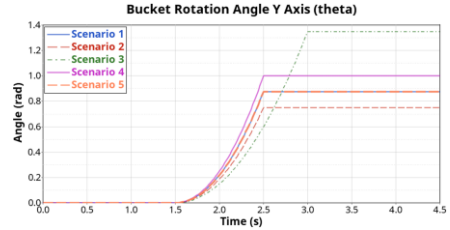
训练数据生成（.csv文件）





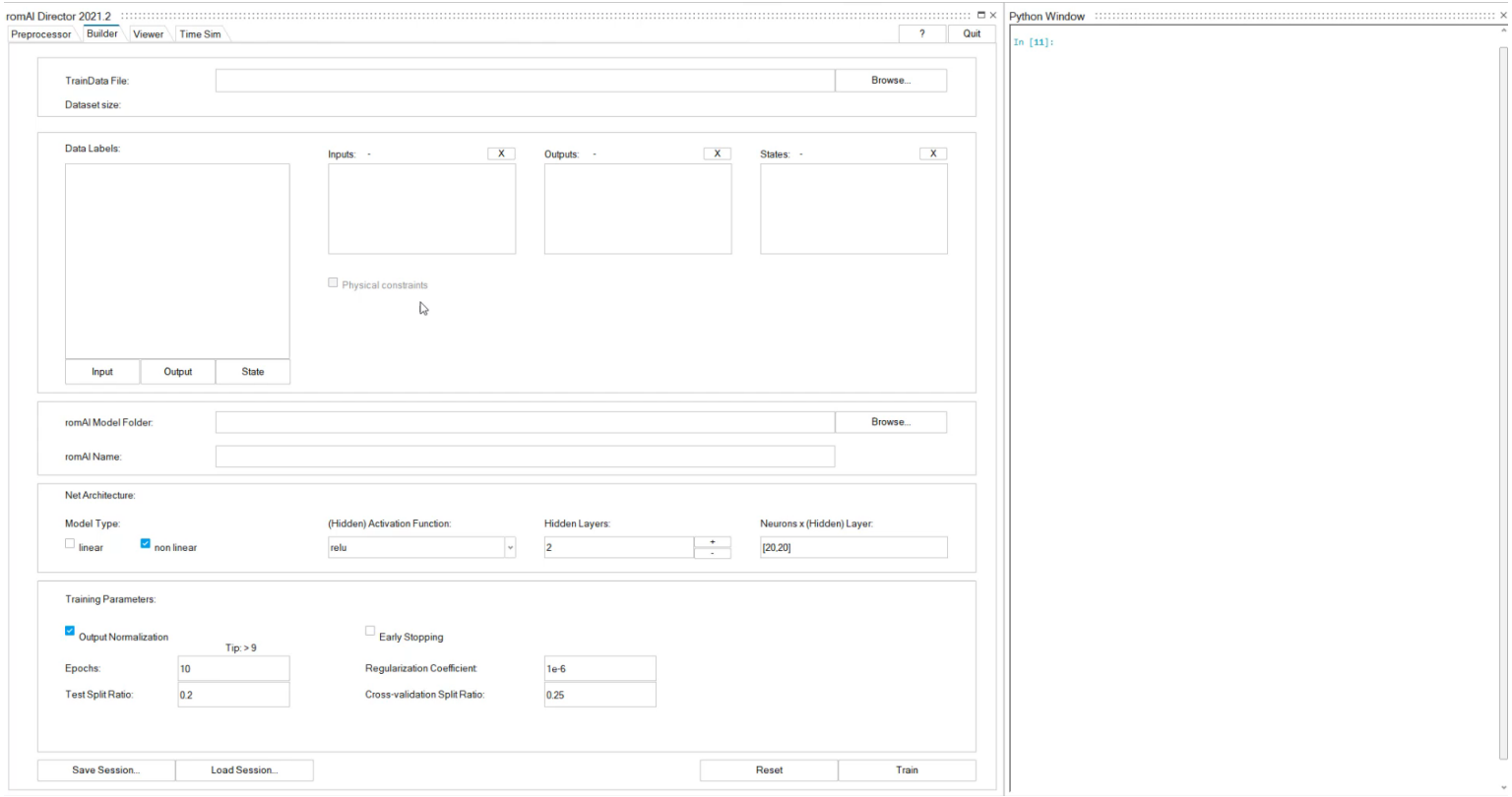




	A	B	C	D	E	F	G	H	I	J	K
1	TIME	X	Z	Xdot	Zdot	AngleYbuc	AngleYdot	Force_X	Force_Z	Torque_Y	m
2	0	-6.273	-0.2452	-4.74	0	0	0	0	0	0	0
3	0.02	-6.3684	-0.2452	-4.74	0	0	0	0	0	0	0
4	0.04	-6.4626	-0.2452	-4.68	0	0	0	0	0	0	0
5	0.06	-6.5556	-0.2452	-4.62	0	0	0	0	0	0	0
6	0.08	-6.6474	-0.2452	-4.56	0	0	0	0	0	0	0
7	0.1	-6.738	-0.2452	-4.5	0	0	0	0	0	0	0
8	0.12	-6.8274	-0.2452	-4.44	0	0	0	0	0	0	0
9	0.14	-6.9156	-0.2452	-4.38	0	0	0	0	0	0	0
10	0.16	-7.0026	-0.2452	-4.32	0	0	0	0	0	0	0
11	0.18	-7.0884	-0.2452	-4.26	0	0	0	0	0	0	0
12	0.2	-7.173	-0.2452	-4.2	0	0	0	0	0	0	0
13	0.22	-7.2564	-0.2452	-4.14	0	0	0	0	0	0	0
14	0.24	-7.3386	-0.2452	-4.08	0	0	0	0	0	0	0
15	0.26	-7.4196	-0.2452	-4.02	0	0	0	0	0	0	0
16	0.28	-7.4994	-0.2452	-3.96	0	0	0	0	0	0	0.2399
17	0.3	-7.578	-0.2452	-3.9	0	0	0	0	0	0	0.7196
18	0.32	-7.6554	-0.2452	-3.84	0	0	0	131.3939	8.0284	-46.7906	0.9595
19	0.34	-7.7316	-0.2452	-3.78	0	0	0	0	0	0	1.679
20	0.36	-7.8066	-0.2452	-3.72	0	0	0	0	0	0	2.3986
21	0.38	-7.8804	-0.2452	-3.66	0	0	0	639.1005	155.8986	-157.428	3.598
22	0.4	-7.953	-0.2452	-3.6	0	0	0	903.5947	-16.2967	-373.388	6.7162
23	0.42	-8.0244	-0.2452	-3.54	0	0	0	1938.924	-250.81	-943.867	8.875
24	0.44	-8.0946	-0.2452	-3.48	0	0	0	3309.716	-379.431	-1601.52	15.1114
25	0.46	-8.1636	-0.2452	-3.42	0	0	0	8204.357	-1318.88	-4244.61	26.385
26	0.48	-8.2314	-0.2452	-3.36	0	0	0	20781.18	-1113.39	-9066.3	40.0573
27	0.5	-8.298	-0.2452	-3.3	0	0	0	25284.27	-441.686	-10315	56.368
28	0.52	-8.3634	-0.2452	-3.24	0	0	0	34529.97	-1000.55	-14196	79.395
29	0.54	-8.4276	-0.2452	-3.18	0	0	0	34452.39	-957.725	-14115.5	108.4185

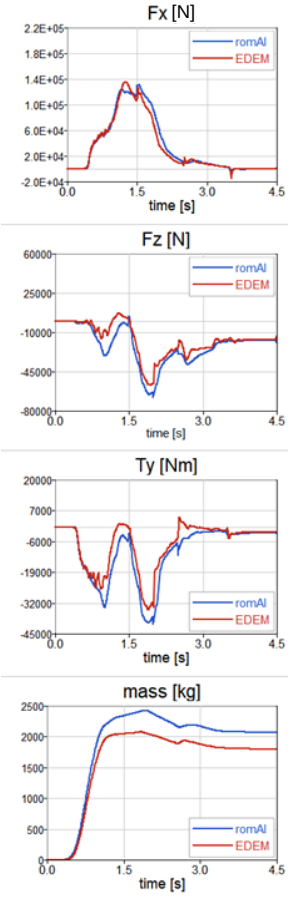
ALTAIR

数据训练（生成ROM）

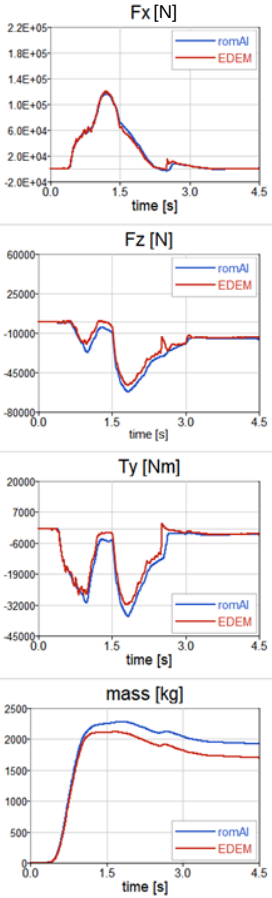


模型验证

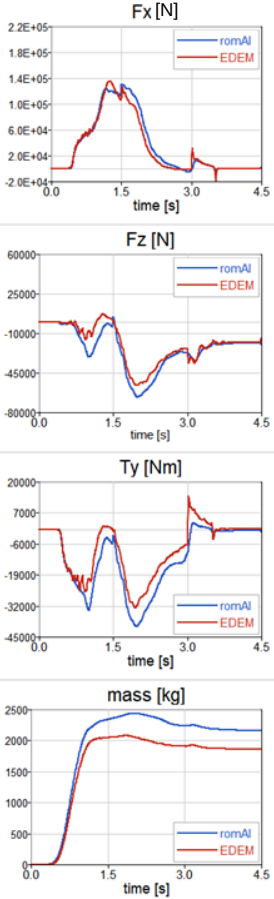
1st Simulation



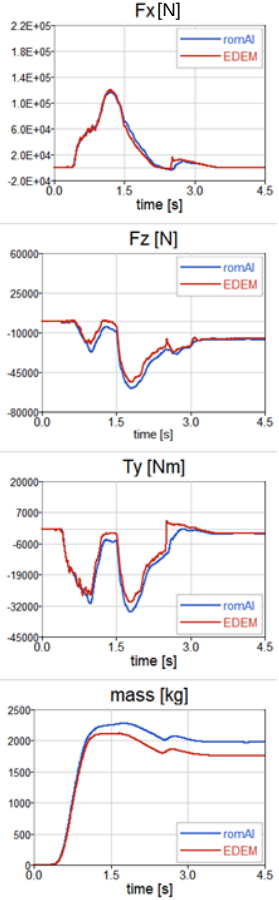
2nd Simulation



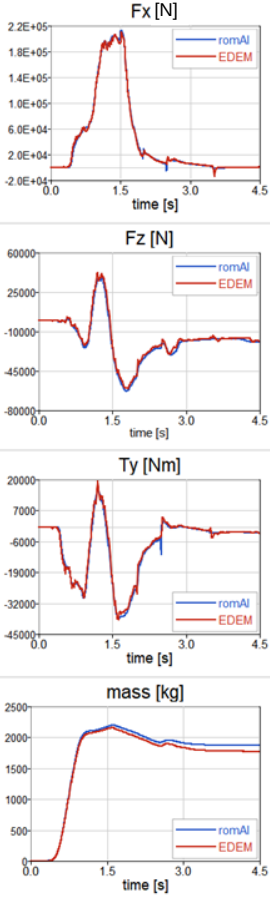
3rd Simulation



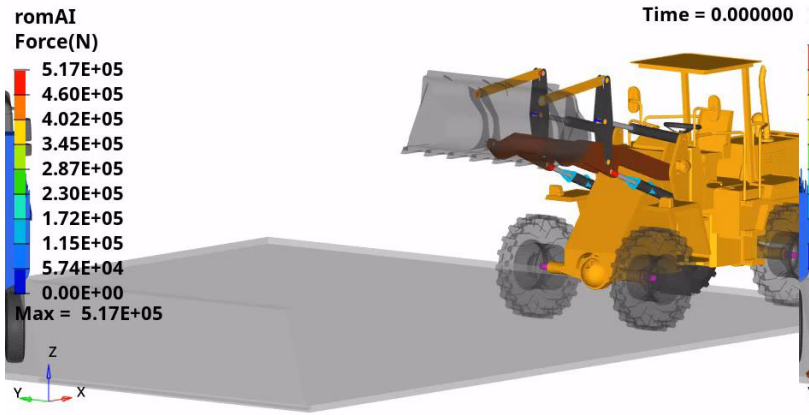
4th Simulation

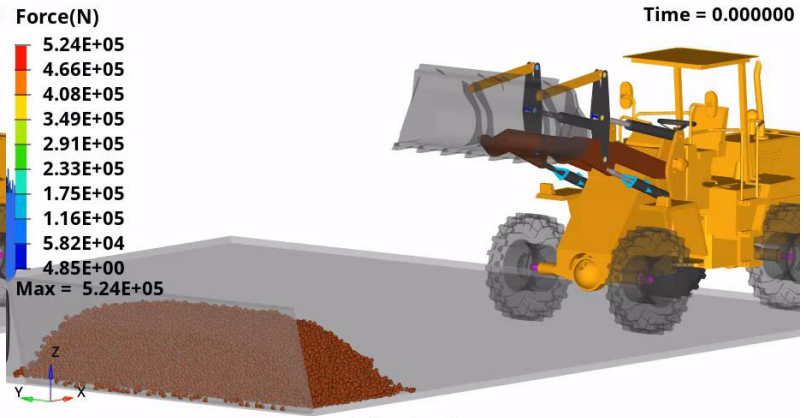


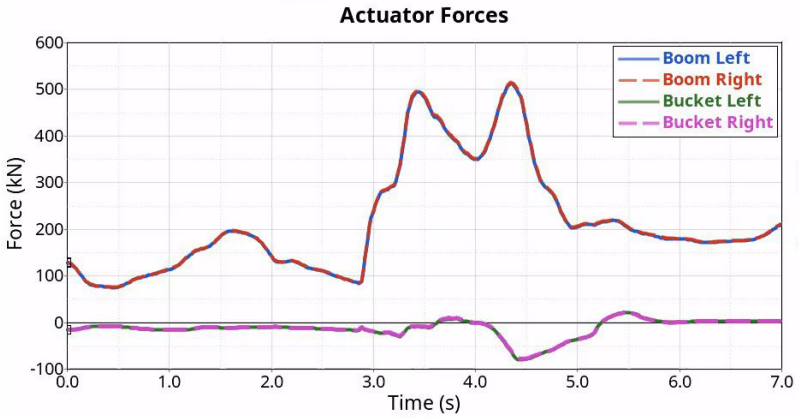
5th Simulation

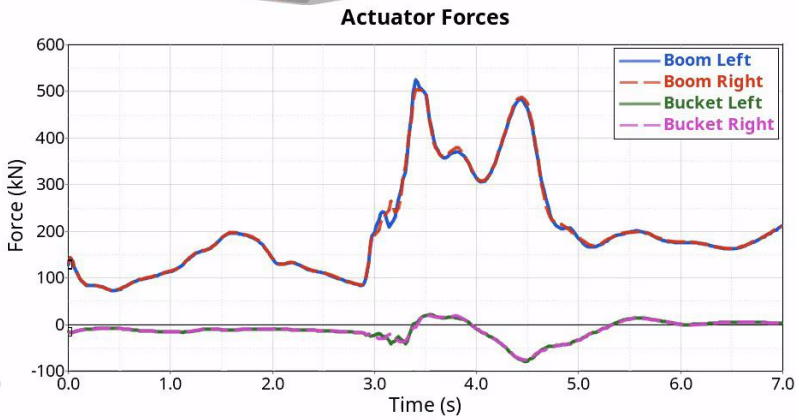


Results: hydraulic forces









Difference on max force <1.4%

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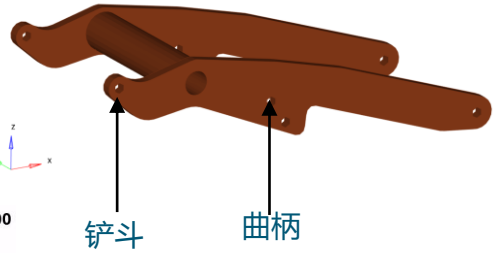
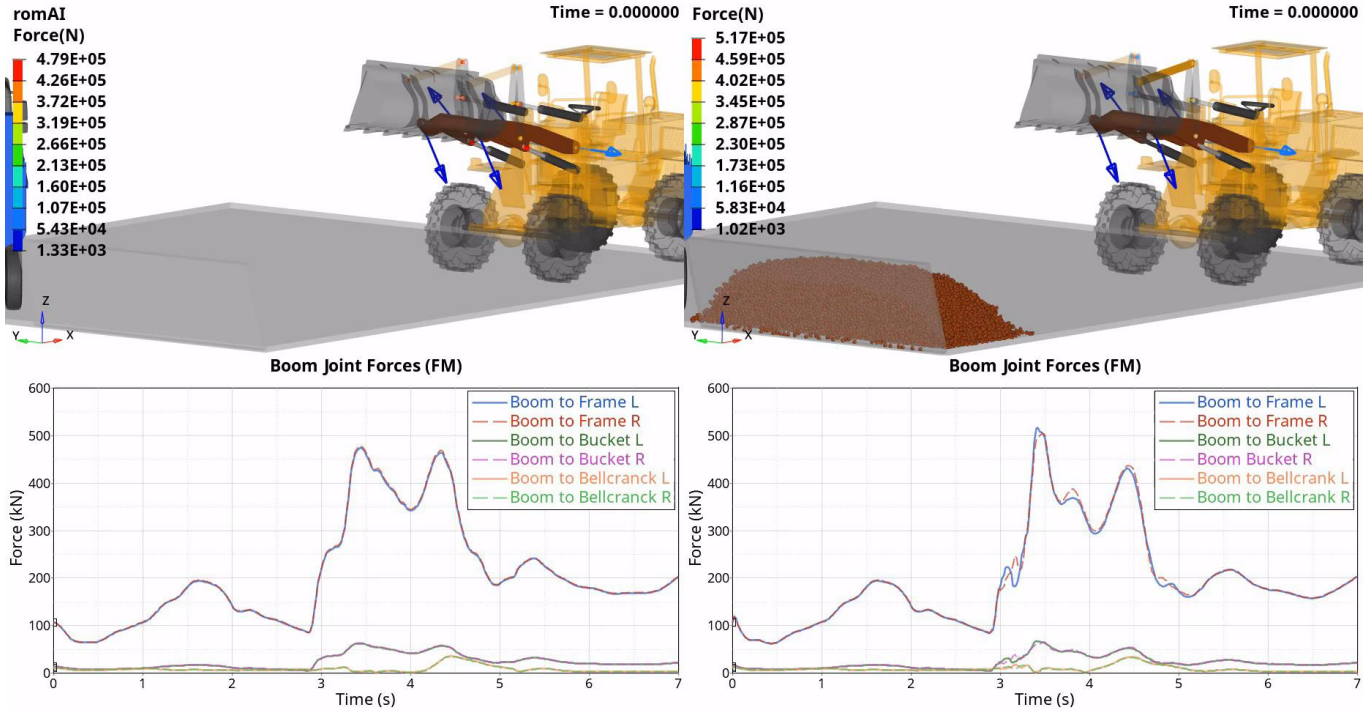
Results: joint forces





Difference on max force <7.4%

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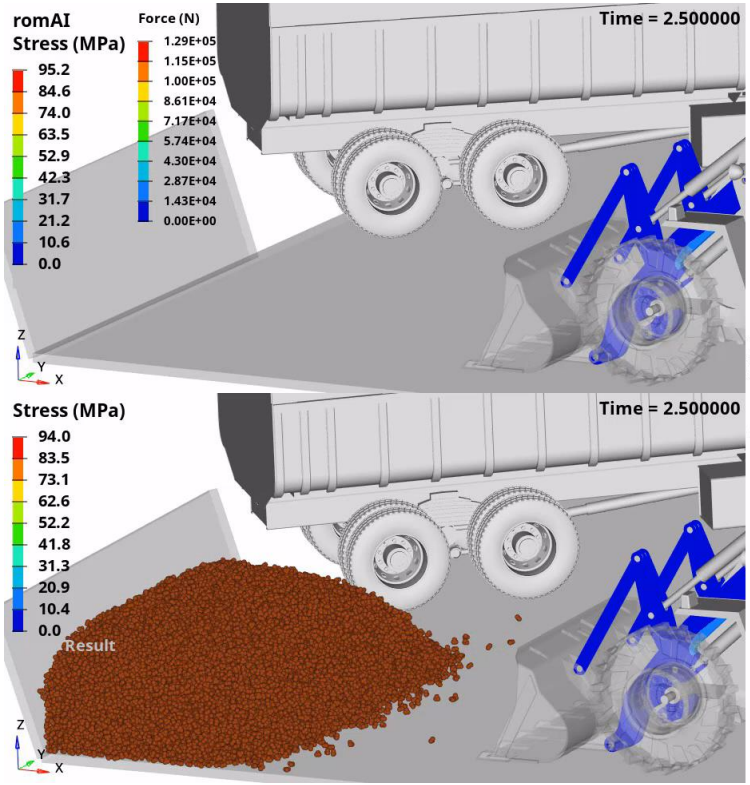
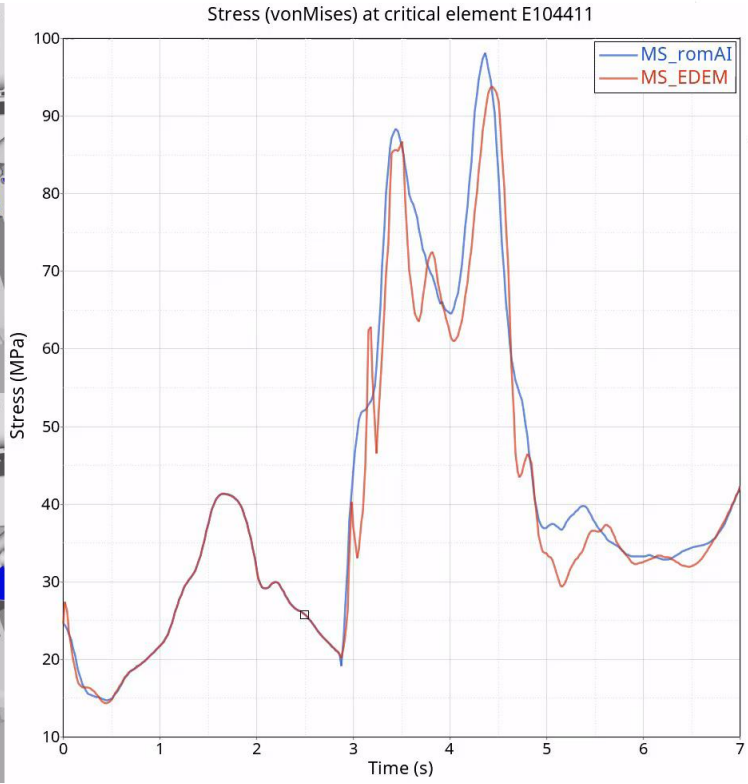
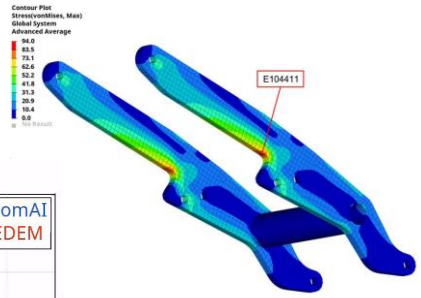
Results: 关键部位的 VonMises 应力







Difference on max stress <1.3%

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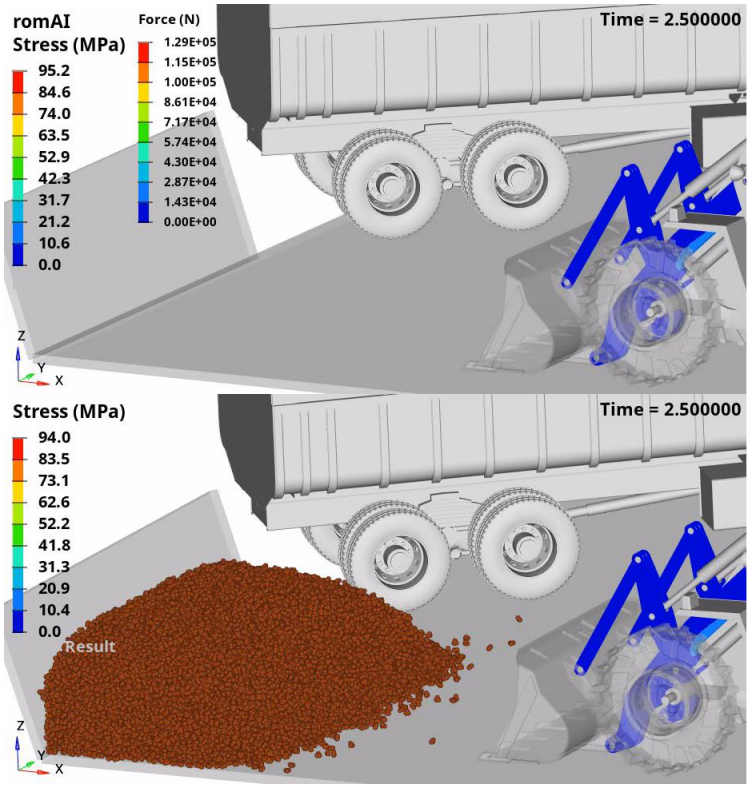
Results: run time



20s
Motion - romAI

Vs

680s
Motion - EDEM

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BATTERY CELL MODEL

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Battery Cell: dynamical system

Input: u_k

i

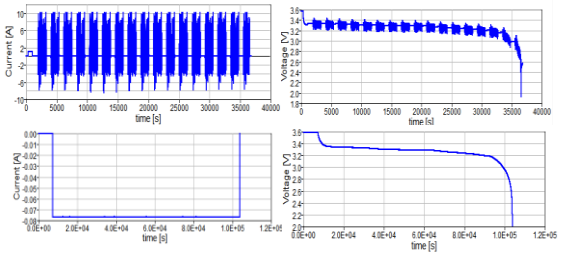
Output: y_k

V, SOC

x: state variables

SOC

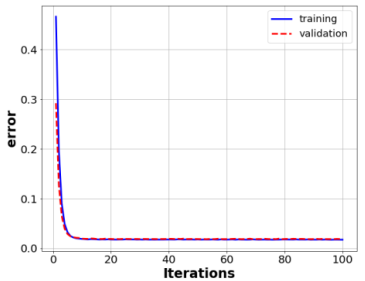
实验数据

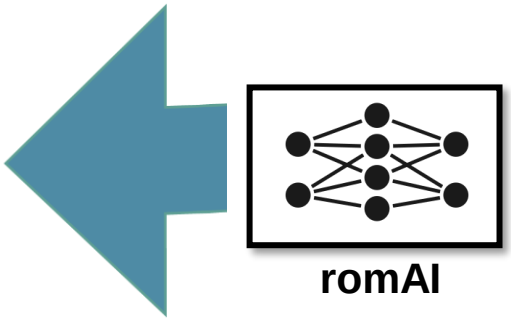


训练数据

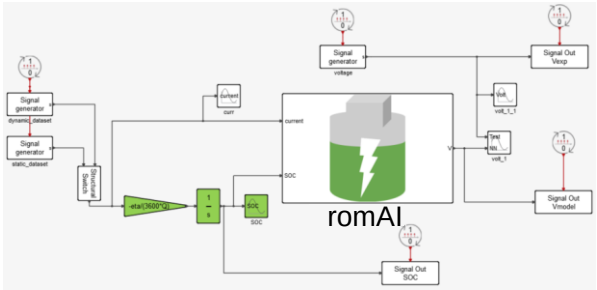
$$\begin{bmatrix} i(t_i) \\ V(t_i) \\ SOC(t_i) \end{bmatrix}$$

机器学习





romAI



系统仿真

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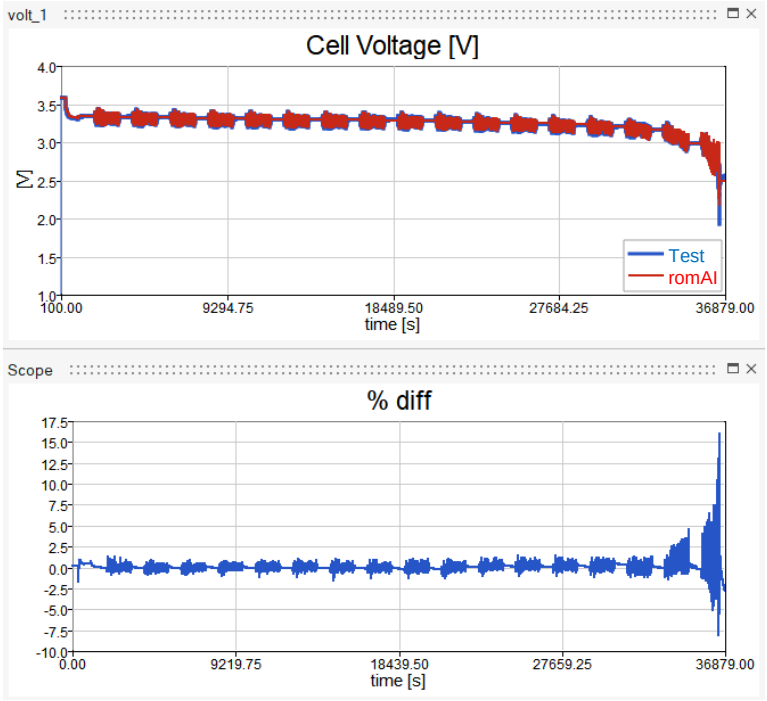
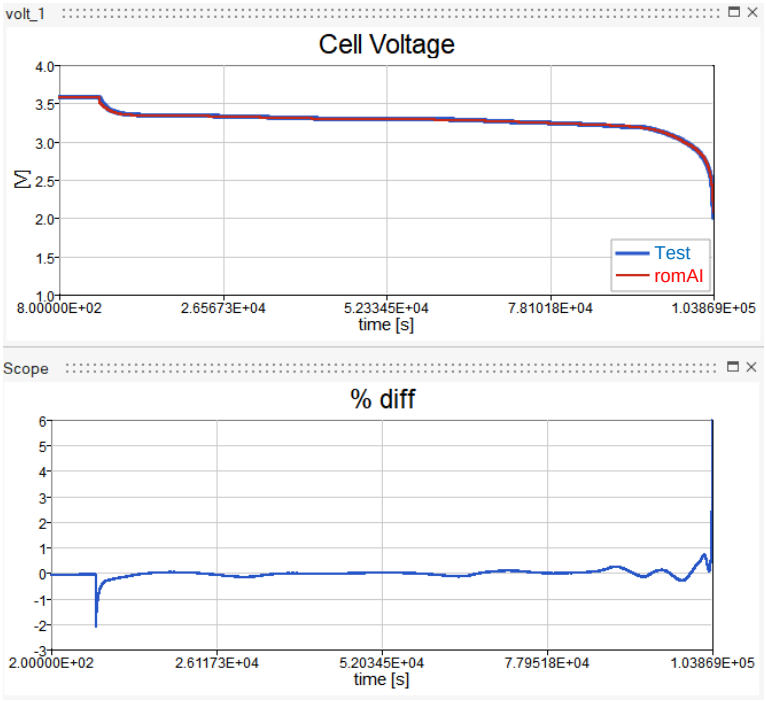
Results: dynamic and quasi-static tests

Dynamic



Quasi-Static



Difference mostly less than 2.5%

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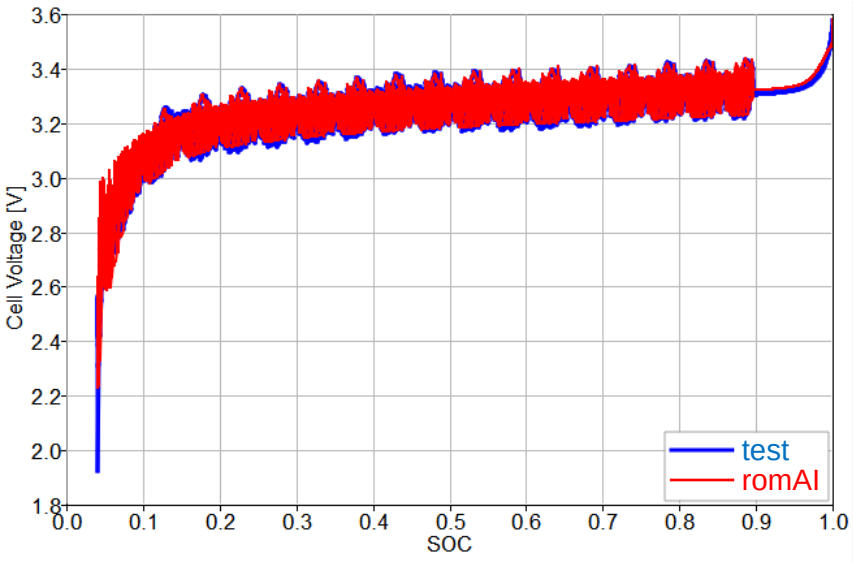
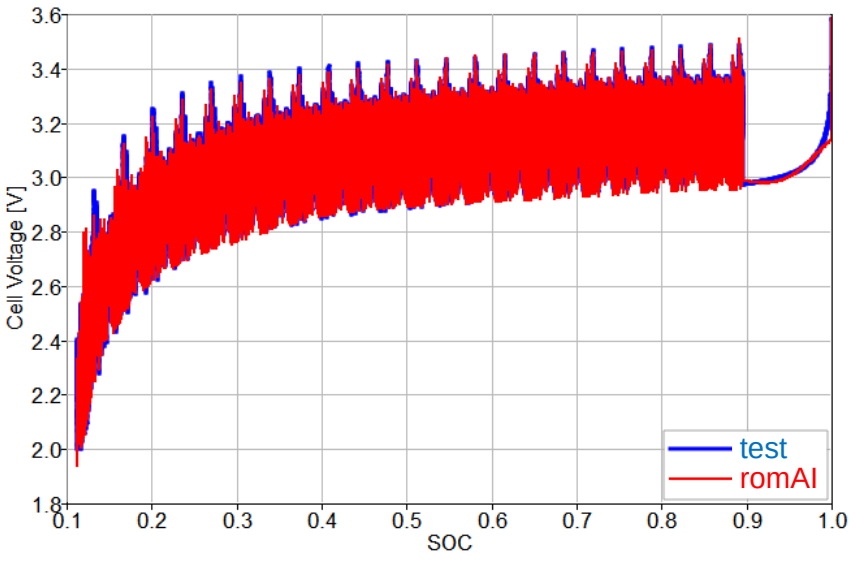
Results: Hysteresis

T = +25 degC



T = -25 degC



Very good modeling of the hysteretic behavior

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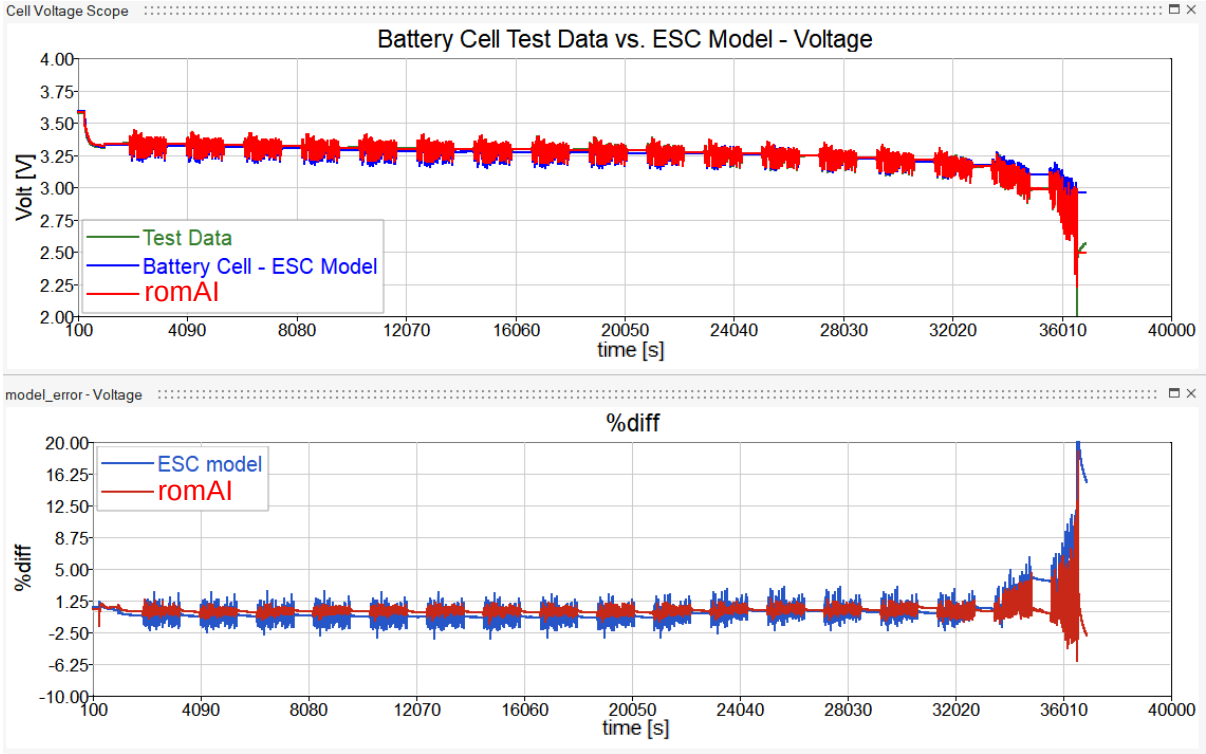
Results: romAI vs ESC battery model



T = +25 degC

romAI performs better than ESC battery model

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BALL AND BALANCING TABLE

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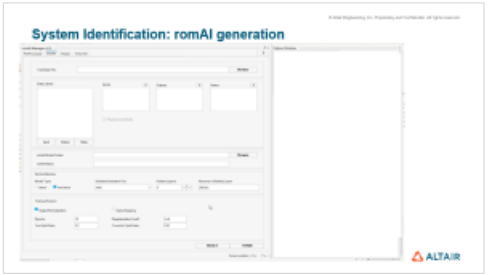
BBT: 利用人工智能设计控制器

Control of the Ball Balancing Table (BBT) from Acrome

数据生成

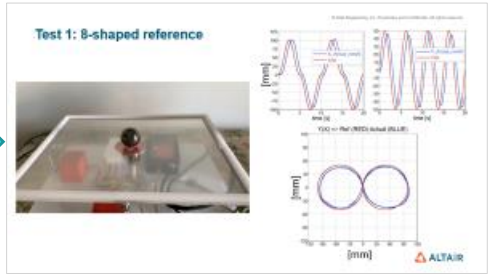
110s

系统辨识 & 控制设计



4.5h

测试



15min

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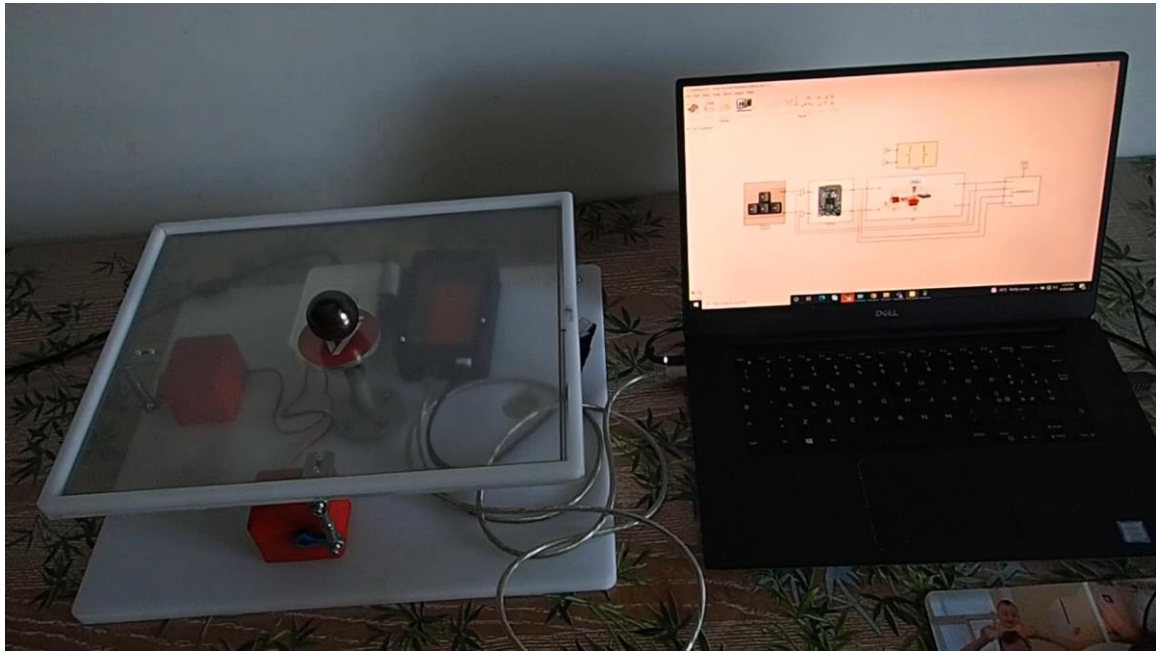
数据生成 （.csv文件）

Randomly playing for 110s



	A	B	C	D	E	F	G	H	I
1	time	Xref_mm	Yref_mm	X_mm	Y_mm	X_dot	Y_dot	TX_deg	TY_deg
2	0	0	0	0.1478	2.29719	0.002035	-5.00691	-0.13154	-0.75129
3	0.005	0	0	0.14781	2.272156	0.001635	-4.02188	-0.1229	-0.64688
4	0.01	0	0	0.147817	2.256972	0.000992	-2.43939	-0.11618	-0.66437
5	0.015	0	0	0.14782	2.247762	0.000601	-1.47957	-0.11099	-0.7383
6	0.02	0	0	0.147823	2.242176	0.000365	-0.8974	-0.107	-0.83284
7	0.025	0	0	0.147824	2.238788	0.000221	-0.5443	-0.10394	-0.92927
8	0.03	0	0	0.147825	2.236733	0.000134	-3.46057	-0.10162	-1.01857
9	0.035	0	0	0.147825	2.204182	6.809494	-9.0794	-0.09988	-0.74168
10	0.04	0	0	0.21592	2.145939	18.91092	-2.3765	-0.98042	-0.34267
11	0.045	0	0	0.336935	2.180417	7.056906	-5.306	-2.24316	-0.92738
12	0.05	0	0	0.286489	2.092879	4.280232	-16.1617	-1.14808	-0.10704
13	0.055	0	0	0.379737	2.0188	14.98058	-11.9009	-2.05039	0.374543
14	0.06	0	0	0.436295	1.97387	9.086187	-7.21829	-2.32564	0.459276
15	0.065	0	0	0.470599	1.946618	5.511053	-4.37812	-2.28084	0.348852
16	0.07	0	0	0.491405	1.930088	3.342624	-2.65546	-2.08883	0.155527
17	0.075	0	0	0.504025	1.920063	2.027405	-1.61062	-1.8441	-0.06046
18	0.08	0	0	0.511679	1.913982	-8.50653	-0.97689	-1.59585	-0.26867
19	0.085	0	0	0.41896	1.910294	-7.55573	-0.59251	-0.13833	-0.45542
20	0.09	0	0	0.436122	1.908057	5.153426	-0.35938	-0.41061	-0.6161
21	0.095	0	0	0.470494	1.9067	12.33139	-0.21797	-0.79145	-0.75081
22	0.1	0	0	0.559436	1.905877	12.52391	-0.13221	-1.81248	-0.86185
23	0.105	0	0	0.595733	1.905378	0.786723	-0.08019	-1.85986	-0.95238
24	0.11	0	0	0.567303	1.905075	-4.56737	-0.04864	-1.18889	-1.02565
25	0.115	0	0	0.550059	1.904892	-2.77025	-0.0295	-0.79696	-1.08473

Yes, only 110s!

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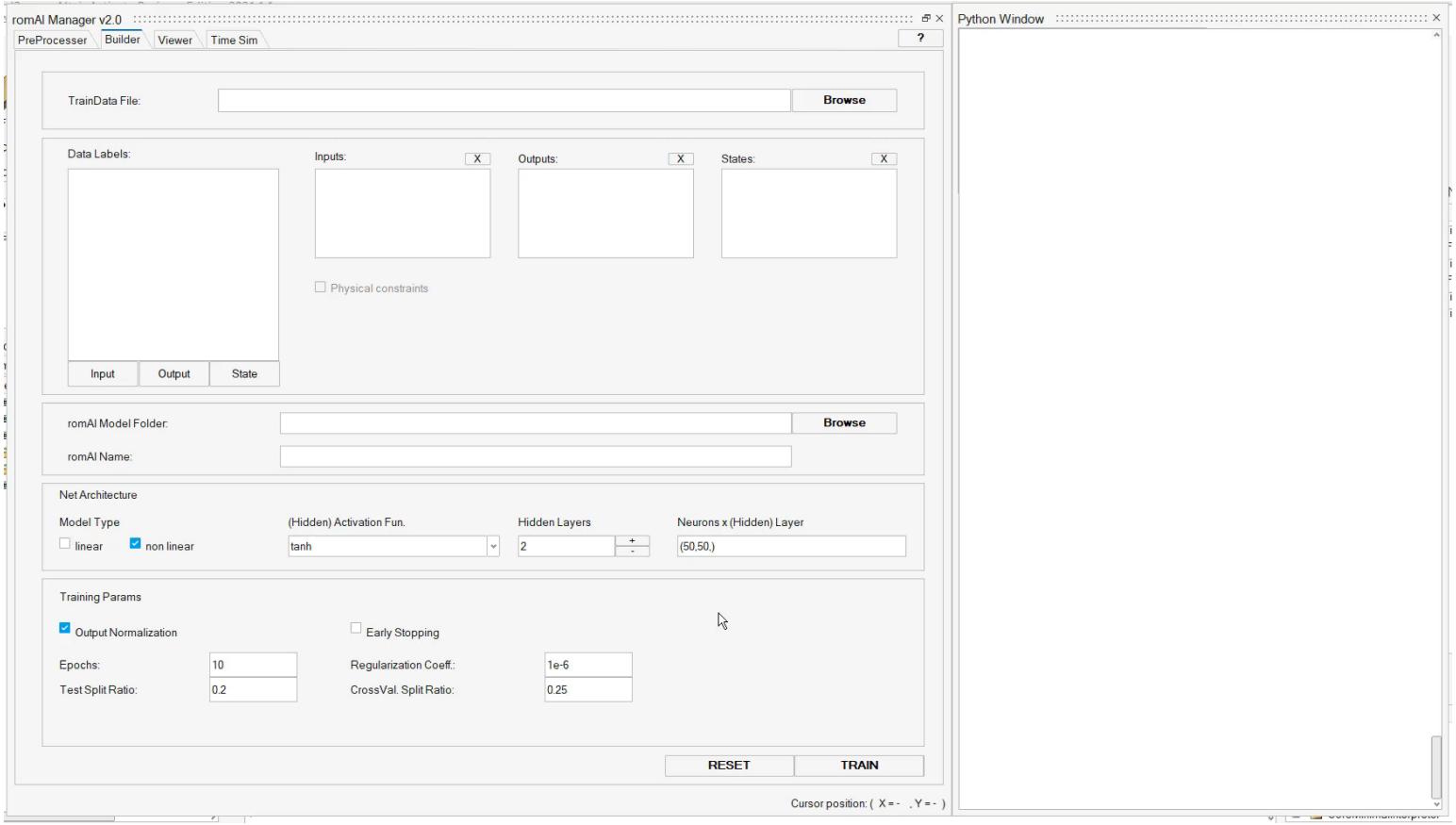
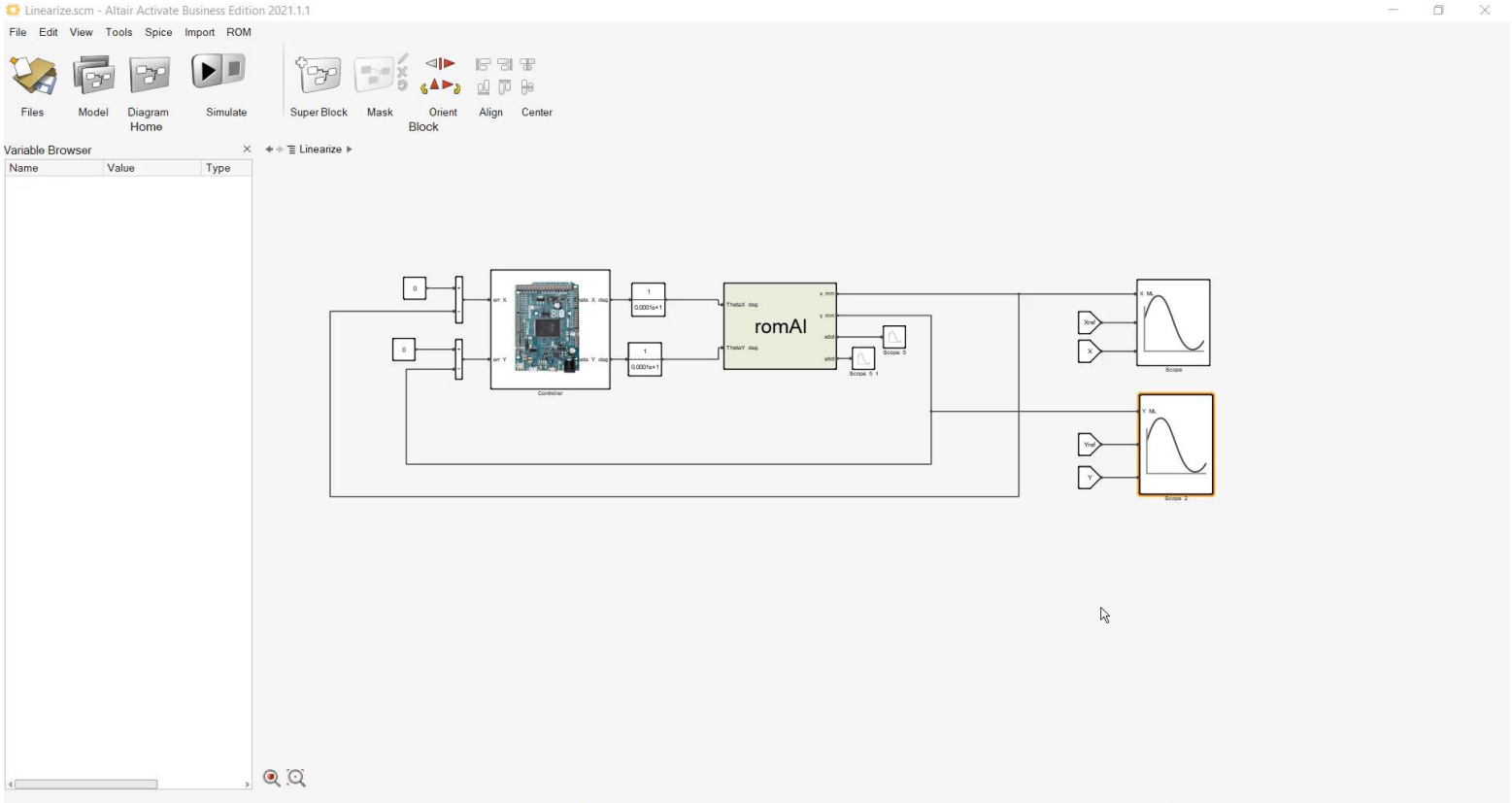
System Identification: romAI generation



Linearization: automatic A,B,C,D matrices generation



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Optimal Control design: automatic gain matrix generation

```
load('ABCD.mat');
Anew=C*A*C^(-1);
Bnew=C*B;
Cnew=eye(4,4);
Dnew=D;

%Optimal Controller

Q(1,1)=1;% X
Q(2,2)=1; %Y
Q(3,3)=0.1; %Xdot
Q(4,4)=0.1; %Ydot
R(1,1)=10;
R(2,2)=10;

K=lqr(Anew,Bnew,Q,R);
```

使用Activate® 控制库中内嵌的 *lqr* 函数

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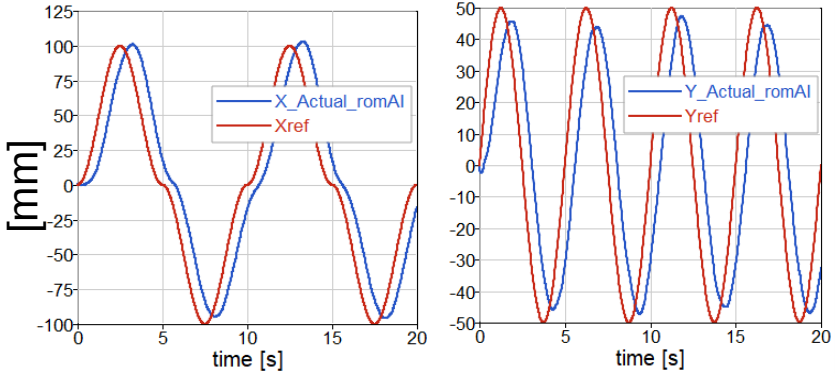
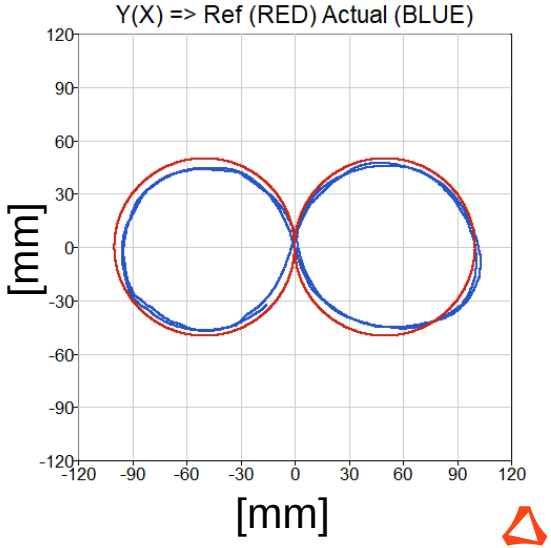
Test 1: 8-shaped reference





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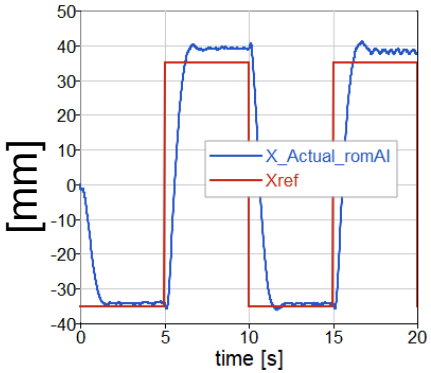
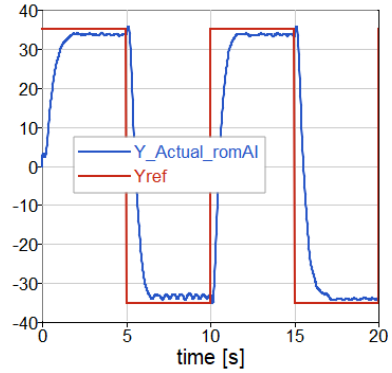
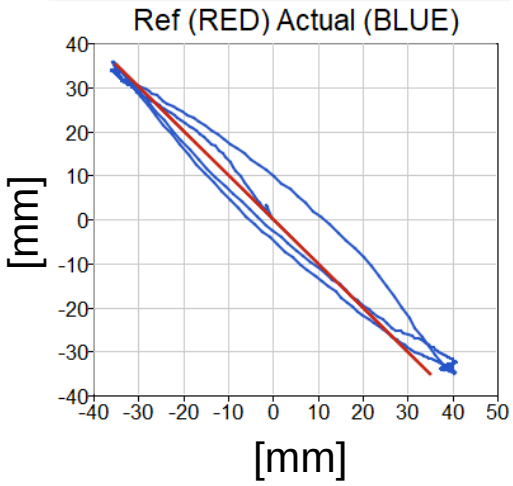
Test 2: Step-wise reference 1







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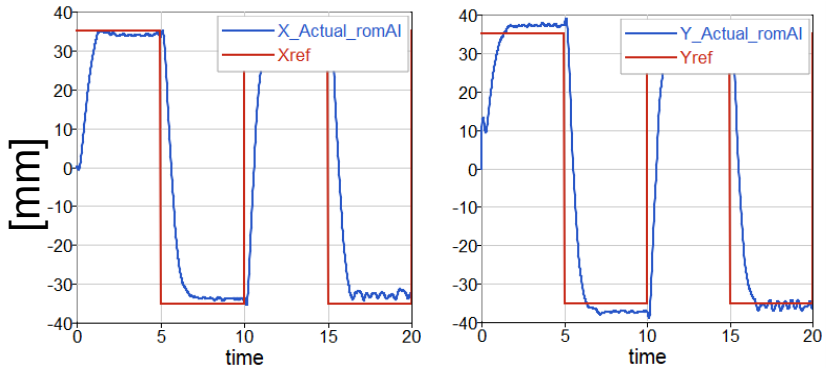
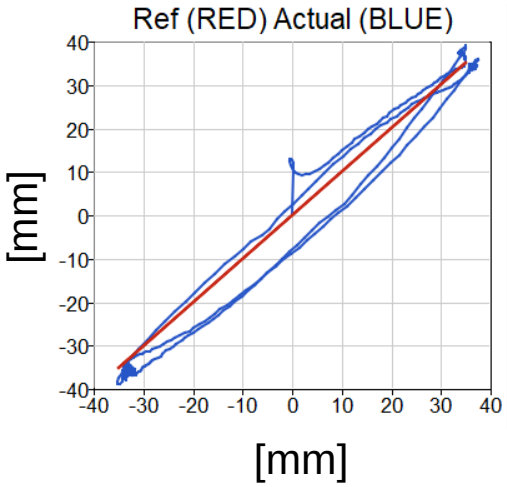
Test 3: Step-wise reference 2





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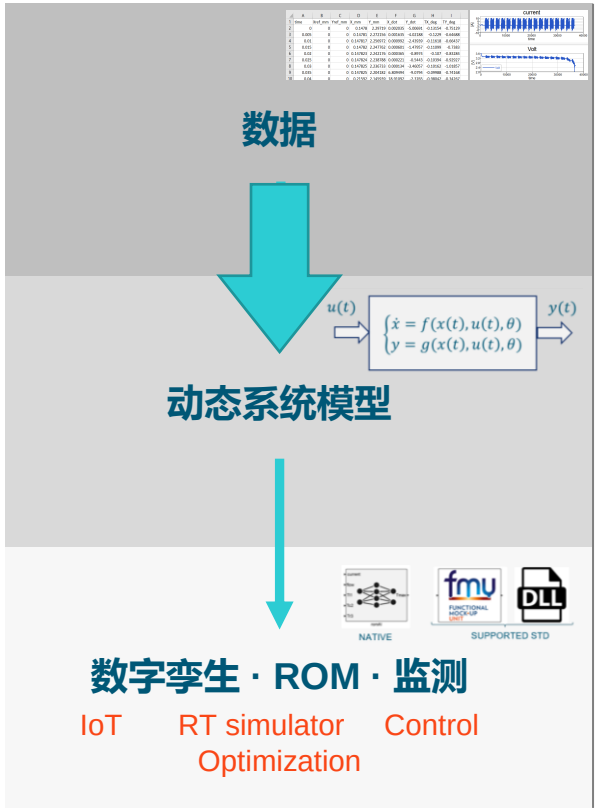
总结



romAI

人工智能

- 少量的仿真/测试
- 不受时间离散化影响
- 集成用户的专业经验
- 满足模型的泛化属性

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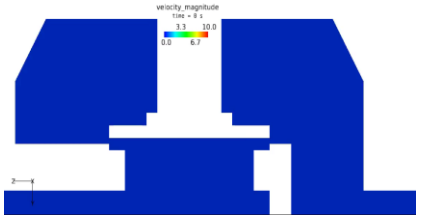
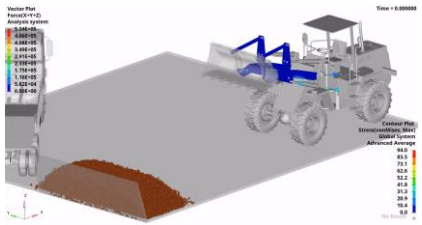
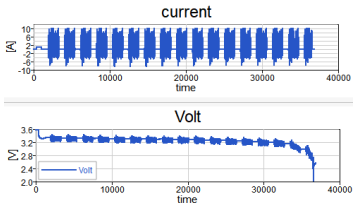
Simulation





Real system



Reduced-Order Model

18h => 1s with romAI

680s => 20s with romAI

System Identification

Higher accuracy than std ESC battery model

Advanced control design:

- No measurements
- No Math calculations

Few simulations/tests needed

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THANK YOU

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#ONLYFORWARD

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