



Combining AI with Model based Design:

battery State-of-charge estimator using Deep Learning

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ENBIS Spring Meeting 2022

Electric batteries are everywhere. Effective management increases vehicle availability and reduces costs



Hybrid electric city bus



Autonomous electric tractor



Industrial robots

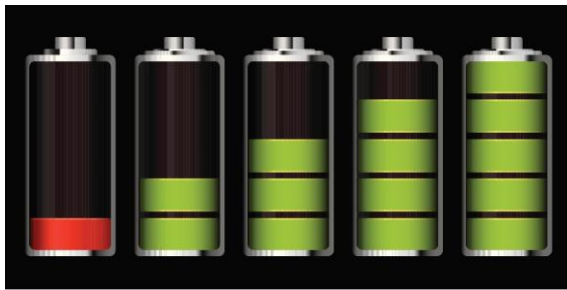
Monitoring battery health is good, but predicting it is better



Create virtual sensor for battery state of charge estimation in a model-based design workflow

- Why Virtual Sensors ?
 - When estimating a quantity that is not measurable

Battery State of Charge (SOC)

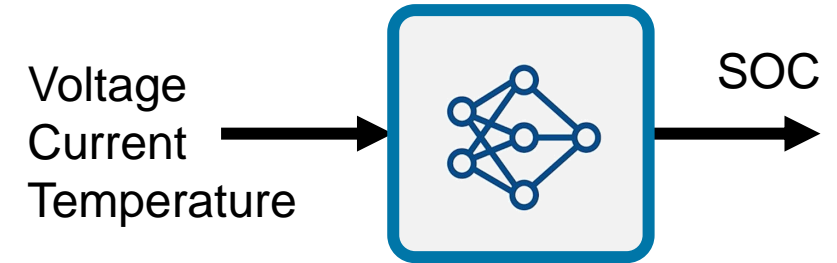


Not directly measurable

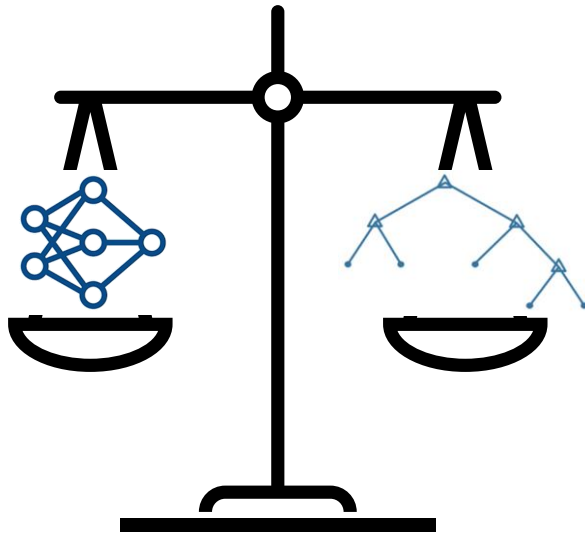
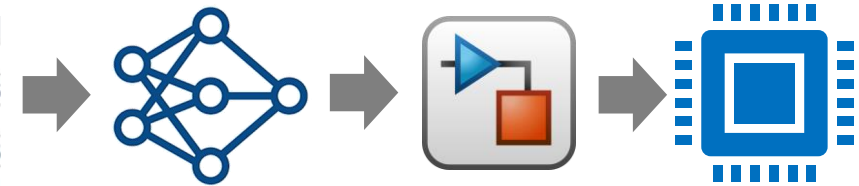
The screenshot illustrates the model-based design workflow for SOC estimation. It shows a Simulink model with an 'SOC Estimation (PIL)' block, which is a virtual sensor. The model takes 'input' and 'measuredSOC' as inputs and outputs 'current', 'voltage', and 'temperature'. A 'Download finished' dialog box indicates that the executable file has been downloaded to the target hardware board. The right side of the image shows three plots: 'SOC' (State of Charge) showing a step response, 'current' showing a noisy signal, and 'voltage' showing a noisy signal. The bottom panel shows the 'Diagnostic Viewer' with a log of messages.

Agenda

- Develop AI-based battery SOC estimation
- Workflow - From data acquisition to hardware deployment
- Compare different AI methods



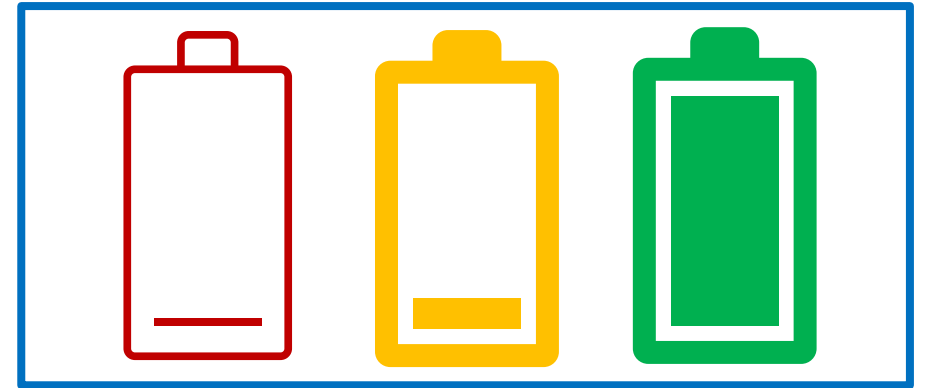
Voltage	Current	Temperature
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0.7510	0.3852	0.3046
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0.7510	0.3852	0.3076
0.7510	0.3852	0.3091



Battery State of Charge (SOC)

$$SOC(t) = \frac{1}{C} \int_0^t I(p) dp$$

capacity *current*

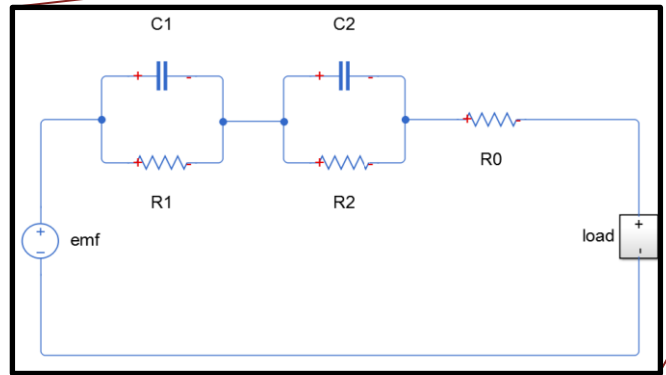
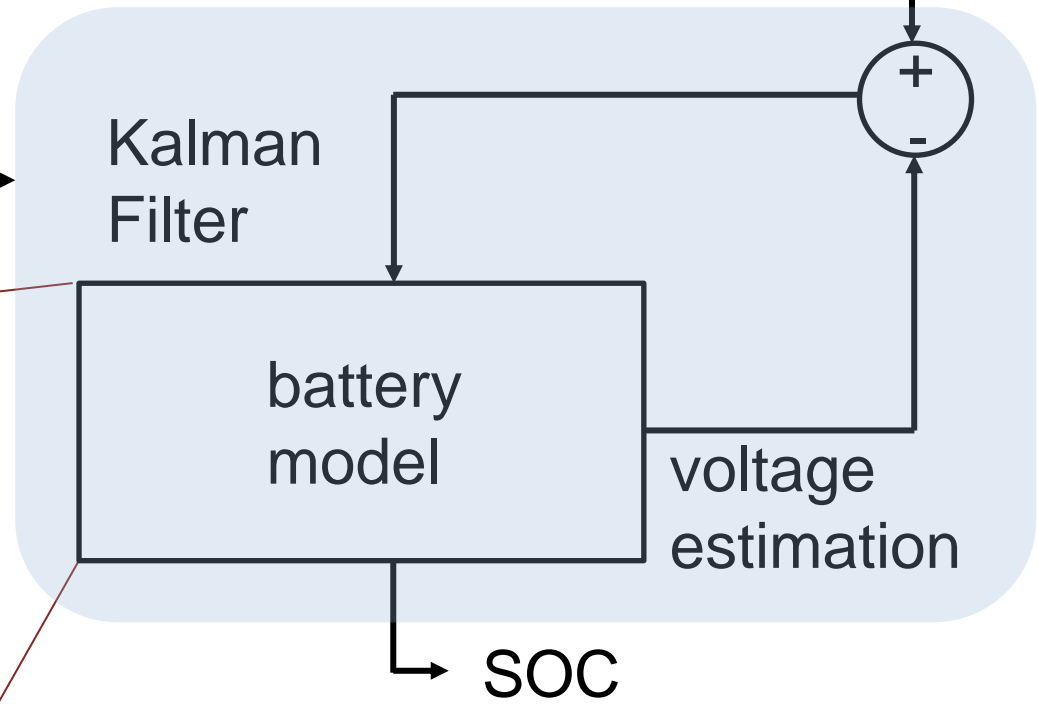


Affected by sensor error

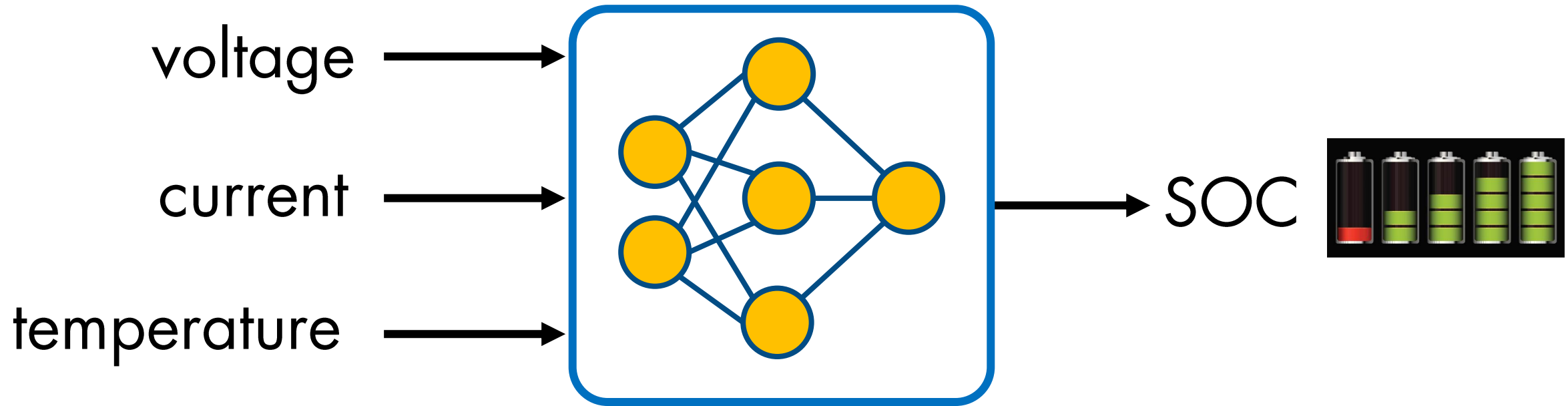
Extended Kalman Filter

- +
 - Well established
 - Accurate

- - Detailed battery model required (operating condition range)
 - Computationally intensive



Using Neural Network as an alternative



- Training on real data
- Capture very complex data relationships
- No need for battery model



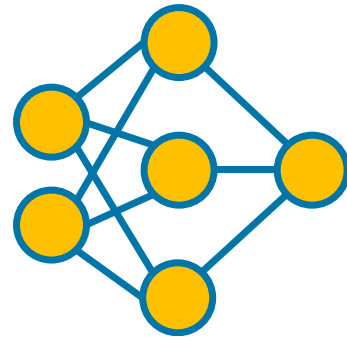
- Interpretability
- Computationally intensive

AI-driven System Design

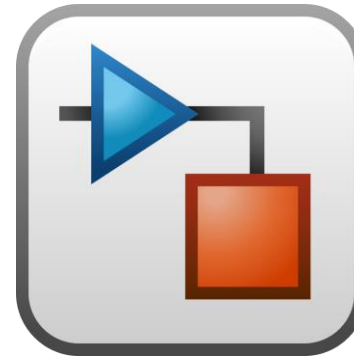
Data Preparation

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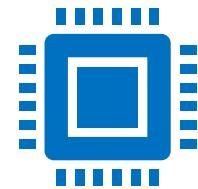
AI Modeling



Simulation & Test



Deployment





Robust xEV Battery State-of-Charge Estimator Design Using a Feedforward Deep Neural Network

Carlos Vidal, Phillip Kollmeyer, and Mina Naguib McMaster Automotive Res. Centre

Pawel Malysz and Oliver Gross FCA US LLC

Ali Emadi McMaster University

Citation: Vidal, C., Kollmeyer, P., Naguib, M., Malysz, P. et al., "Robust xEV Battery State-of-Charge Estimator Design Using a Feedforward Deep Neural Network," SAE Technical Paper 2020-01-1181, 2020, doi:10.4271/2020-01-1181.

Abstract

Battery state-of-charge (SOC) is critical information for the vehicle energy management system and must be accurately estimated to ensure reliable and affordable electrified vehicles (xEV). However, due to the nonlinear temperature, health, and SOC dependent behaviour of Li-ion

(FNN) approach. The method includes a description of data acquisition, data preparation, development of an FNN, FNN tuning, and robust validation of the FNN to sensor noise. To develop a robust estimator, the FNN was exposed, during training, to datasets with errors intentionally added to the data, e.g. adding cell voltage variation of $\pm 4\text{mV}$, cell current

Read data

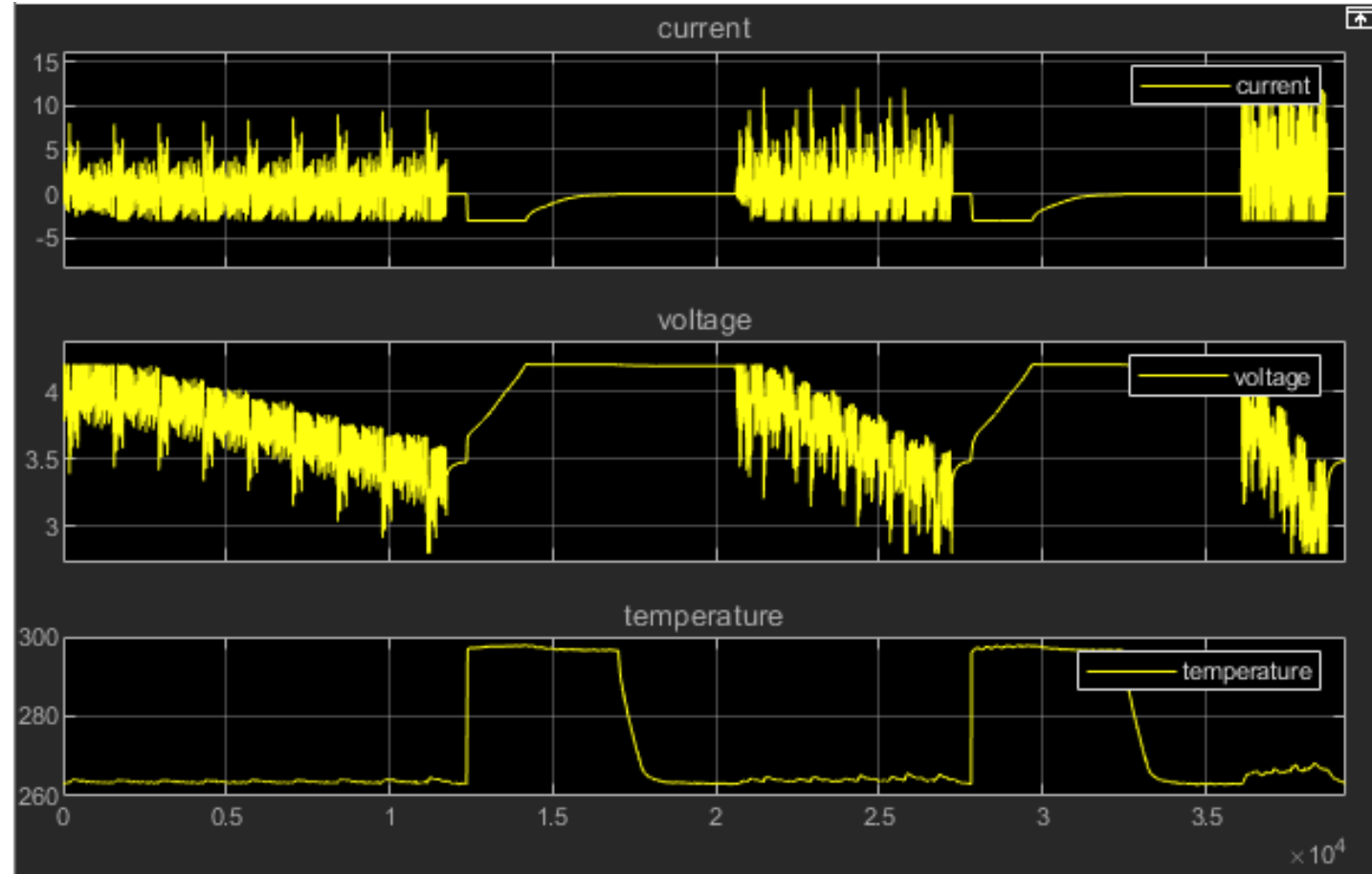
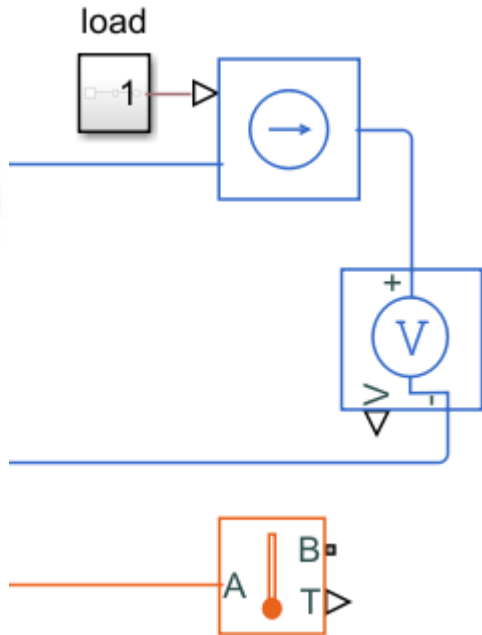
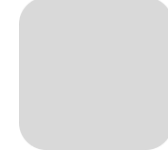
Data Preparation

AI Modeling

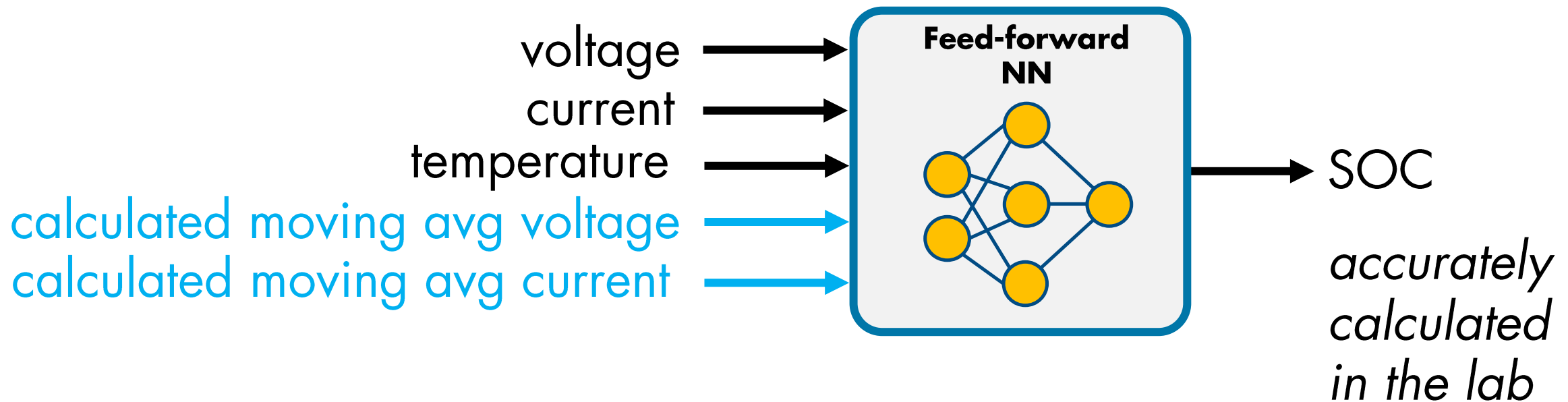
Simulation & Test

Deployment

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0.7510	0.3852	0.3076
0.7510	0.3852	0.3091



Data were collected experimentally



Create, configure, train & assess AI model performance

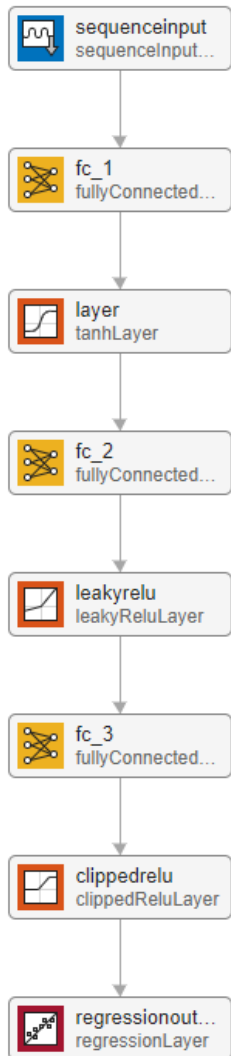
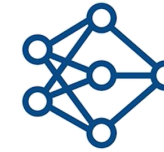
Data Preparation

AI Modeling

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Training Options

SOLVER

Solver:

InitialLearnRate:

BASIC

ValidationFrequency:

MaxEpochs:

MiniBatchSize:

ExecutionEnvironment:

SEQUENCE

SequenceLength:

SequencePaddingValue:

SequencePaddingDirection:

ADVANCED

L2Regularization:

GradientThresholdMethod:

GradientThreshold:

ValidationPatience:

Shuffle:

CheckpointPath:

CheckpointFrequency:

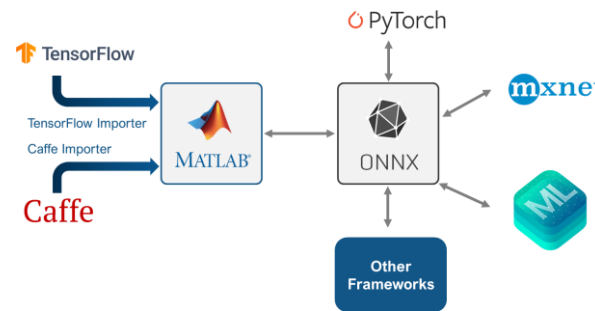
Deep Network Designer

TRAINING

Training Options | **Train** | Export Training Plot | Export

DESIGNER | DATA | TRAINING

Trial	Status	Progress	Elapsed Time	myInitialLearn...	convFilterSize	Training Accu...	Training Loss	Validation Ac...
1	Complete	100.0%	0 hr 0 min 16 sec	1.0000e-6	3.0000	12.5000	2.4441	19.2
2	Complete	100.0%	0 hr 0 min 15 sec	1.0000e-5	3.0000	25.7913	2.1229	20.2
3	Complete	100.0%	0 hr 0 min 14 sec	0.0001	3.0000	44.9418	1.8979	42.2
4	Complete	100.0%	0 hr 0 min 16 sec	0.0005	3.0000	90.6230	0.4448	47.2
5	Complete	100.0%	0 hr 0 min 15 sec	1.0000e-4	4.0000	11.7188	2.4907	4.2
6	Complete	100.0%	0 hr 0 min 15 sec	1.0000e-5	4.0000	23.4375	2.1213	14.2
7	Complete	100.0%	0 hr 0 min 17 sec	0.0001	4.0000	72.6543	1.8283	39.2
8	Running	30.7%	0 hr 0 min 4 sec	0.0005	4.0000			
9	Queued	0.0%		1.0000e-6	5.0000			
10	Queued	0.0%		1.0000e-5	5.0000			
11	Queued	0.0%		0.0001	5.0000			
12	Queued	0.0%		0.0005	5.0000			
13	Queued	0.0%		1.0000e-4	4.0000			
14	Queued	0.0%		1.0000e-5	6.0000			
15	Queued	0.0%		0.0001	6.0000			
16	Queued	0.0%		0.0005	6.0000			



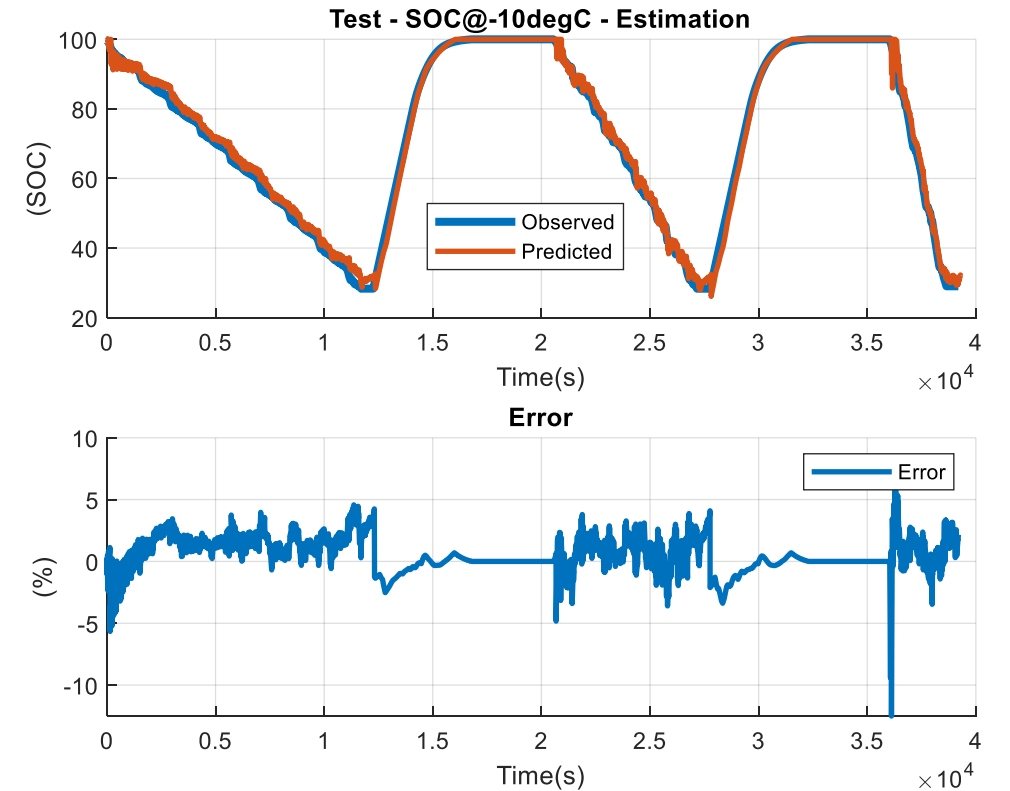
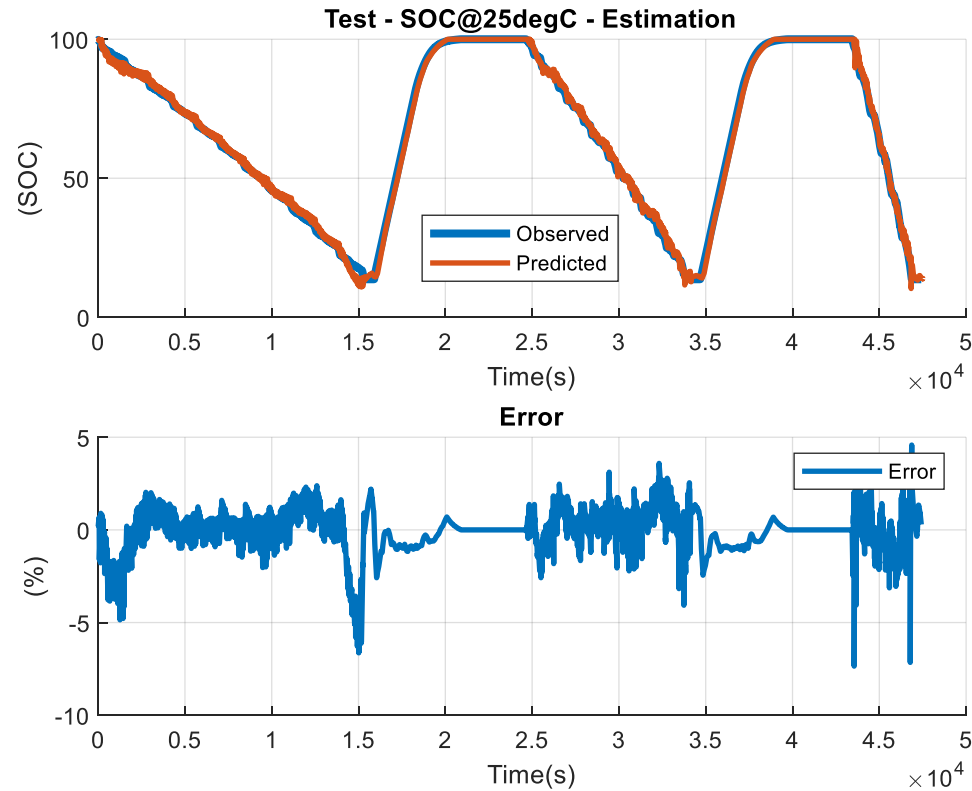
Optimize various hyperparameters, manage multiple deep learning experiments, analyze and compare results

Collaboration is very important: You can also import Model from other DL frameworks

Results

25°C

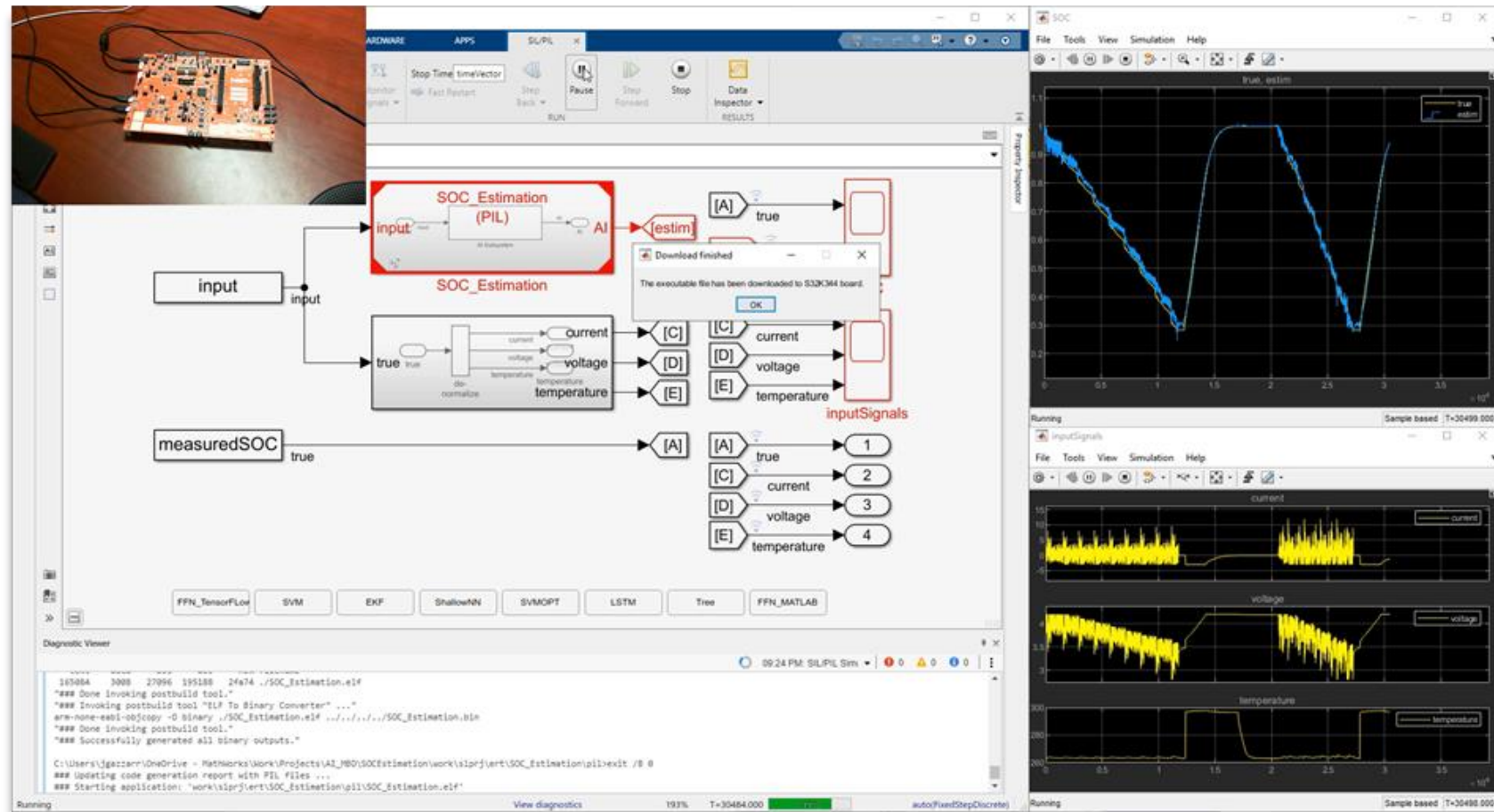
-10°C



prediction
ground truth

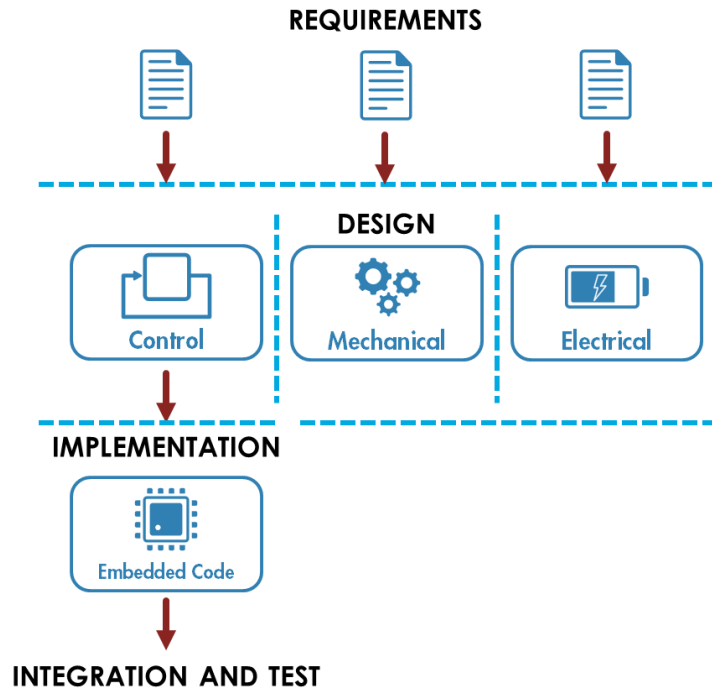
AI is part of a larger system

Simulate and test all components together



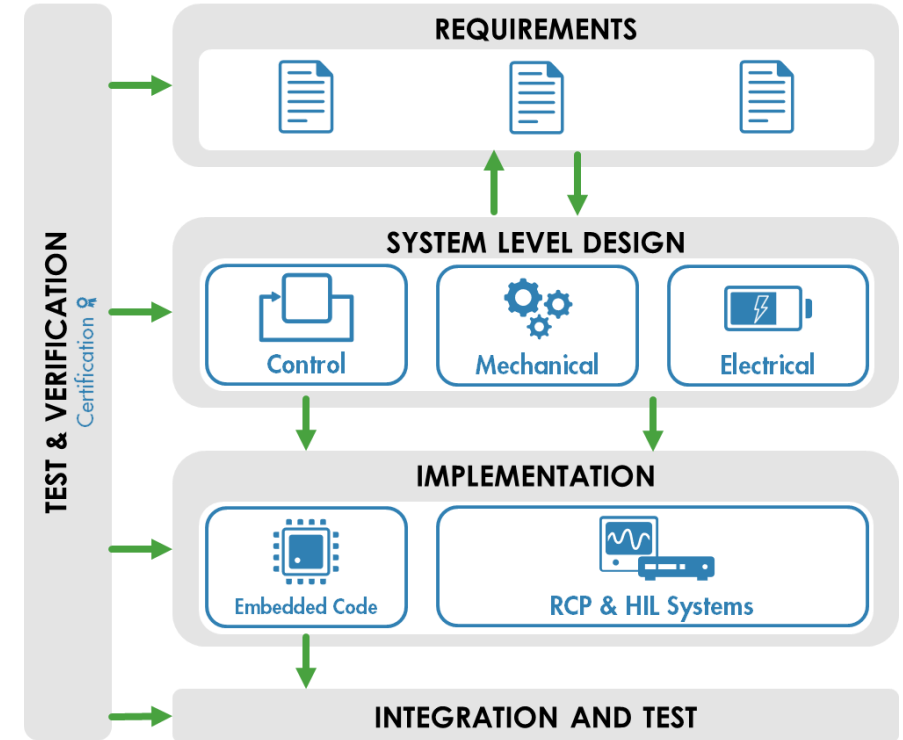
Development workflow with Model-Based Design

Traditional Design Process



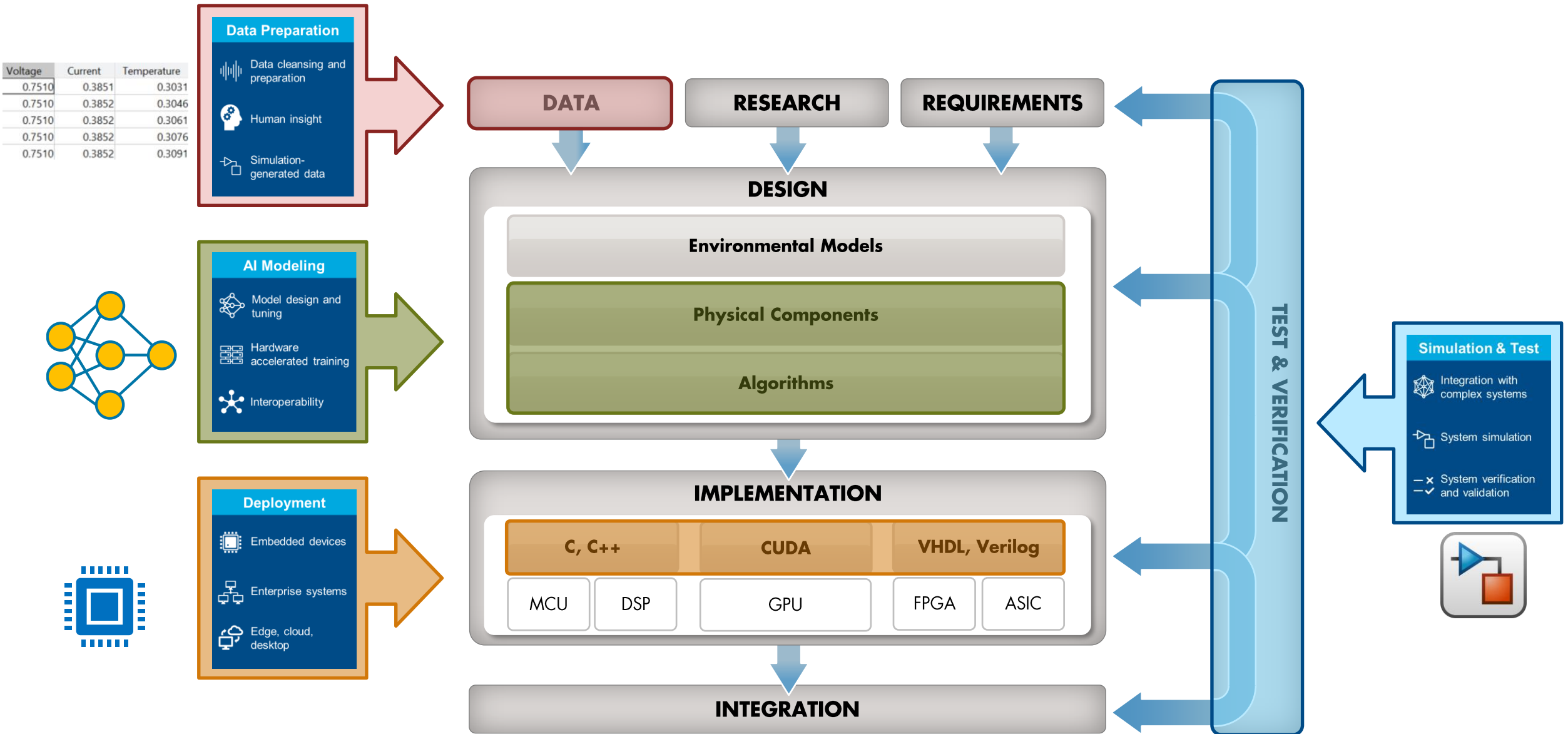
- Manual coding is slow, buggy, and hard to verify
- Can only find problems using hardware prototypes
- Cannot test or optimize fully integrated design
- Cannot validate design against requirements

Model-Based Design



- System Level Representation that is componentized
- Unified lifecycle stages, executable specifications
- Test/fail early, continuous testing, reuse, What-if analysis
- Automation, Path to implementation and production

Integrate AI into MBD for system-level simulation and code generation



Simulink Integration

Data Preparation

AI Modeling

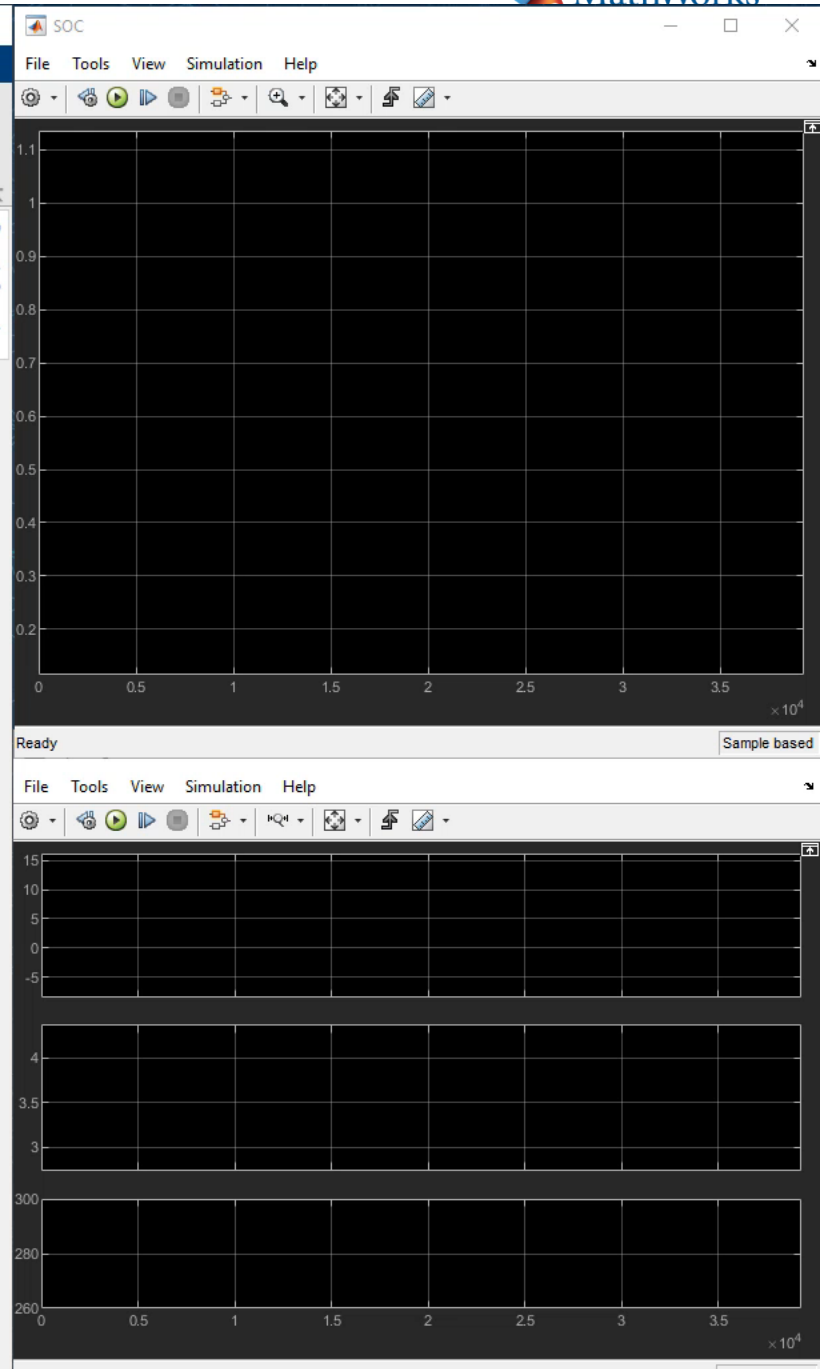
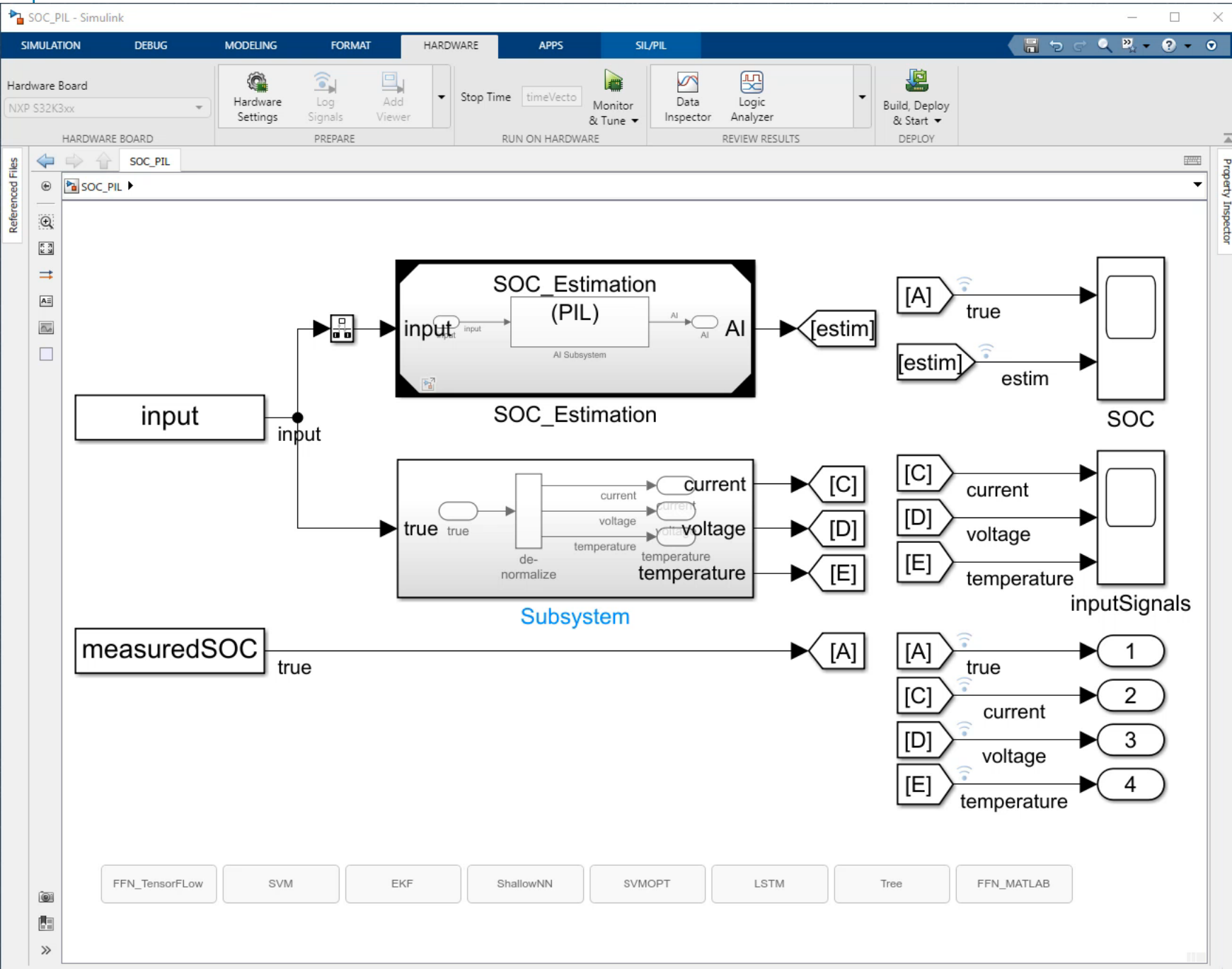
Simulation & Test

Deployment

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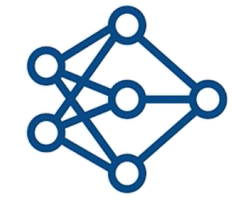
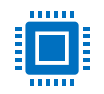
The screenshot displays the Simulink environment. On the left, the Simulink Library Browser shows the 'Deep Learning Toolbox/Deep Neural Networks' section expanded, listing various neural network models like 'Image Classifier', 'Predict', and 'Stateful Classify'. The main workspace contains a Simulink model with an 'input' block connected to a 'u^T' block. The bottom window shows a scope plot with a grid and axes ranging from 0 to 1 on the y-axis and 0 to 3.5 x 10⁴ on the x-axis.



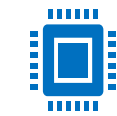
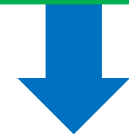
Processor-in-the-Loop (PIL) Testing on ARM Cortex-M7 Processor



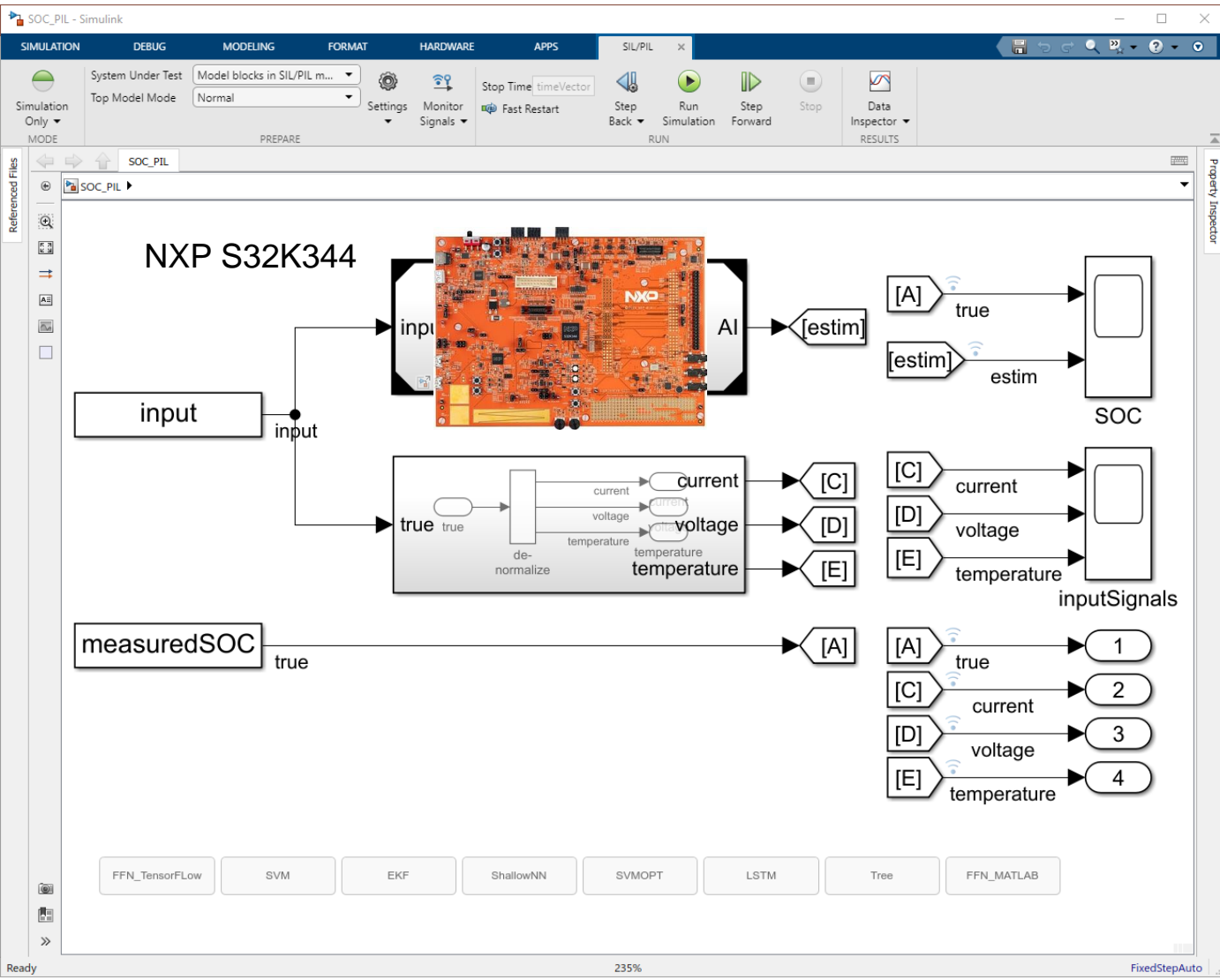
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Automatic Library-Free C Code



Any CPU
Inc. ARM Cortex-M



SOC_PIL - Simulink

SIMULATION DEBUG MODELING FORMAT HARDWARE APPS SIL/PIL

System Under Test: Model blocks in SIL/PIL m...
 Top Model Mode: Normal

Stop Time: timeVector
 Fast Restart Step Back Run SIL/PIL Step Forward Stop Data Inspector

input SOC_Estimation (PIL) AI [estim] SOC

measuredSOC true current voltage temperature [C] [D] [E] inputSignals

FFN_TensorFlow SVM EKF ShallowNN SVMOPT LSTM Tree FFN_MATLAB

Diagnostic Viewer

```

09:04 PM: SIL/PIL Simulink
##### Done invoking postbuild tool.
##### Invoking postbuild tool "ELF To Binary Converter" ...
arm-none-eabi-objcopy -O binary ./SOC_Estimation.elf ../.././././././././SOC_Estimation.bin
##### Done invoking postbuild tool.
##### Successfully generated all binary outputs.

C:\Users\jgazzarr\OneDrive - MathWorks\Work\Projects\AI_MBD\SOCestimation\work\s1prj\ert\SOC_Estimation\pil>exit /B 0
##### Updating code generation report with PIL files ...
##### Starting application: 'work\s1prj\ert\SOC_Estimation\pil\SOC_Estimation.elf'
  
```

View diagnostics 193% auto(FixedStepDiscrete)

SOC

File Tools View Simulation Help

true, estim

Property Inspector

Ready Sample based T=6629.000

inputSignals

File Tools View Simulation Help




















current

voltage

temperature

Ready Sample based T=6629.000

Tradeoffs and Benchmark

	EKF Extended Kalman Filter	Tree Fine Regression Tree	FFN 1-hidden layer Feedforward Network	LSTM Stacked Long Short-Term Memory Network
Training Speed	N/A			
Interpretability				
Inference Speed *				
Model Size *				
Accuracy (RMSE)				

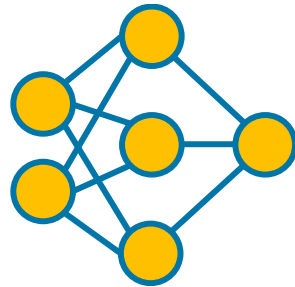
Results are specific to this example

Reducing AI Model size for embedded deployment

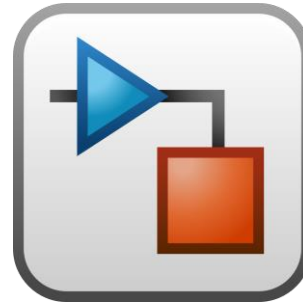
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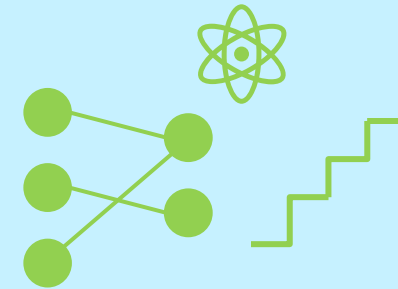
AI Modeling



Simulation & Test

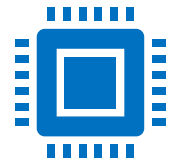


Compression



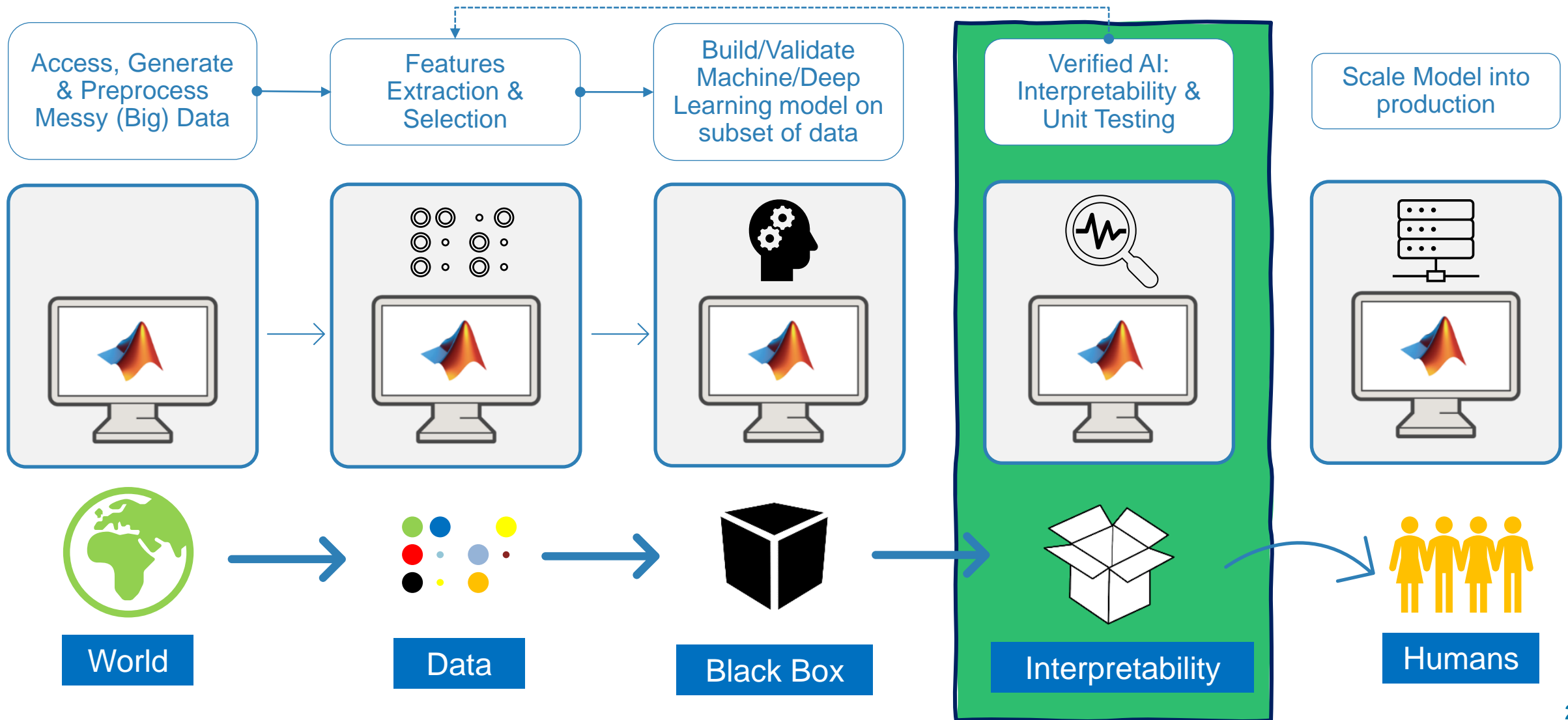
Model compression techniques to reduce model size and speed up inference

Deployment



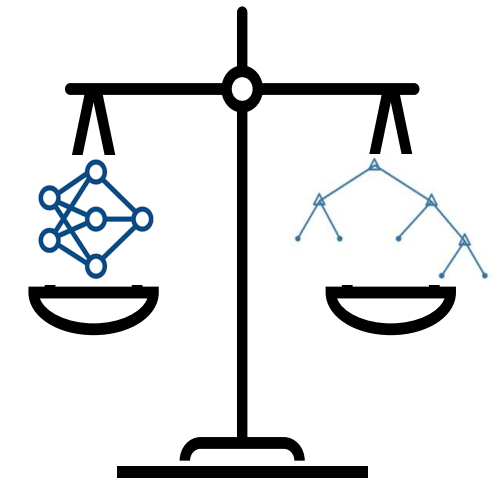
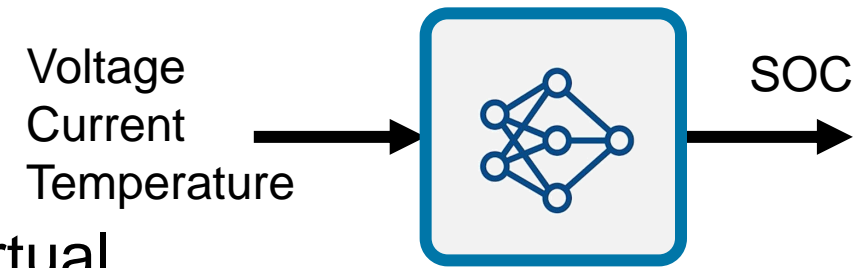
Workflow with interpretability: Validated & Verified AI

Until satisfied Accuracy & Explainability

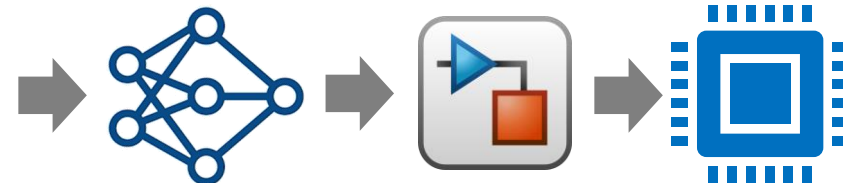


Summary

- **AI is an alternative to state-based methods** for Virtual Sensor Modeling in the case of Battery SOC Estimation
- Compare Different AI Methods to evaluate and manage tradeoffs
- Integrate AI models into Simulink for system-level simulation and code generation
- End to end Workflow - From Data Acquisition to Hardware Deployment



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Thank You!

A complex network diagram consisting of numerous light blue nodes connected by thin, light blue lines. The nodes are scattered across the right half of the image, with a higher density of connections in the lower-right quadrant. The overall appearance is that of a large, interconnected graph or network structure.