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

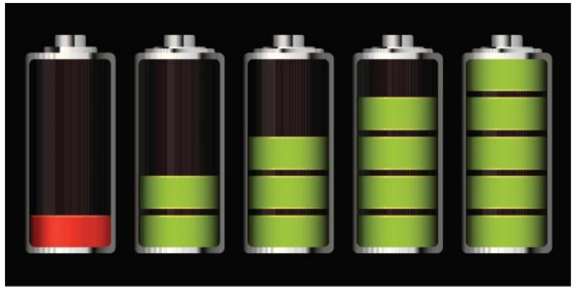
Industrial robots

Monitoring battery health is good, but predicting it is better

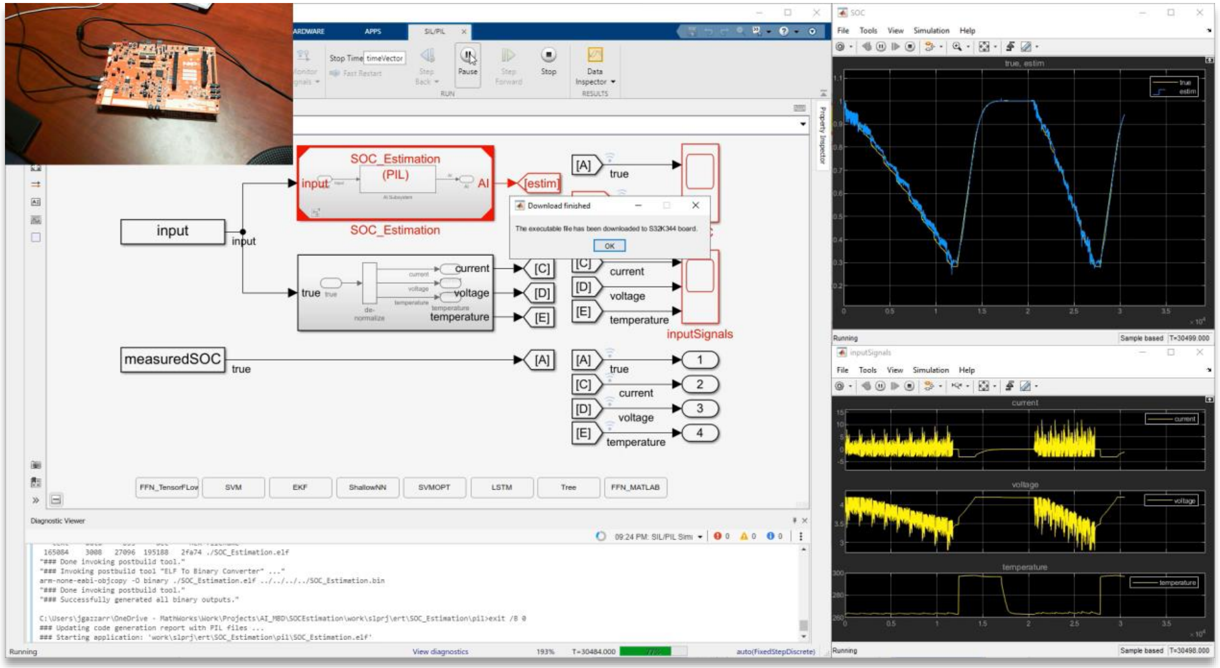
Create virtual sensor for battery state of charge estimation in a model-based design workflow

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

Battery State of Charge (SOC)

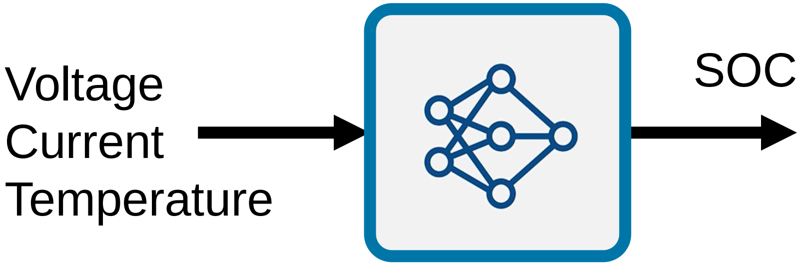


Not directly measurable



Agenda

- Develop AI-based battery SOC estimation



- Workflow - From data acquisition to hardware deployment

Voltage	Current	Temperature
0.7510	0.3851	0.3031
0.7510	0.3852	0.3046
0.7510	0.3852	0.3061
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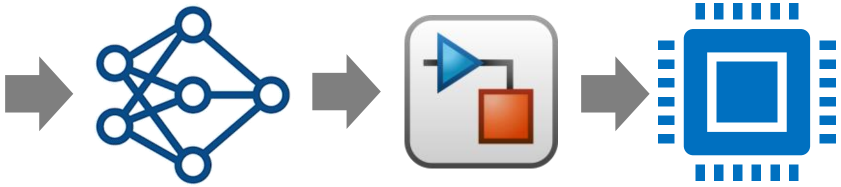
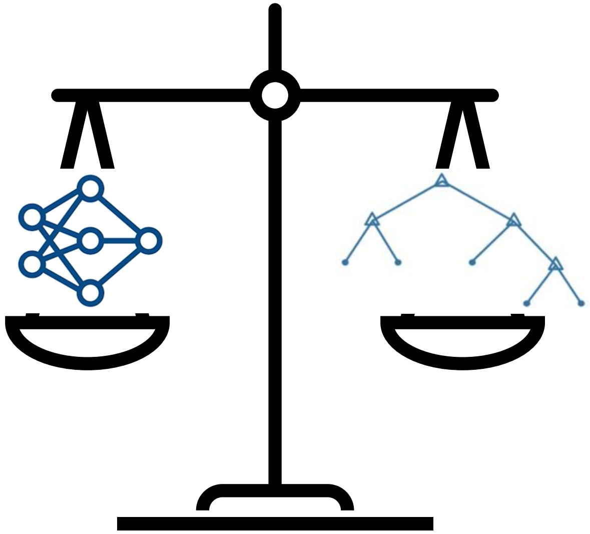
0.7510	0.3852	0.3091



- Compare different AI methods

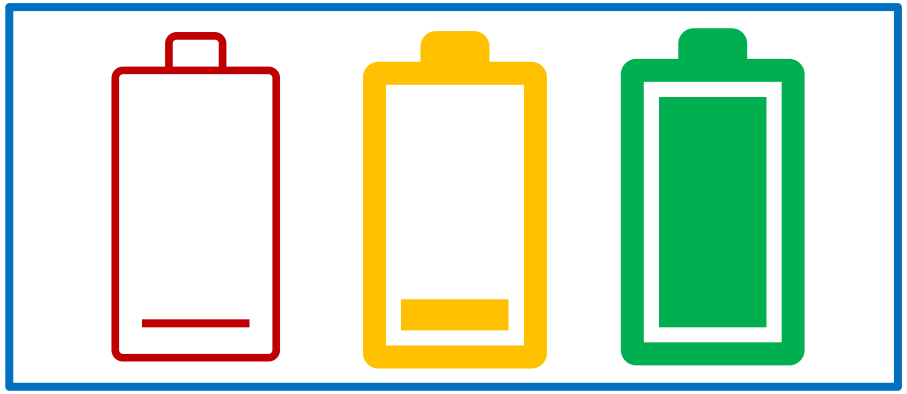


Battery State of Charge (SOC)

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

capacity

current

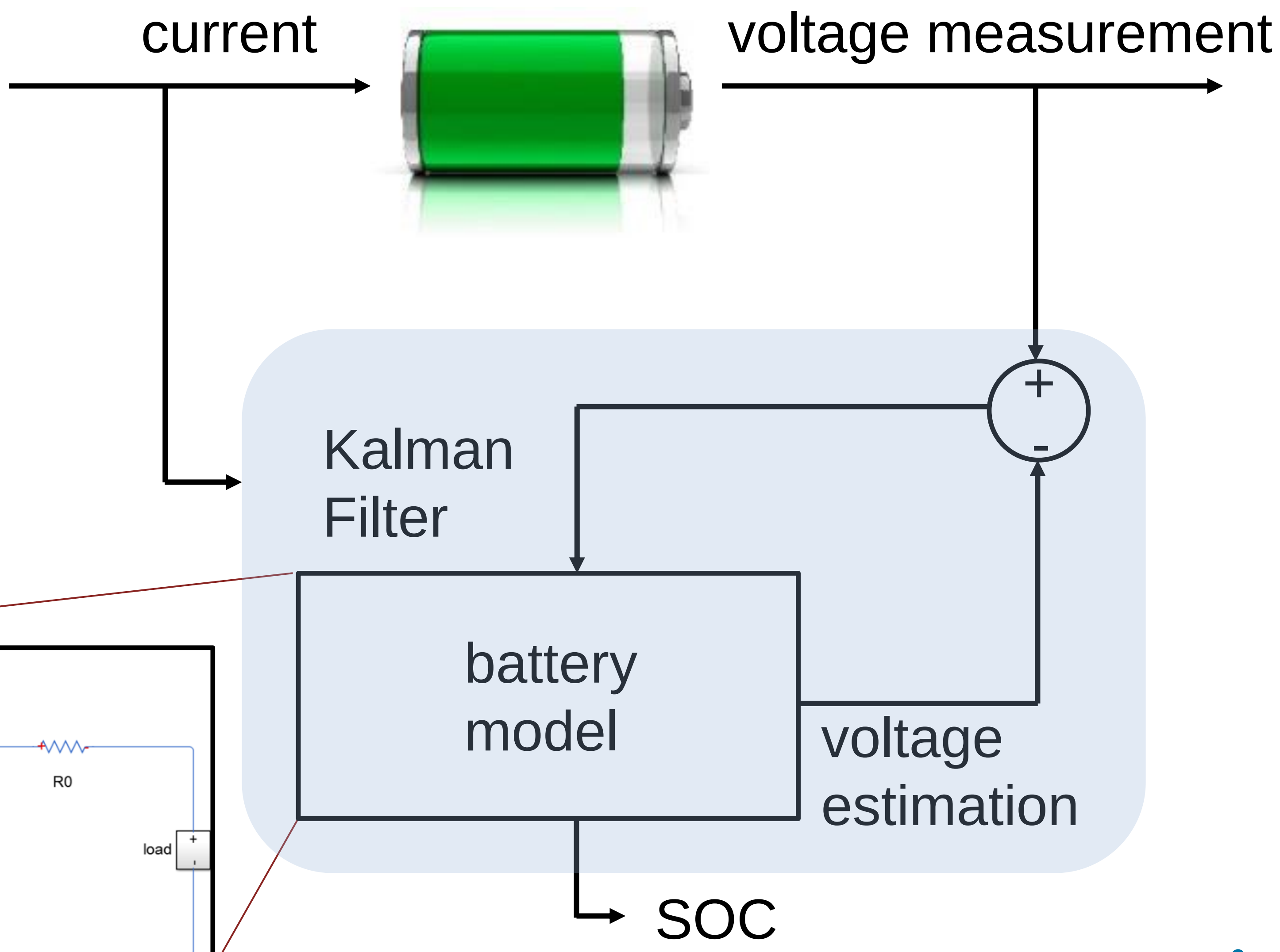


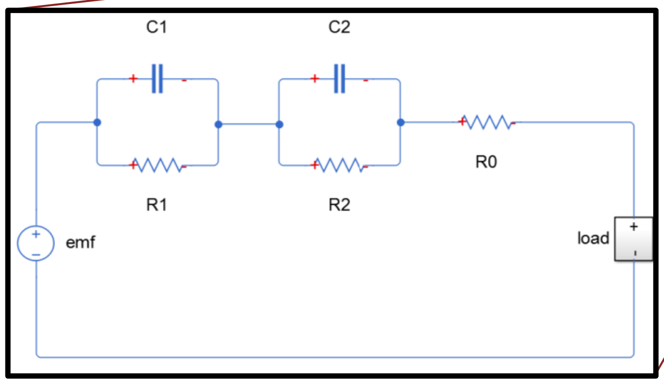
Affected by sensor error

Extended Kalman Filter

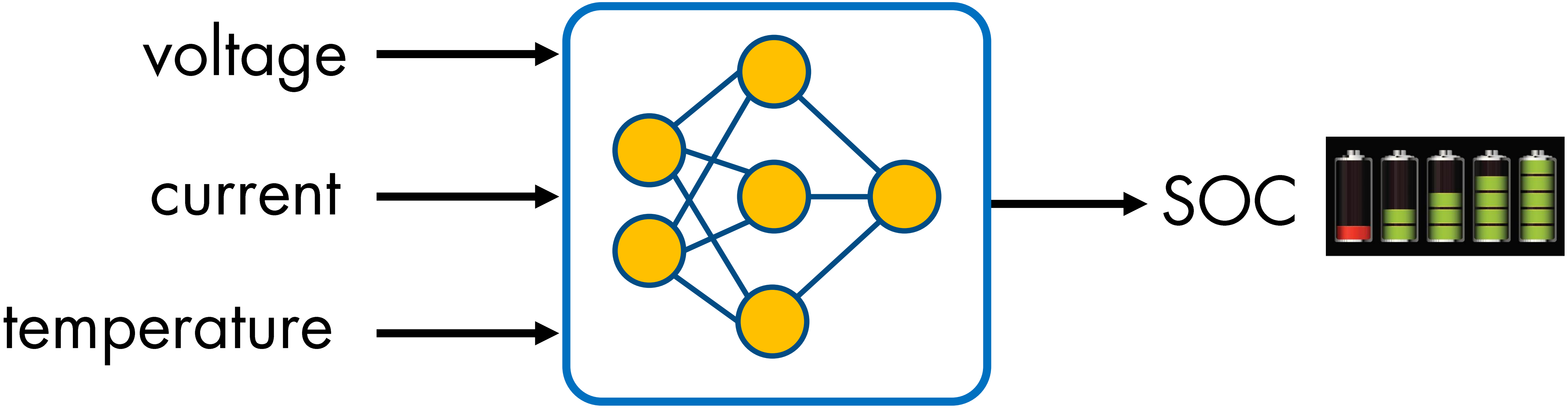
+
- Well established
- Accurate

−
- 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

Voltage	Current	Temperature
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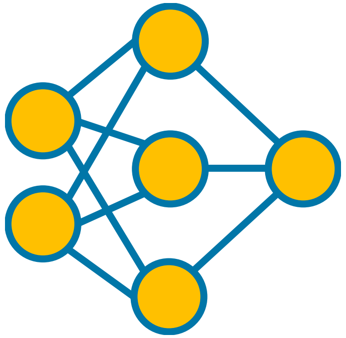
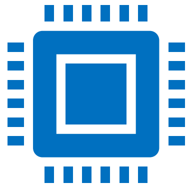
AI Modeling



Simulation & Test

Deployment



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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

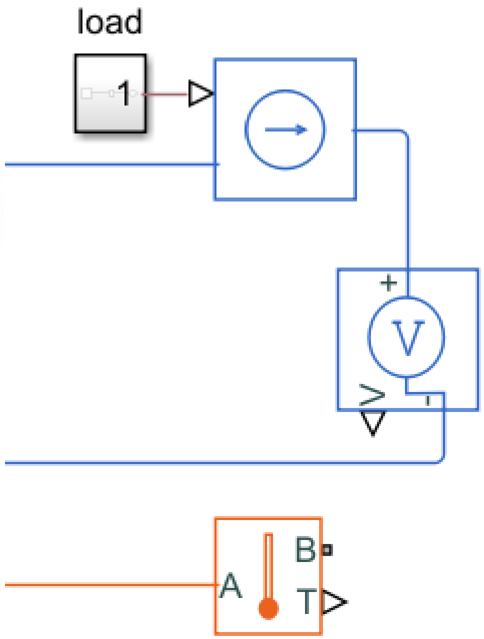
Battery state-of-charge (SOC) is critical information for the vehicle energy management system and must be accurately estimated to ensure reliable and affordable electrified vehicles (xEV). However, due to the nonlinear temperature, health, and SOC dependent behaviour of Li-ion

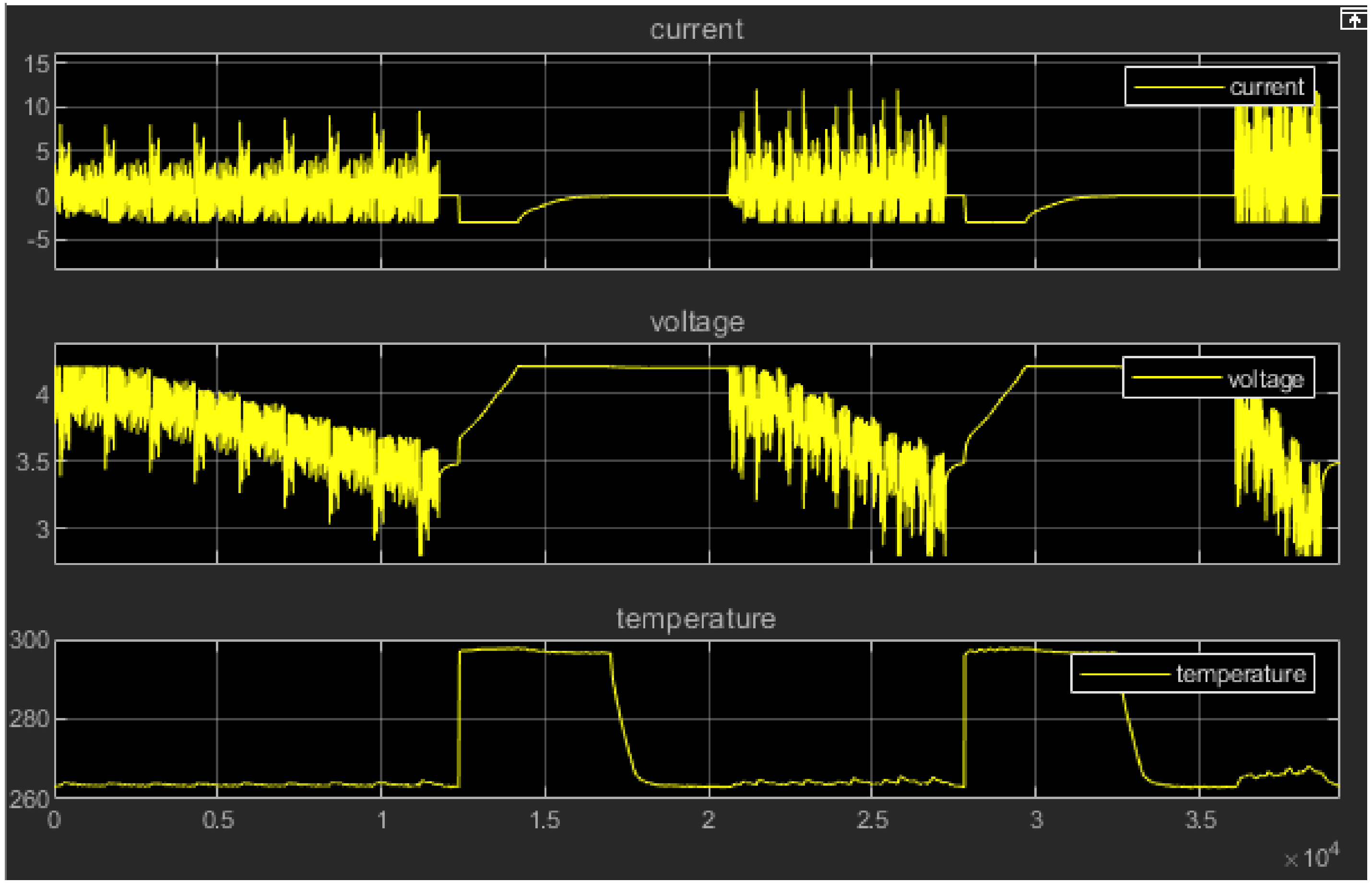
(FNN) approach. The method includes a description of data acquisition, data preparation, development of an FNN, FNN tuning, and robust validation of the FNN to sensor noise. To develop a robust estimator, the FNN was exposed, during training, to datasets with errors intentionally added to the data, e.g.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

Data Preparation | AI Modeling | Simulation & Test | Deployment

Voltage	Current	Temperature
0.7510	0.3851	0.3031
0.7510	0.3852	0.3046
0.7510	0.3852	0.3061
0.7510	0.3852	0.3076
0.7510	0.3852	0.3091

Read data

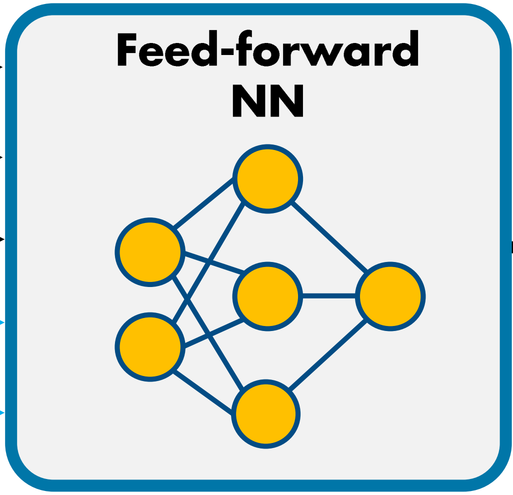




Data were collected experimentally

McMaster University

voltage
current
temperature
calculated moving avg voltage
calculated moving avg current



SOC

accurately calculated in the lab

Data source https://data.mendeley.com/datasets/cp3473x7xv/3

Create, configure, train & assess AI model performance

Data Preparation | **AI Modeling** | Simulation & Test | Deployment

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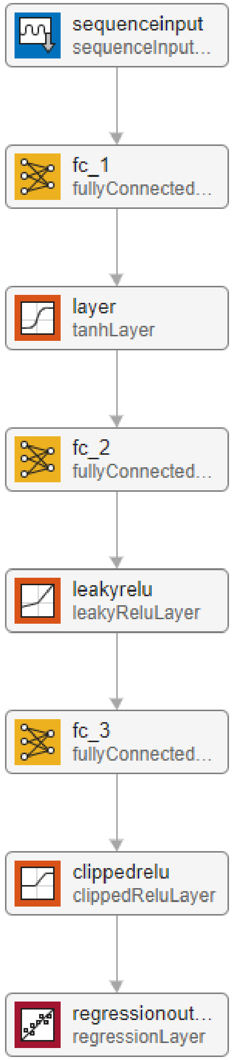
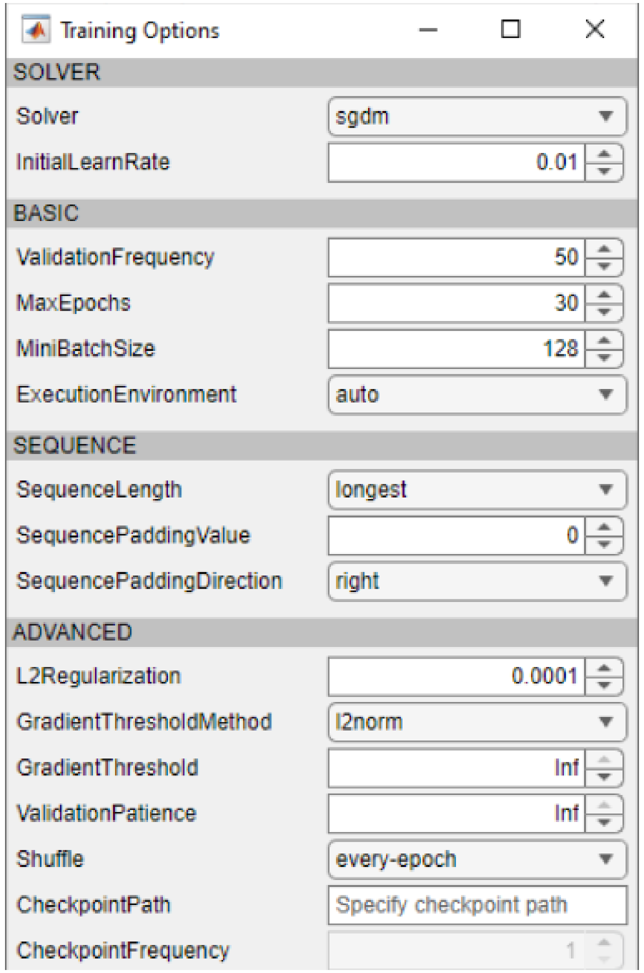
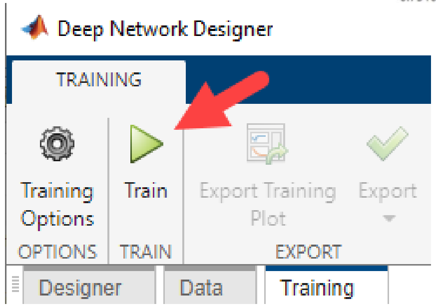
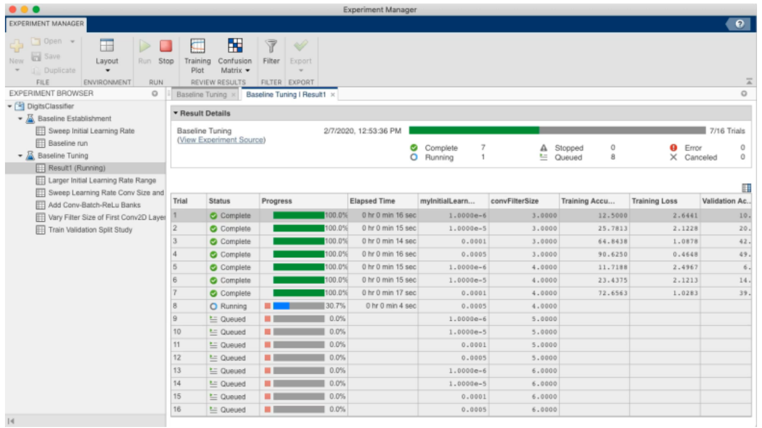
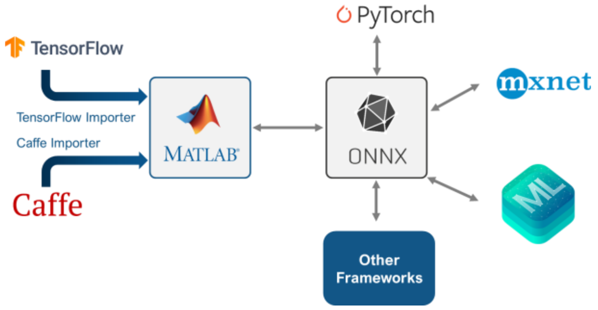








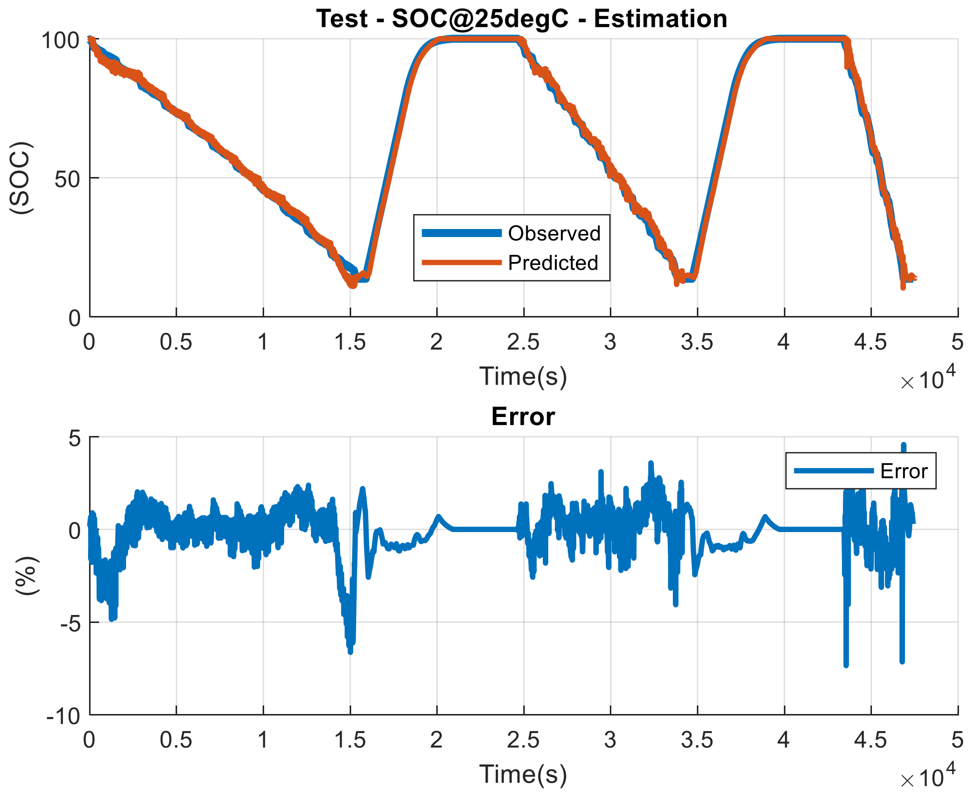
Optimize various hyperparameters, manage multiple deep learning experiments, analyze and compare results



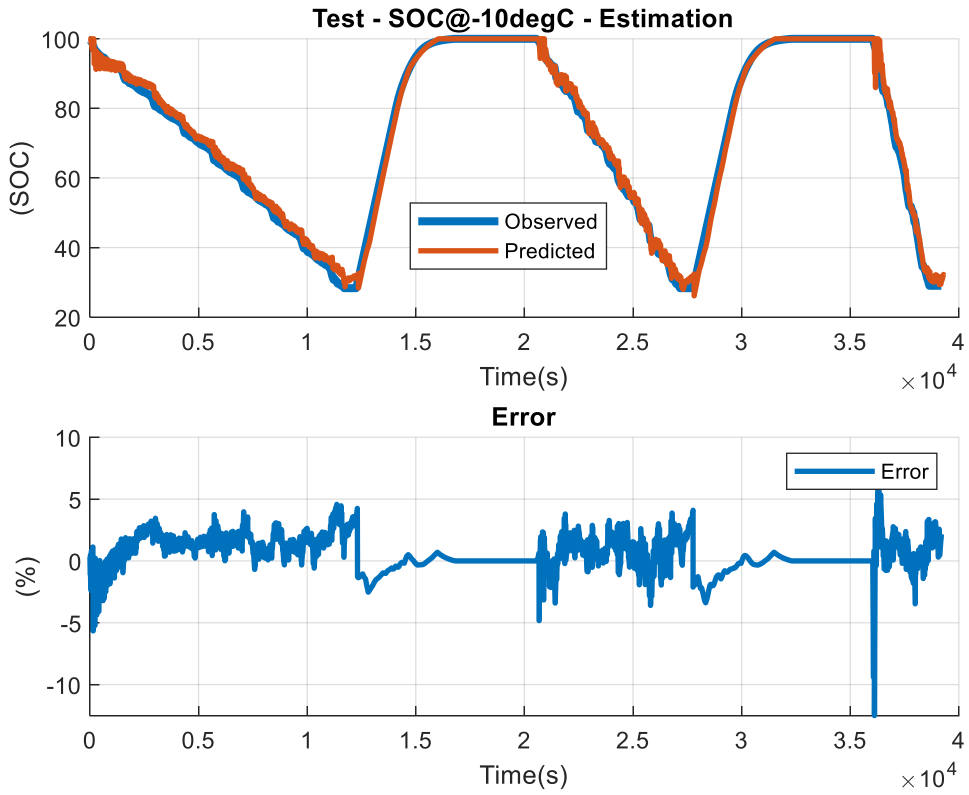
Collaboration is very important: You can also import Model from other DL frameworks

Results

25ºC



-10ºC

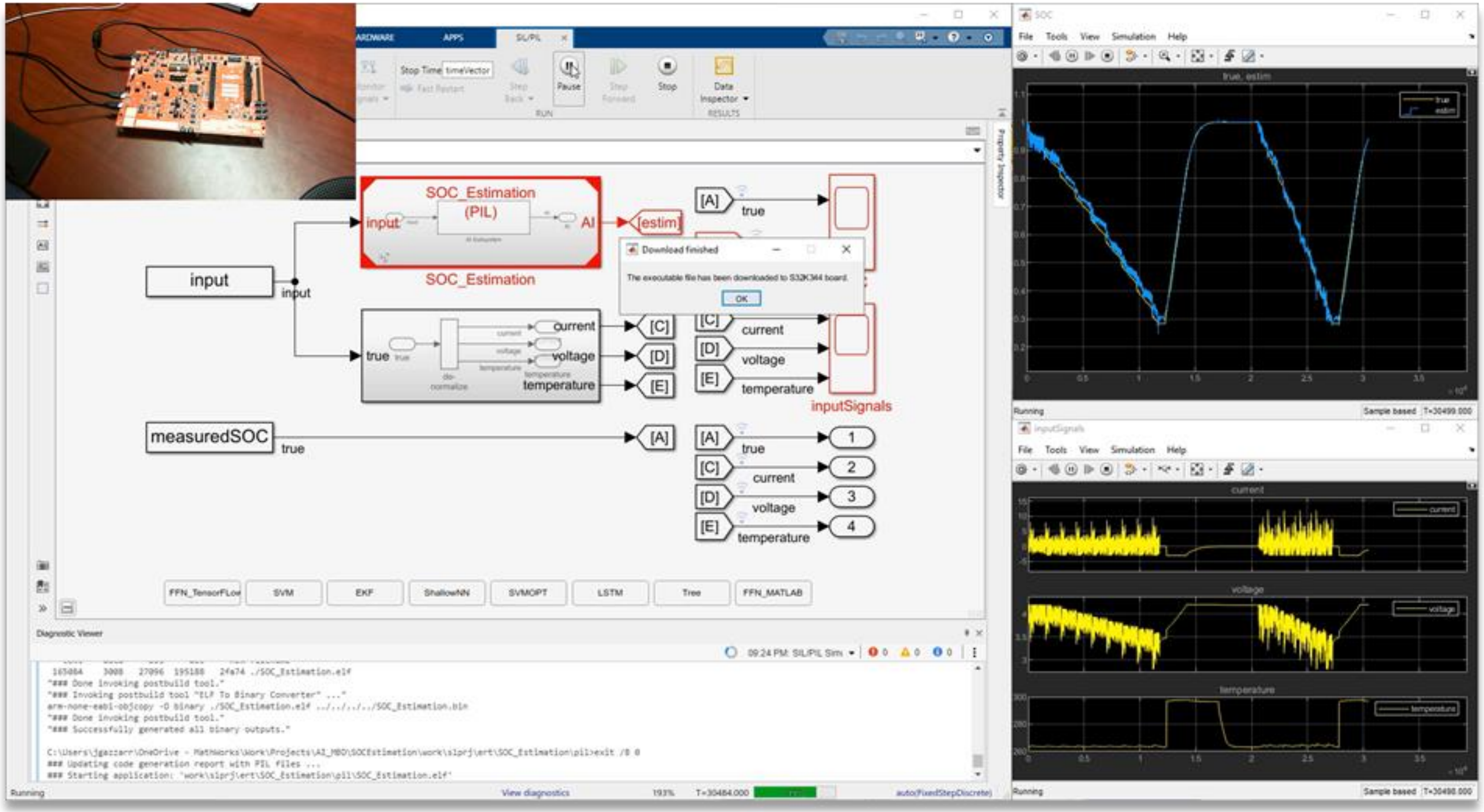


prediction

ground truth

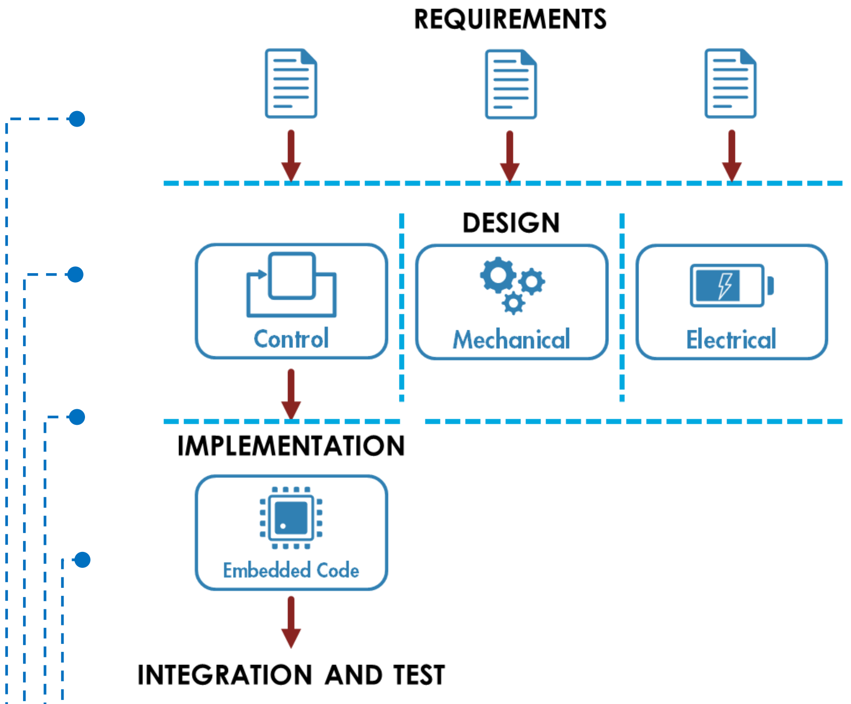
AI is part of a larger system

Simulate and test all components together



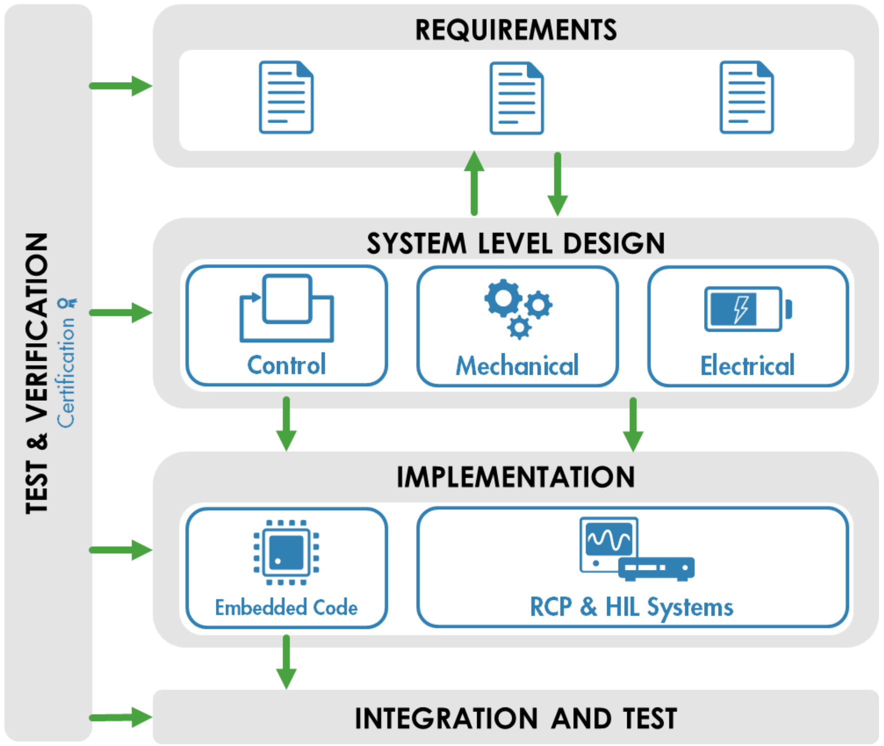
Development workflow with Model-Based Design

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

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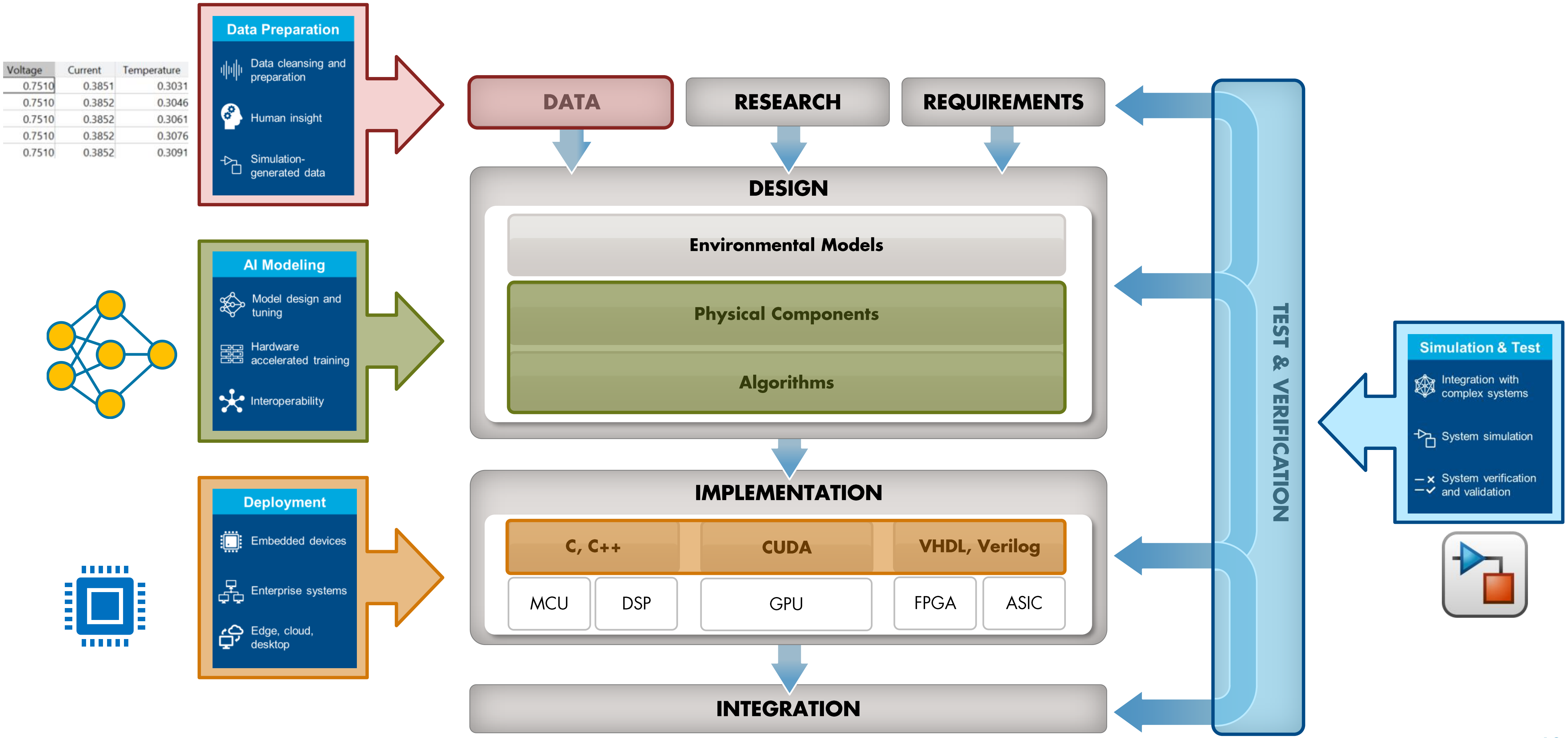
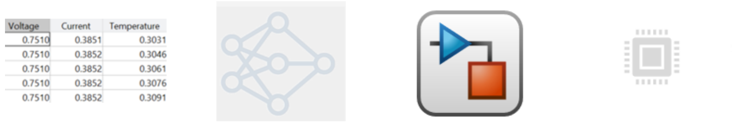
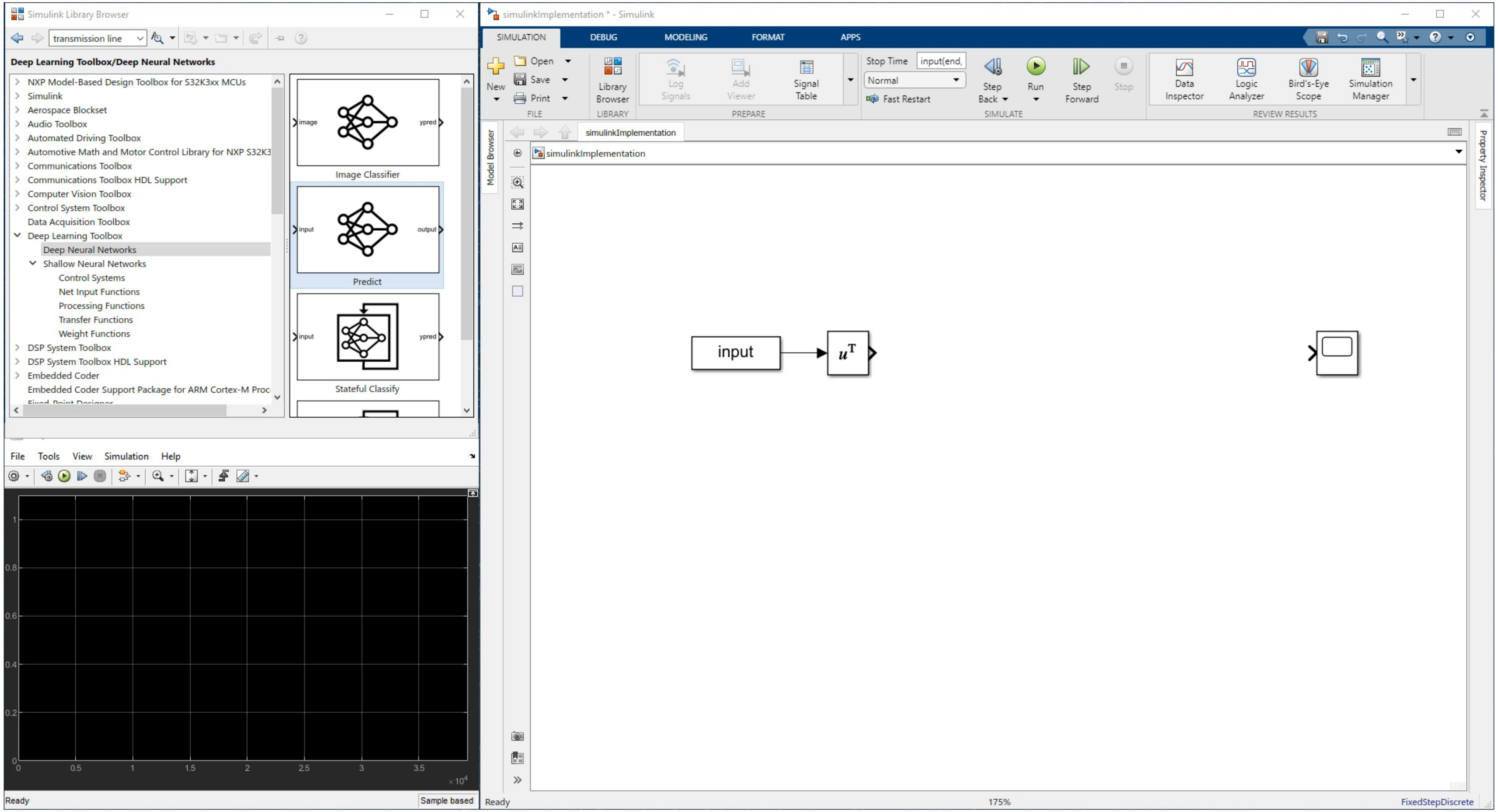
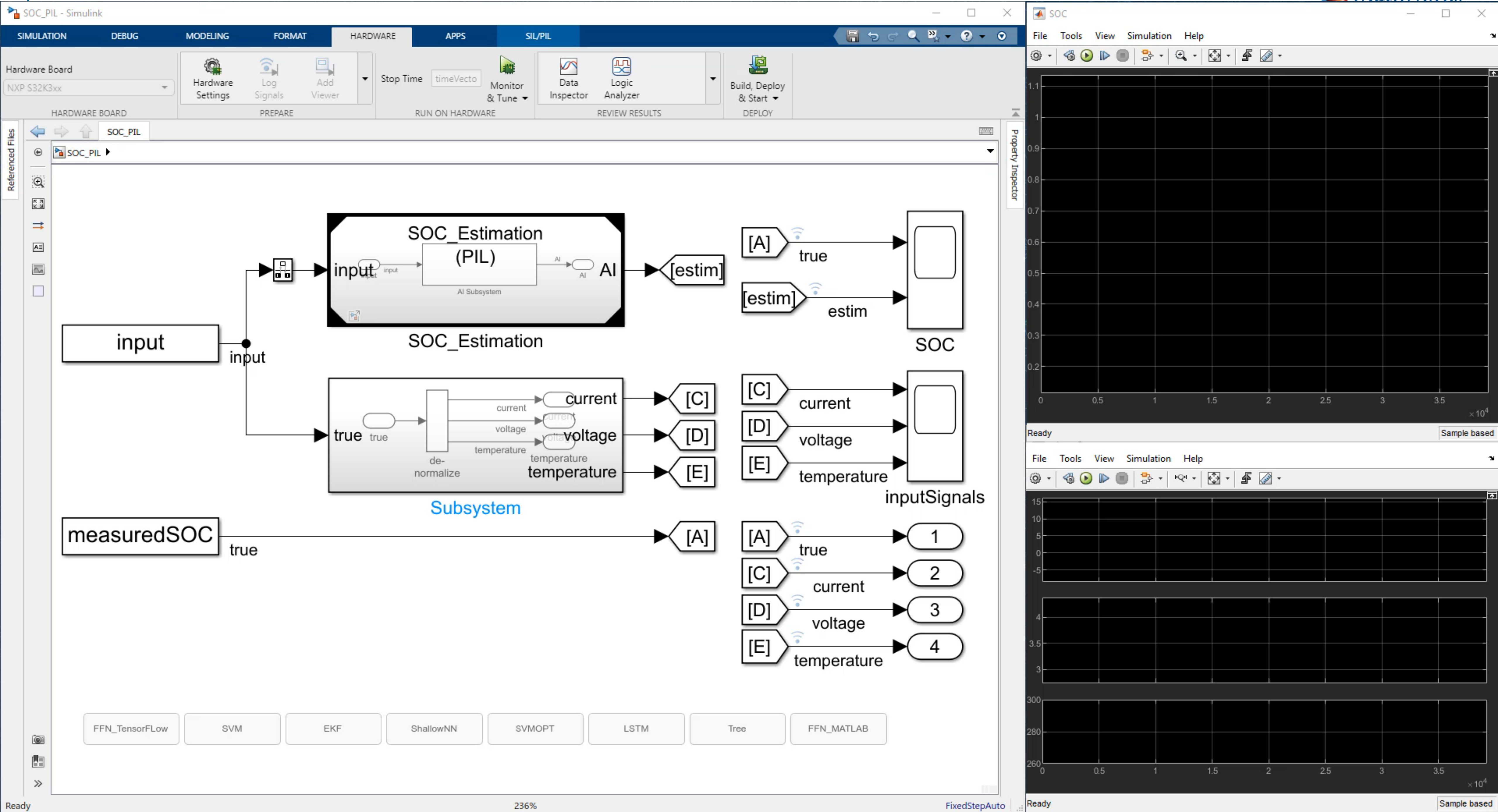


Simulink Integration

Data Preparation | AI Modeling | **Simulation & Test** | Deployment






SOC_PIL - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
HARDWARE
APPS
SIL/PIL
Hardware Board
NXP S32K3xx
HARDWARE BOARD
Hardware Settings
Log Signals
Add Viewer
PREPARE
Stop Time
timeVecto
Monitor & Tune
RUN ON HARDWARE
Data Inspector
Logic Analyzer
REVIEW RESULTS
Build, Deploy & Start
DEPLOY
SOC_PIL
SOC_Estimation
(PIL)
input
AI
AI Subsystem
[estim]
input
SOC_Estimation
true
current
voltage
temperature
de-normalize
Subsystem
[C]
[D]
[E]
measuredSOC
true
[A]
[A]
true
[estim]
estim
SOC
[C]
current
[D]
voltage
[E]
temperature
inputSignals
1
2
3
4
FFN_TensorFLow
SVM
EKF
ShallowNN
SVMOPT
LSTM
Tree
FFN_MATLAB
Ready
236%
FixedStepAuto
SOC
File
Tools
View
Simulation
Help
Ready
Sample based

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

Data Preparation | AI Modeling | Simulation & Test | **Deployment**

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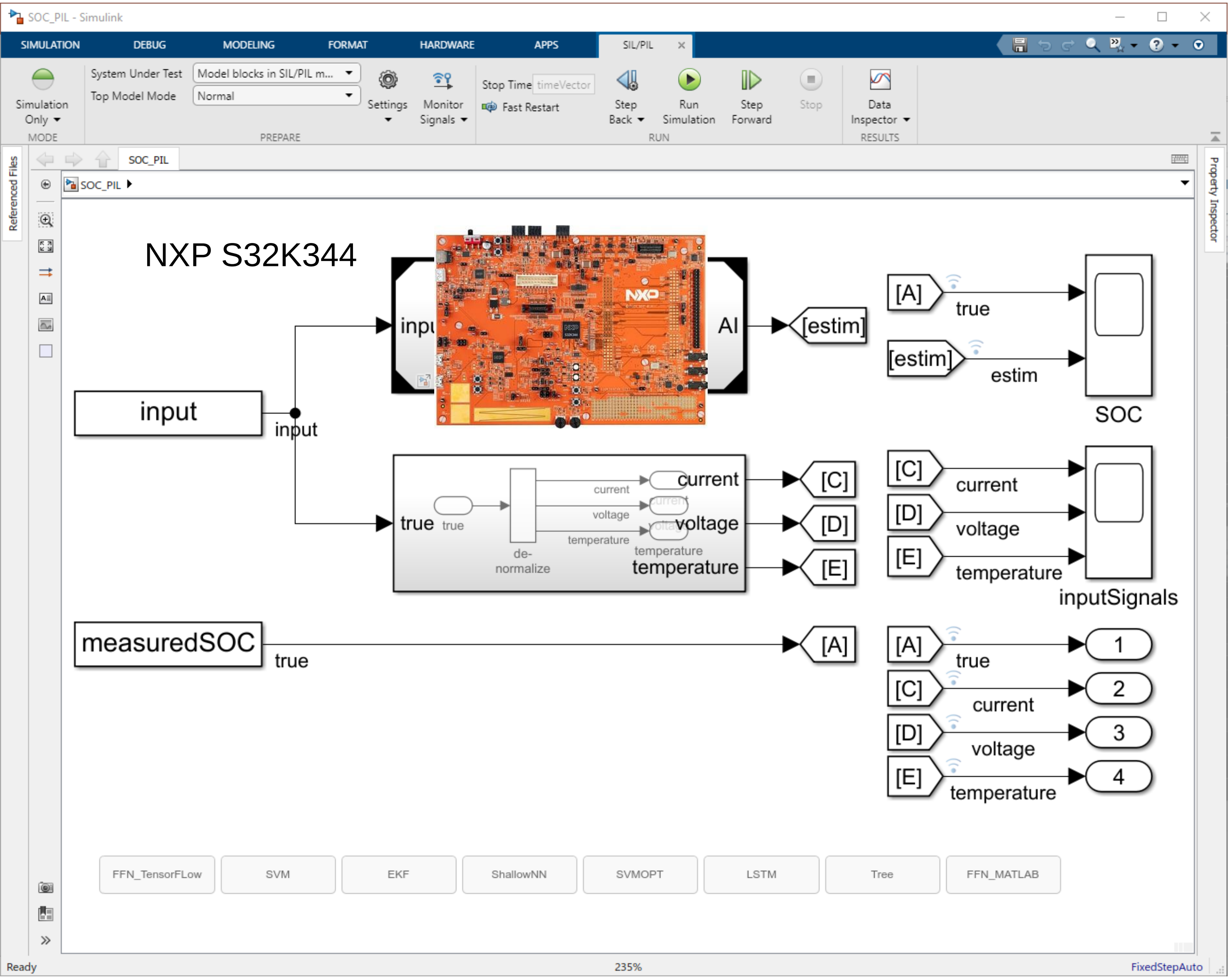
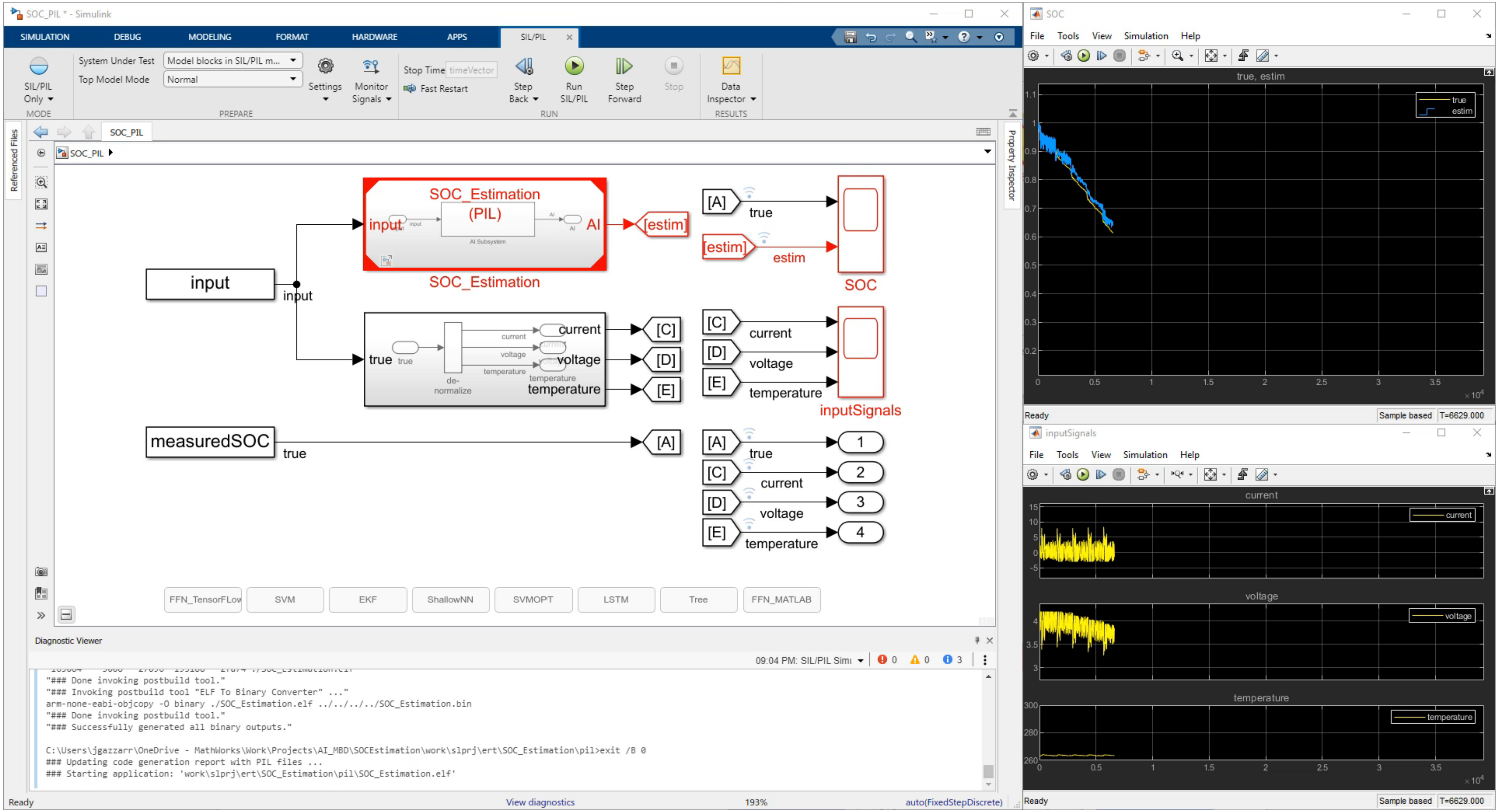


Automatic Library-Free C Code

Any CPU
Inc. ARM Cortex-M

life.augmented


SOC_PIL * - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
HARDWARE
APPS
SIL/PIL
SIL/PIL Only
MODE
System Under Test
Model blocks in SIL/PIL m...
Top Model Mode
Normal
Settings
Monitor Signals
PREPARE
Stop Time
timeVector
Fast Restart
Step Back
Run SIL/PIL
Step Forward
Stop
RUN
Data Inspector
RESULTS
SOC_PIL
SOC_Estimation (PIL)
input
AI
AI Subsystem
[estim]
SOC_Estimation
input
true
current
voltage
temperature
de-normalize
[A]
[C]
[D]
[E]
measuredSOC
estim
SOC
inputSignals
1
2
3
4
FFN_TensorFlow
SVM
EKF
ShallowNN
SVMOPT
LSTM
Tree
FFN_MATLAB
Diagnostic Viewer
09:04 PM: SIL/PIL Simu
"### 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\slprj\ert\SOC_Estimation\pil>exit /B 0
Updating code generation report with PIL files ...
Starting application: 'work\slprj\ert\SOC_Estimation\pil\SOC_Estimation.elf'
Ready
View diagnostics
193%
auto(FixedStepDiscrete)
SOC
File
Tools
View
Simulation
Help
true, estim
true
estim
Ready
Sample based
T=6629.000
inputSignals
current
voltage
temperature
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

** NXP S32K344 board*

Reducing AI Model size for embedded deployment

Data Preparation

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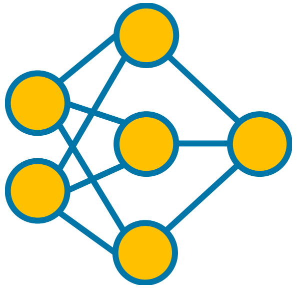
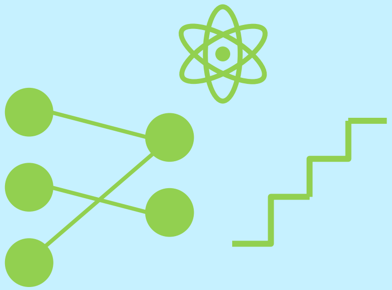
0.7510	0.3852	0.3076
0.7510	0.3852	0.3091

AI Modeling



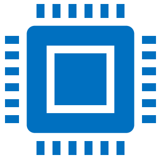
Simulation & Test

Compression

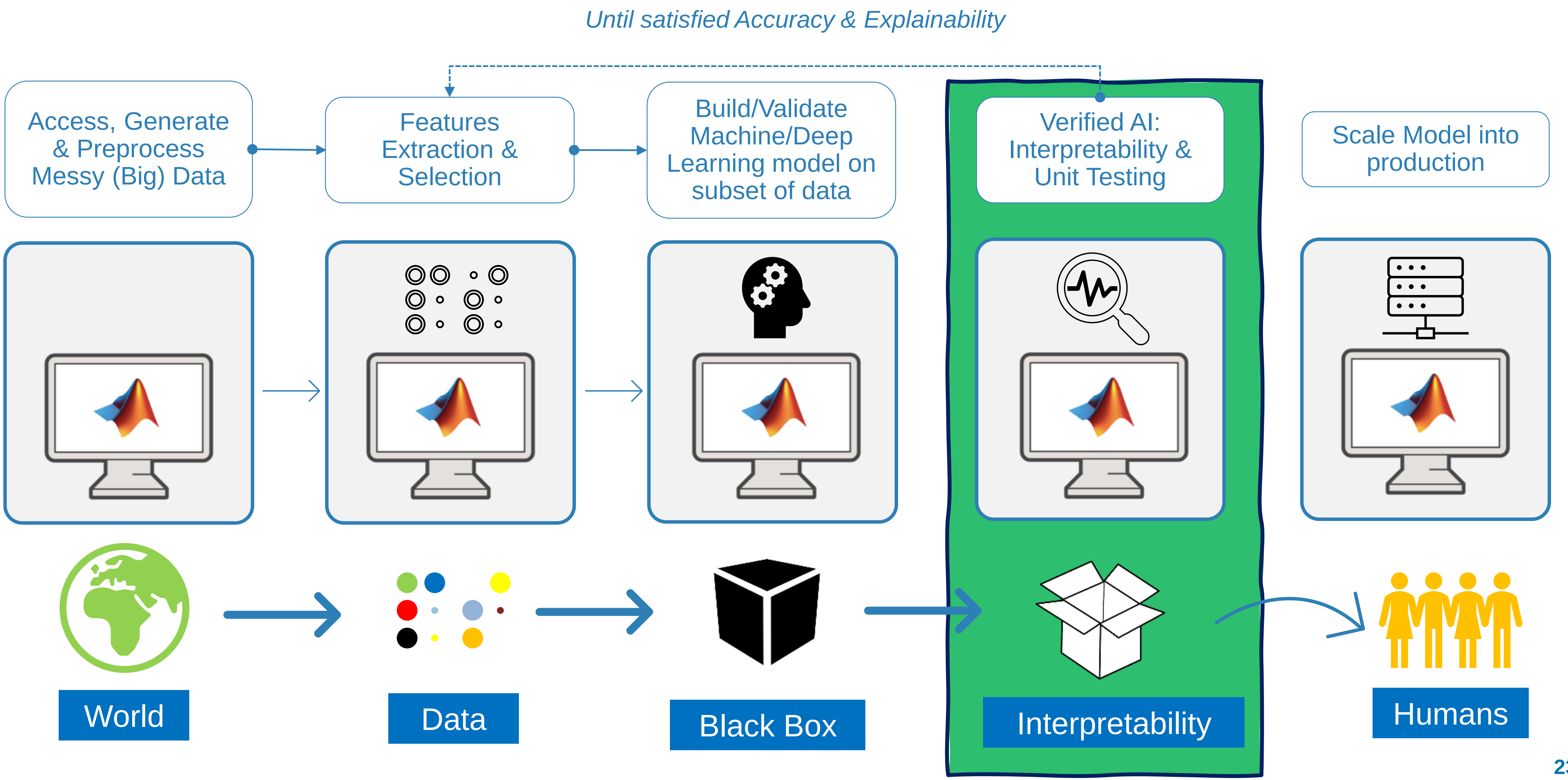


Model compression techniques to reduce model size and speed up inference

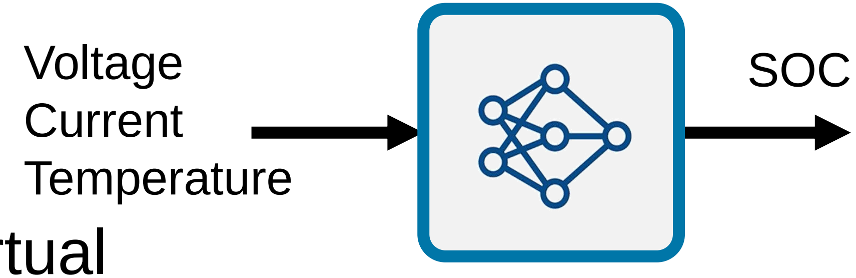
Deployment



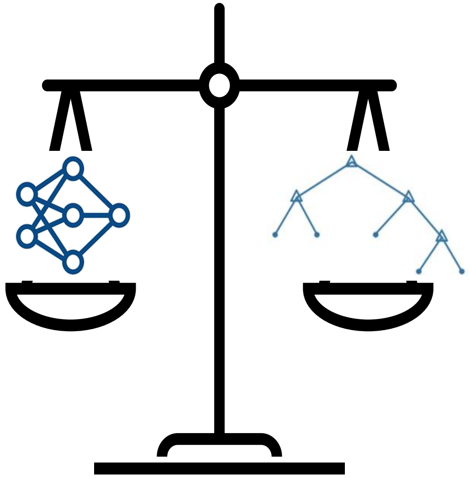
Workflow with interpretability: Validated & Verified AI



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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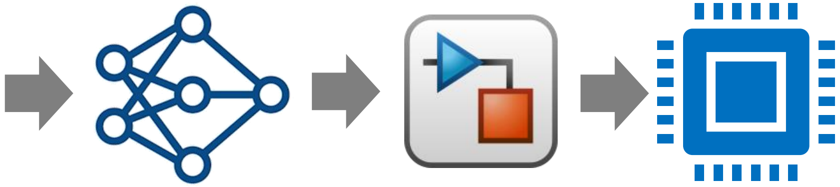

Thank You!