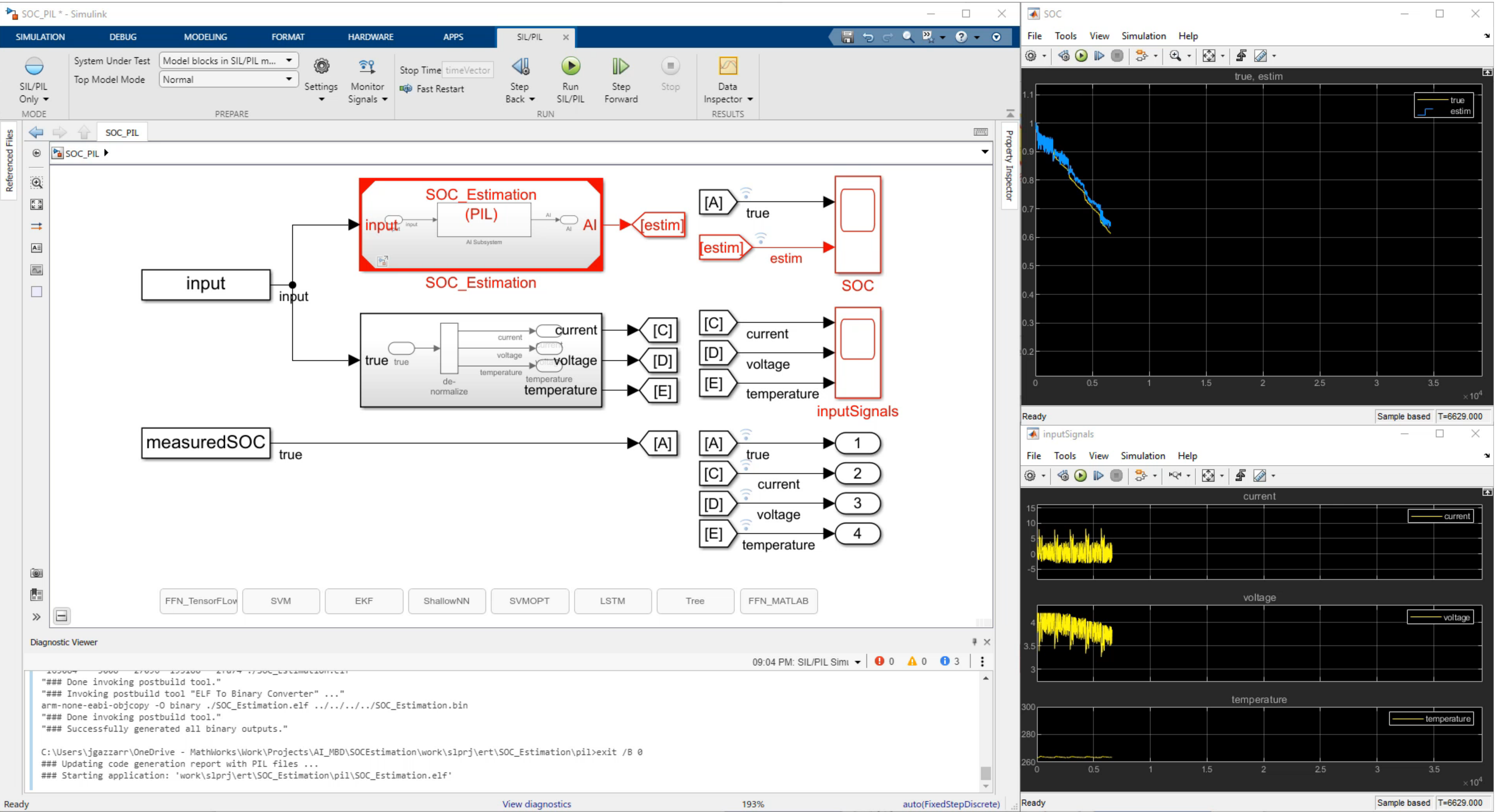
MathWorks
AUTOMOTIVE CONFERENCE 2022
North America

AI Workflows for Battery State Estimation

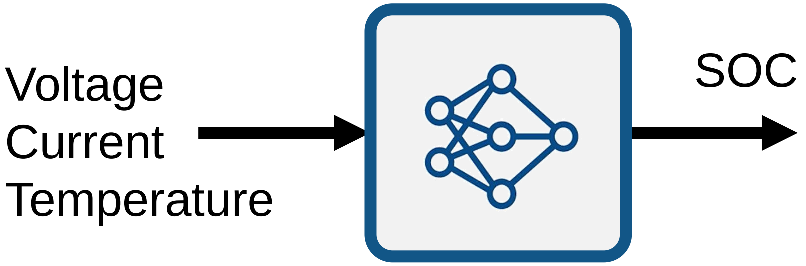
Javier Gazzarri, MathWorks

MathWorks

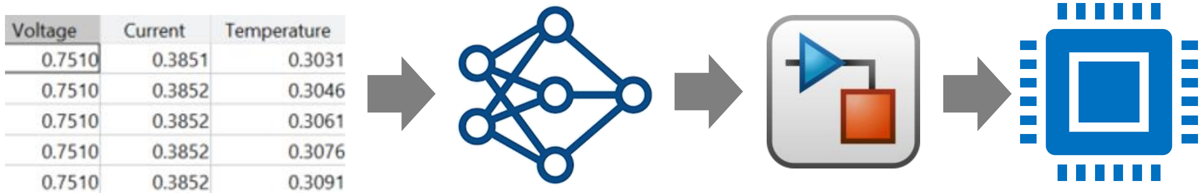

SOC_PIL * - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
HARDWARE
APPS
SIL/PIL
SIL/PIL Only
MODE
System Under Test
Model blocks in SIL/PIL m...
Top Model Mode
Normal
Settings
Monitor Signals
PREPARE
Stop Time
timeVector
Fast Restart
Step Back
Run SIL/PIL
Step Forward
Stop
RUN
Data Inspector
RESULTS
SOC_PIL
SOC_Estimation
(PIL)
input
AI
AI Subsystem
[estim]
SOC_Estimation
input
input
true
current
voltage
temperature
de-normalize
[C]
[D]
[E]
measuredSOC
true
[A]
[A]
true
[estim]
estim
SOC
[C]
current
[D]
voltage
[E]
temperature
inputSignals
[A]
true
1
[C]
current
2
[D]
voltage
3
[E]
temperature
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
File Tools View Simulation Help
current
voltage
temperature
Ready
Sample based
T=6629.000

Agenda

- Develop AI-based battery SOC estimation

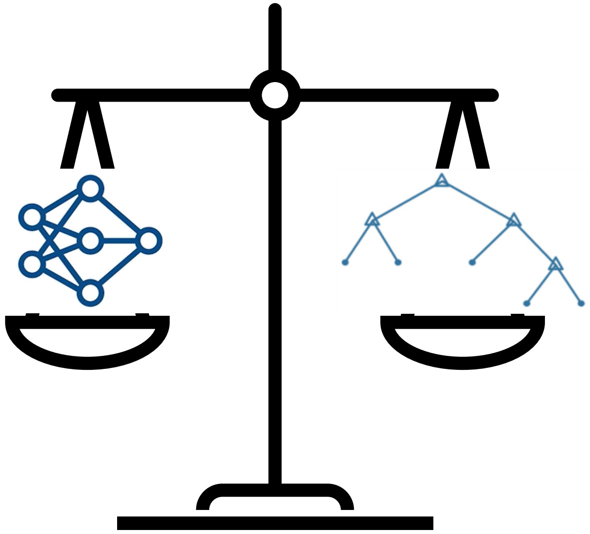


- Workflow - From data acquisition to hardware deployment



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

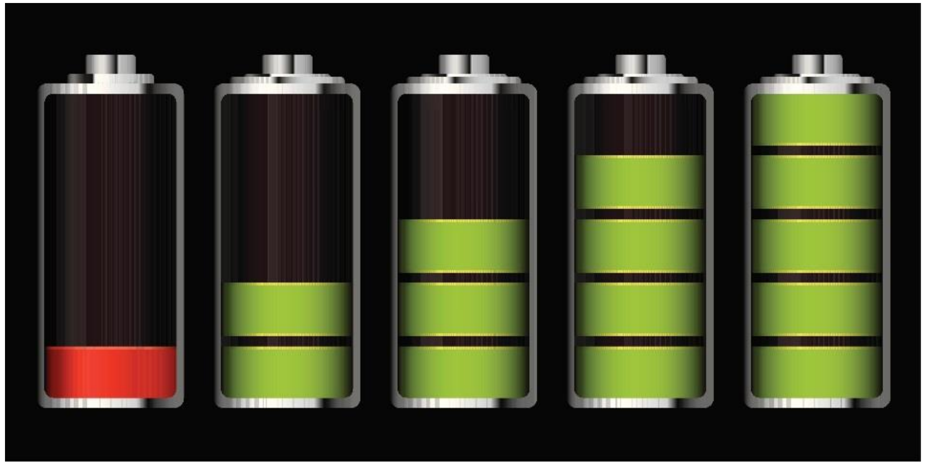
- Compare different AI methods



Battery State of Charge (SOC)

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

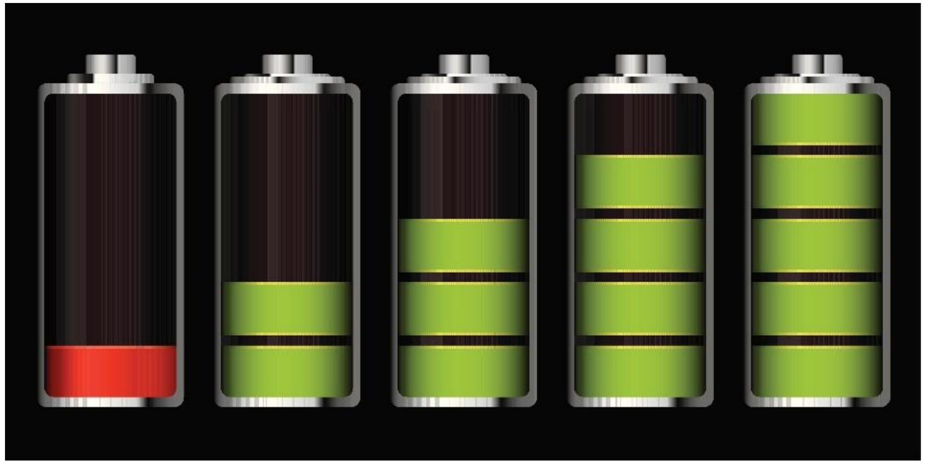
capacity *current*



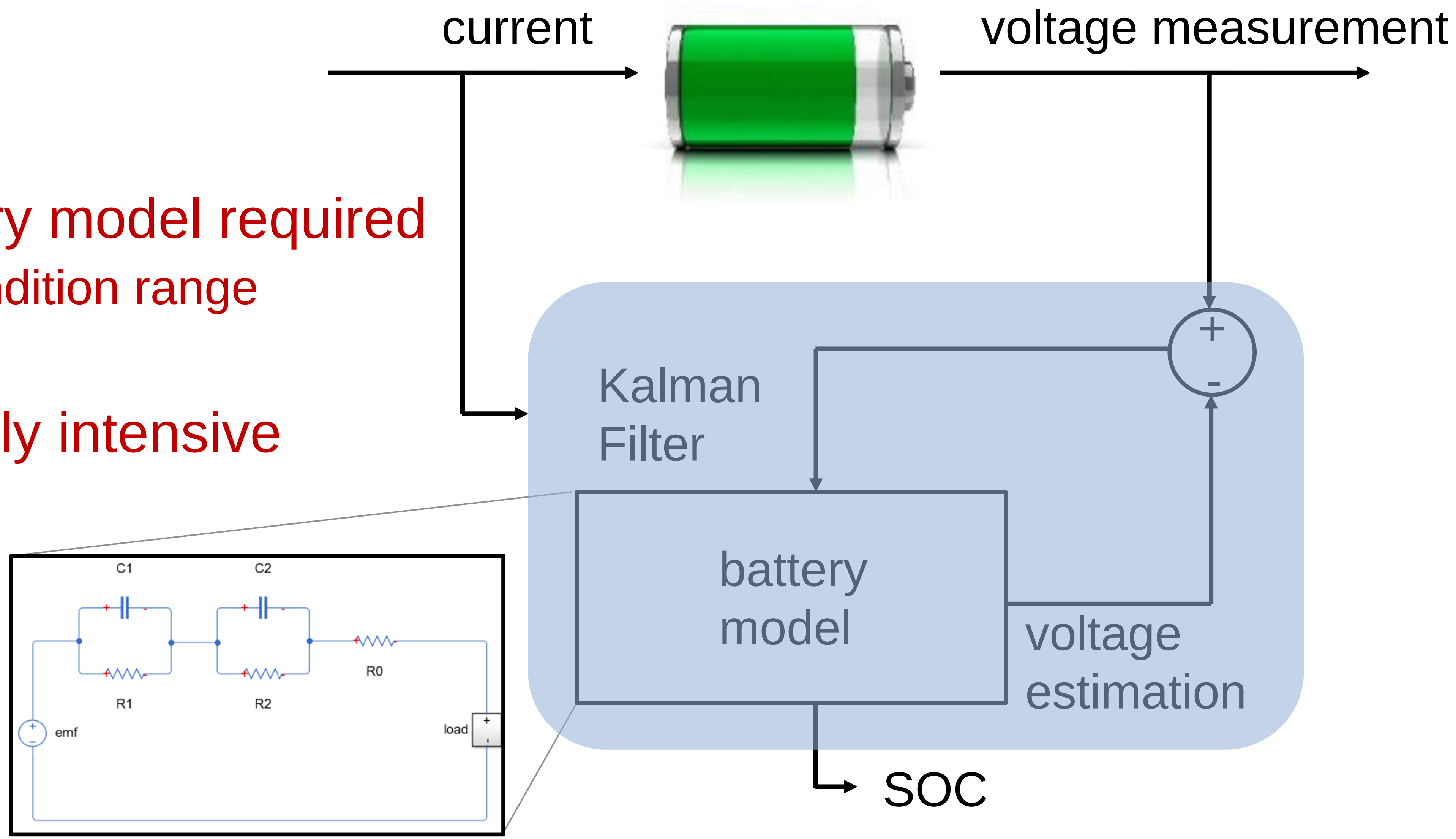
- Not directly measurable

- Affected by sensor error

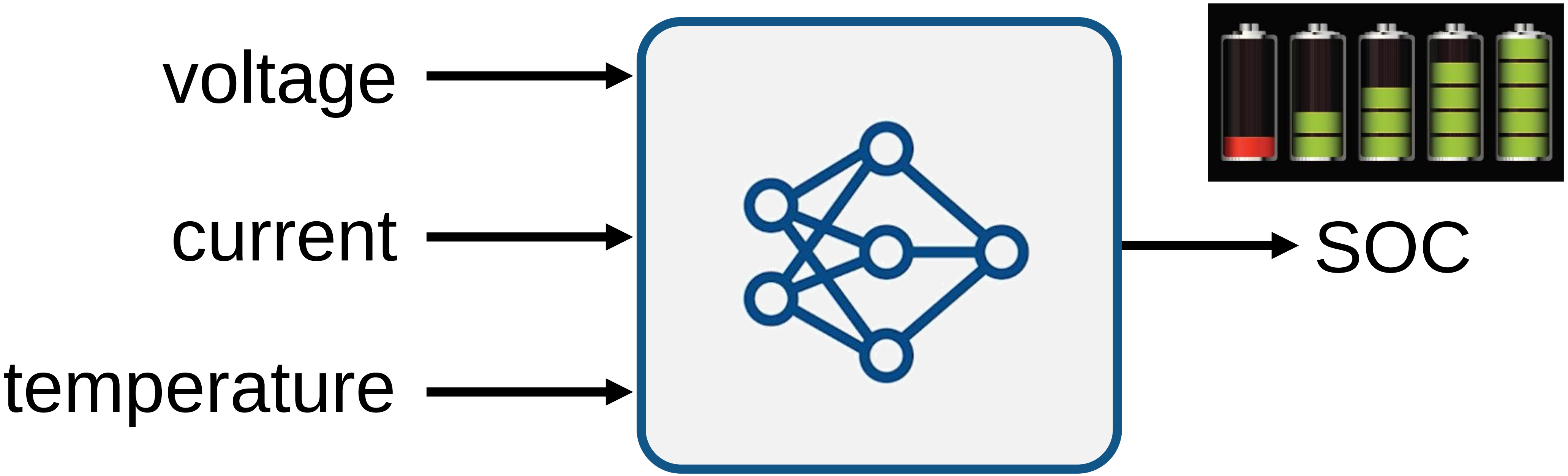
Kalman Filter



- Well understood
- Accurate
- Detailed battery model required
  - Operating condition range
- Computationally intensive



How About…



Comparison

EKF

- Well understood
- Accurate
- Detailed battery model required
  - Operating condition range
- Computationally intensive

AI

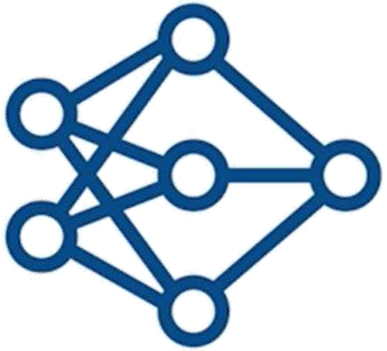
- No need for battery model
- Training on real data
- Capture very complex data relationships
- Difficult to interpret
- Computationally intensive

AI-driven System Design

Data Preparation

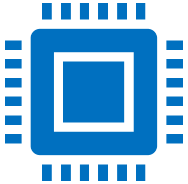
Voltage	Current	Temperature
0.7510	0.3851	0.3031
0.7510	0.3852	0.3046
0.7510	0.3852	0.3061
0.7510	0.3852	0.3076
0.7510	0.3852	0.3091

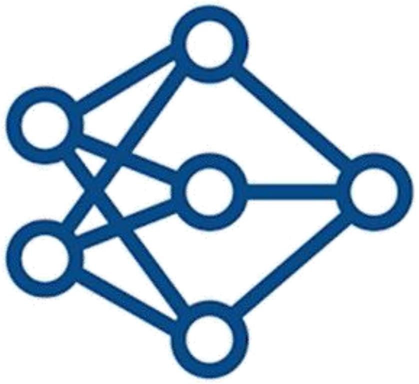
AI Modeling

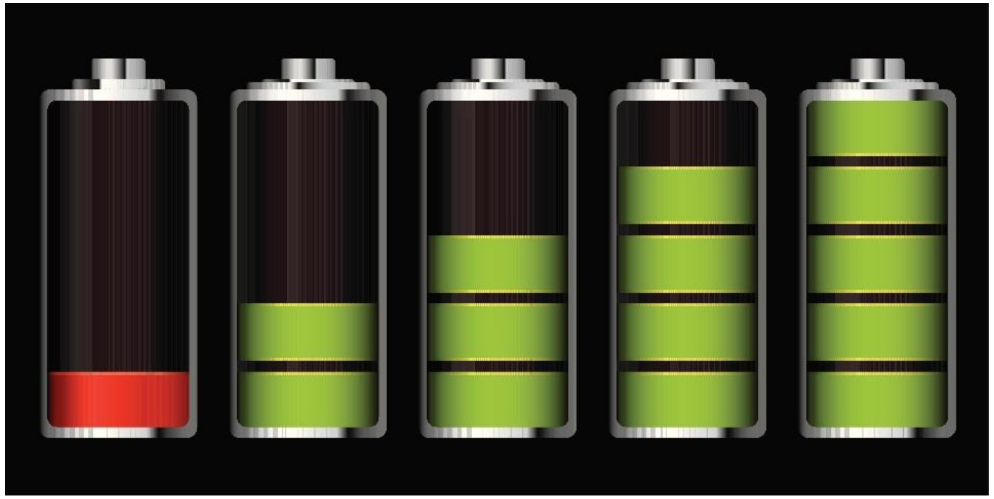


Simulation & Test

Deployment







2020-01-1181 Published 14 Apr 2020

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

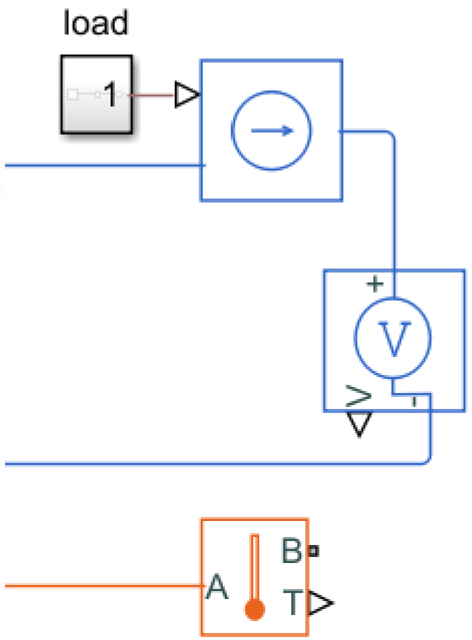
Battery state-of-charge (SOC) is critical information for the vehicle energy management system and must be accurately estimated to ensure reliable and affordable electrified vehicles (xEV). However, due to the nonlinear temperature, health, and SOC dependent behaviour of Li-ion

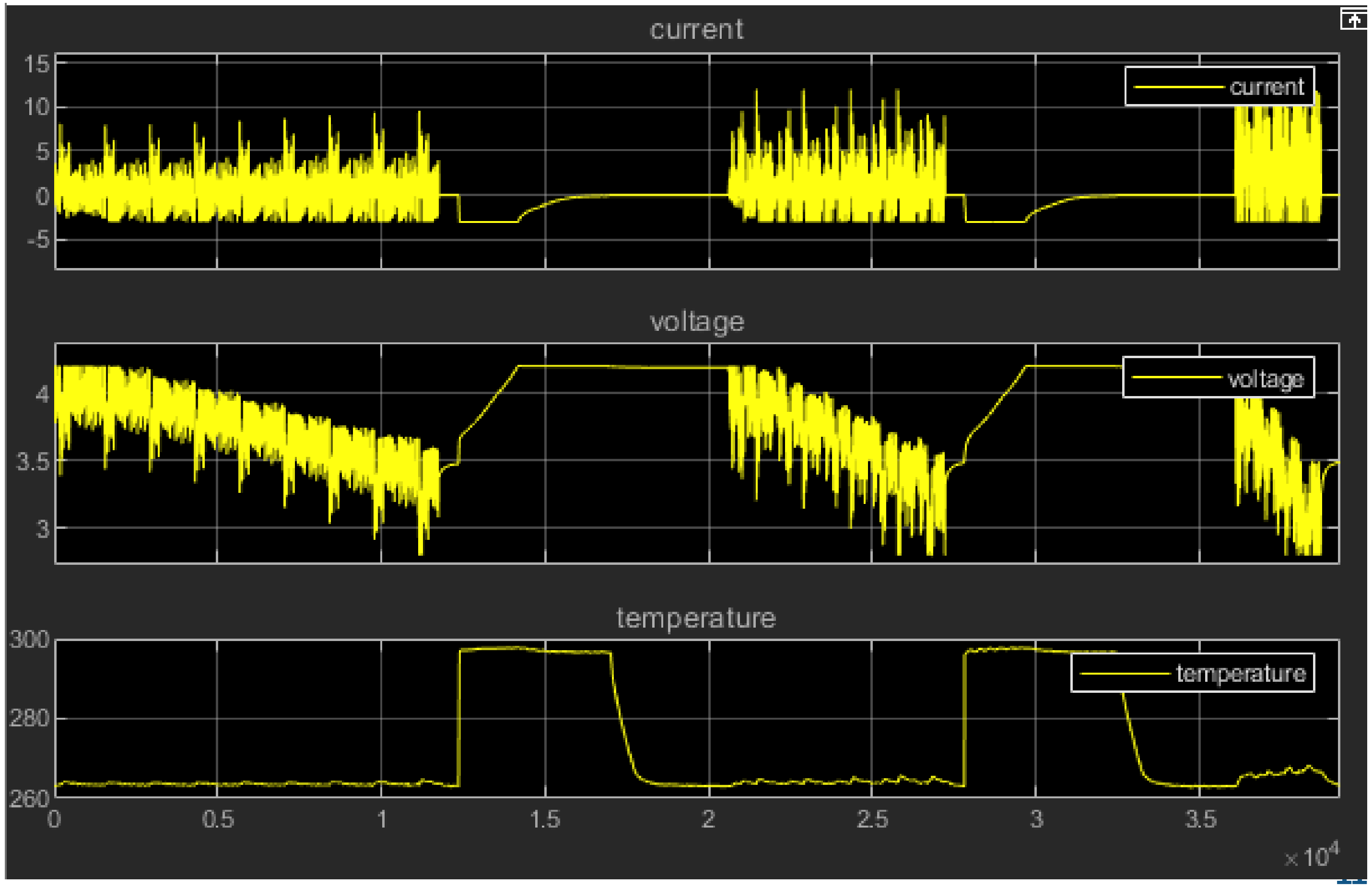
(FNN) approach. The method includes a description of data acquisition, data preparation, development of an FNN, FNN tuning, and robust validation of the FNN to sensor noise. To develop a robust estimator, the FNN was exposed, during training, to datasets with errors intentionally added to the data, e.g.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

Acquire and prepare data

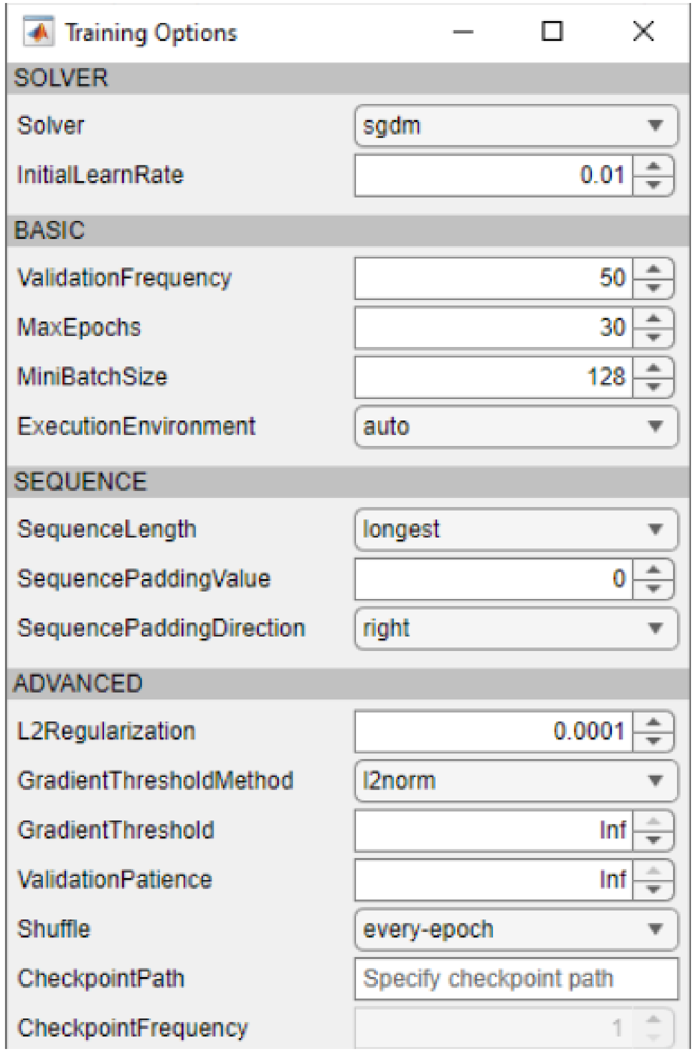
Data Preparation | AI Modeling | Simulation & Test | Deployment

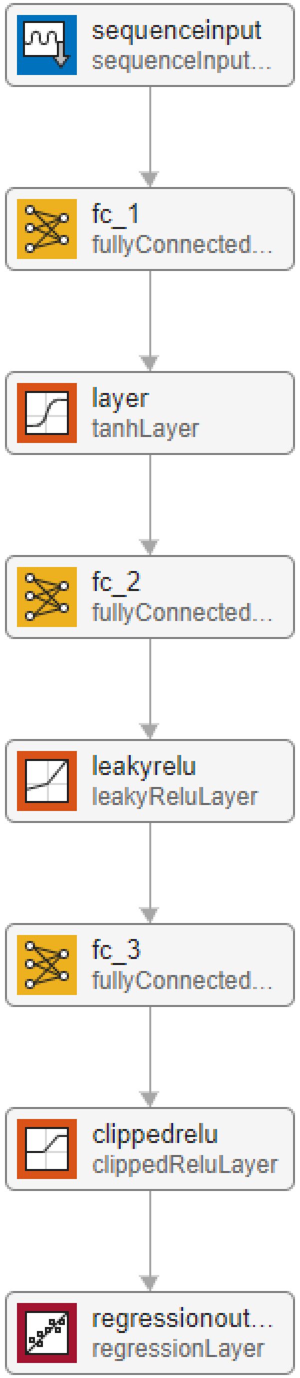
Voltage	Current	Temperature
0.7510	0.3851	0.3031
0.7510	0.3852	0.3046
0.7510	0.3852	0.3061
0.7510	0.3852	0.3076
0.7510	0.3852	0.3091

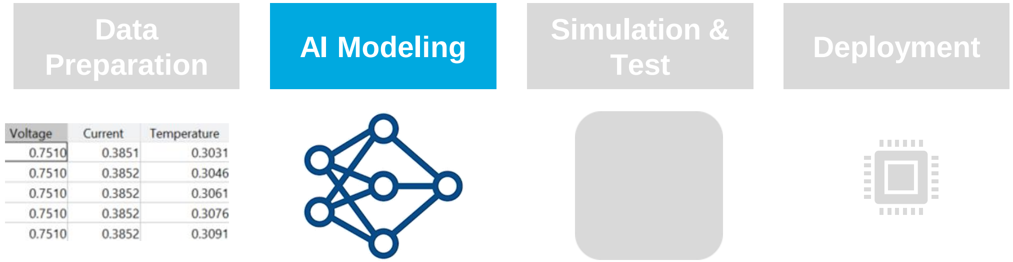


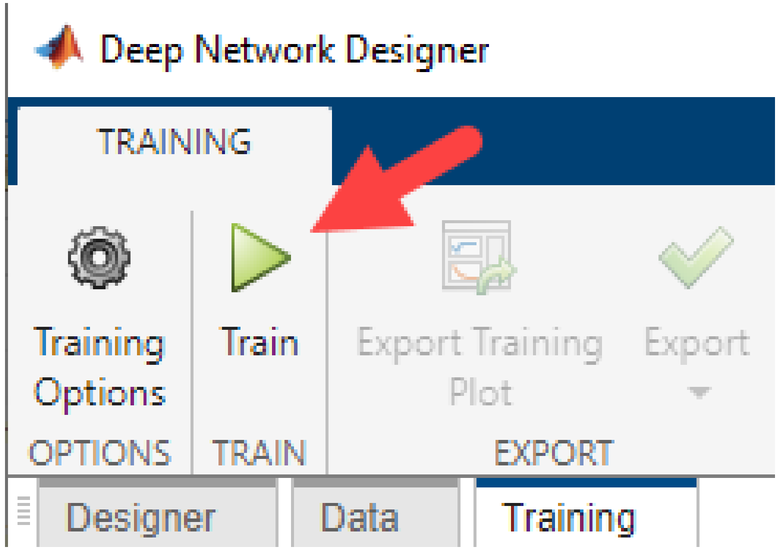


- Configure AI function
- Train and Test AI function

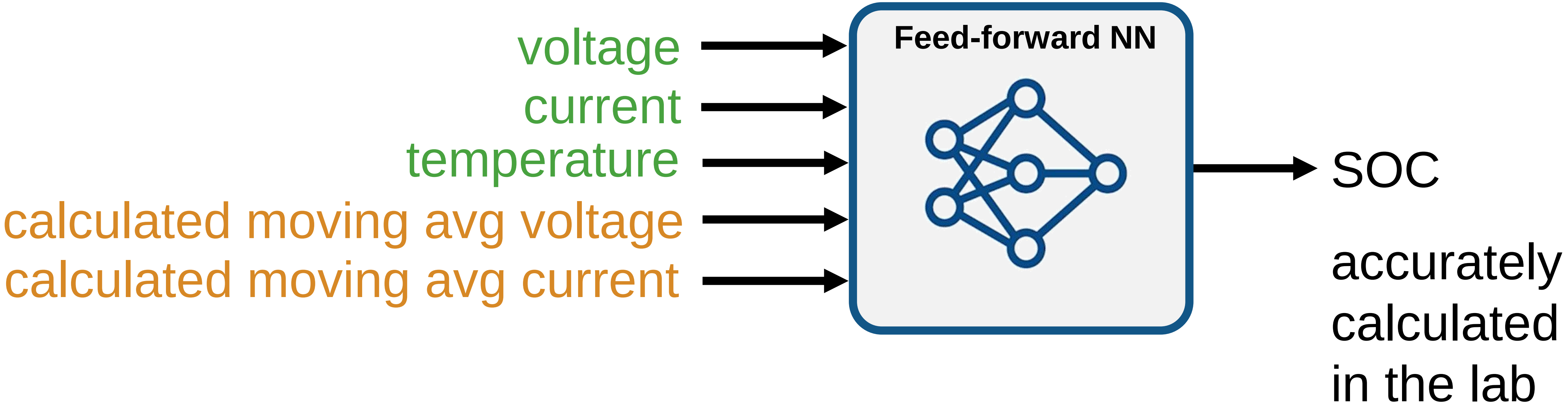








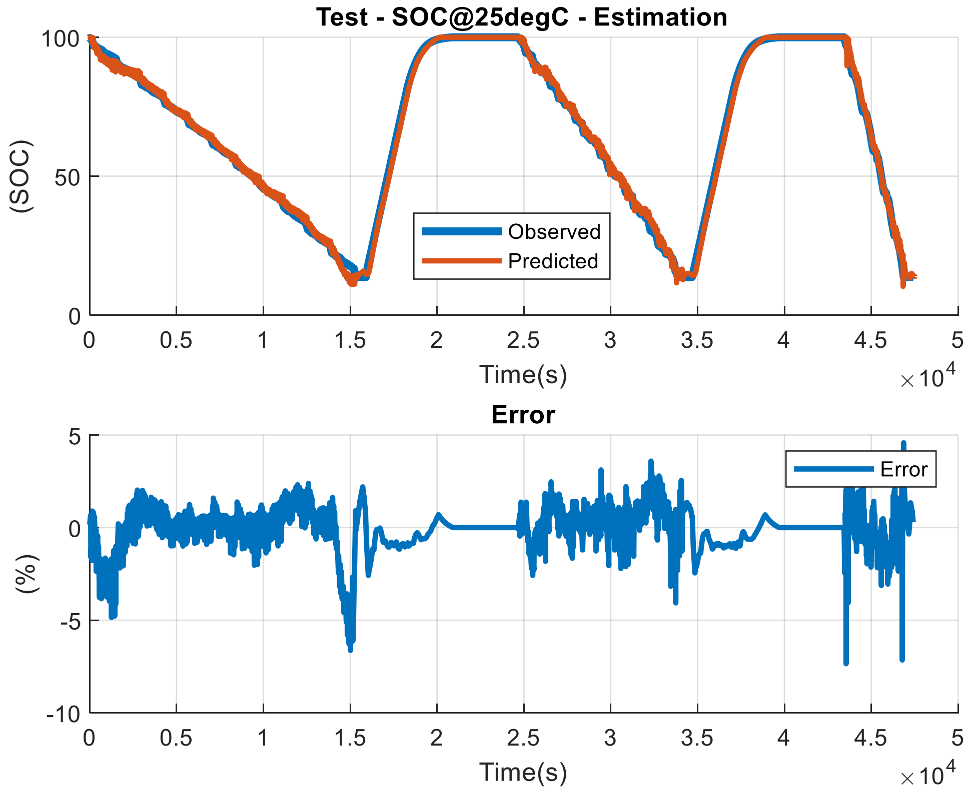
McMaster University



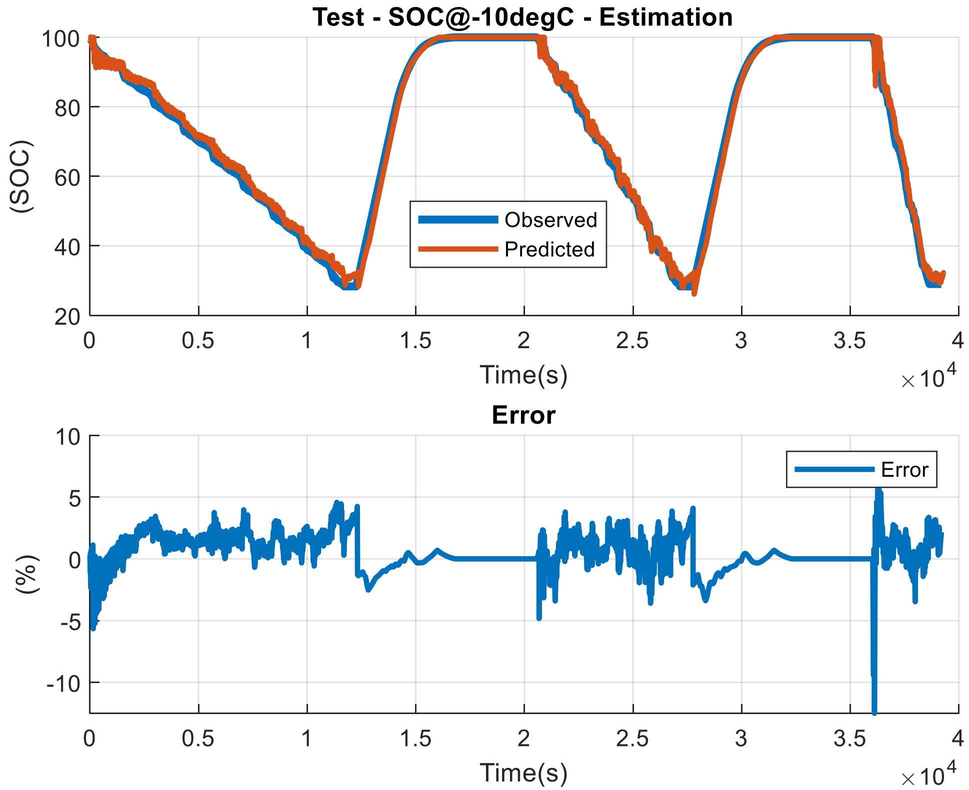
Data source https://data.mendeley.com/datasets/cp3473x7xv/3

Results

25ºC



-10ºC

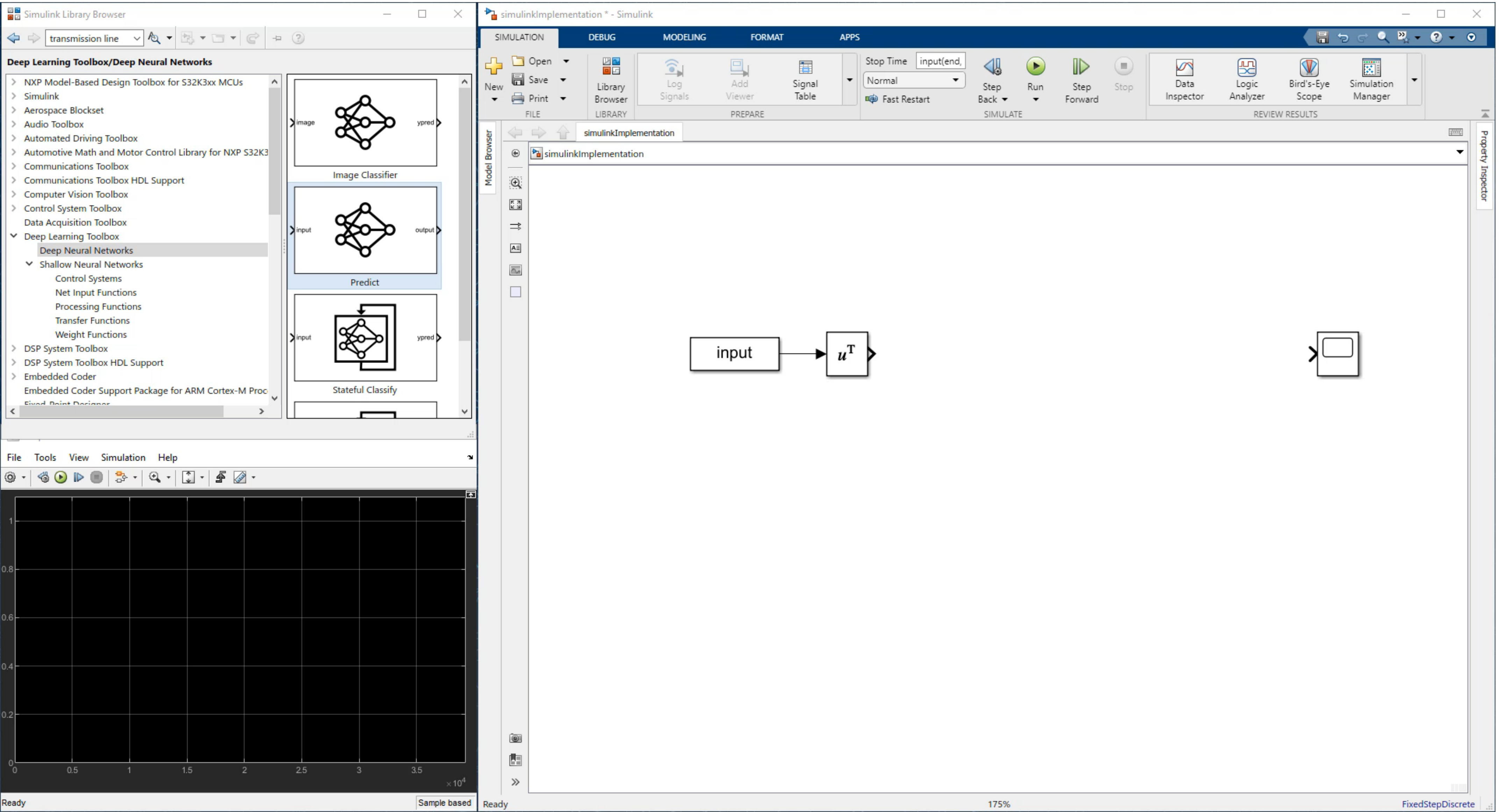


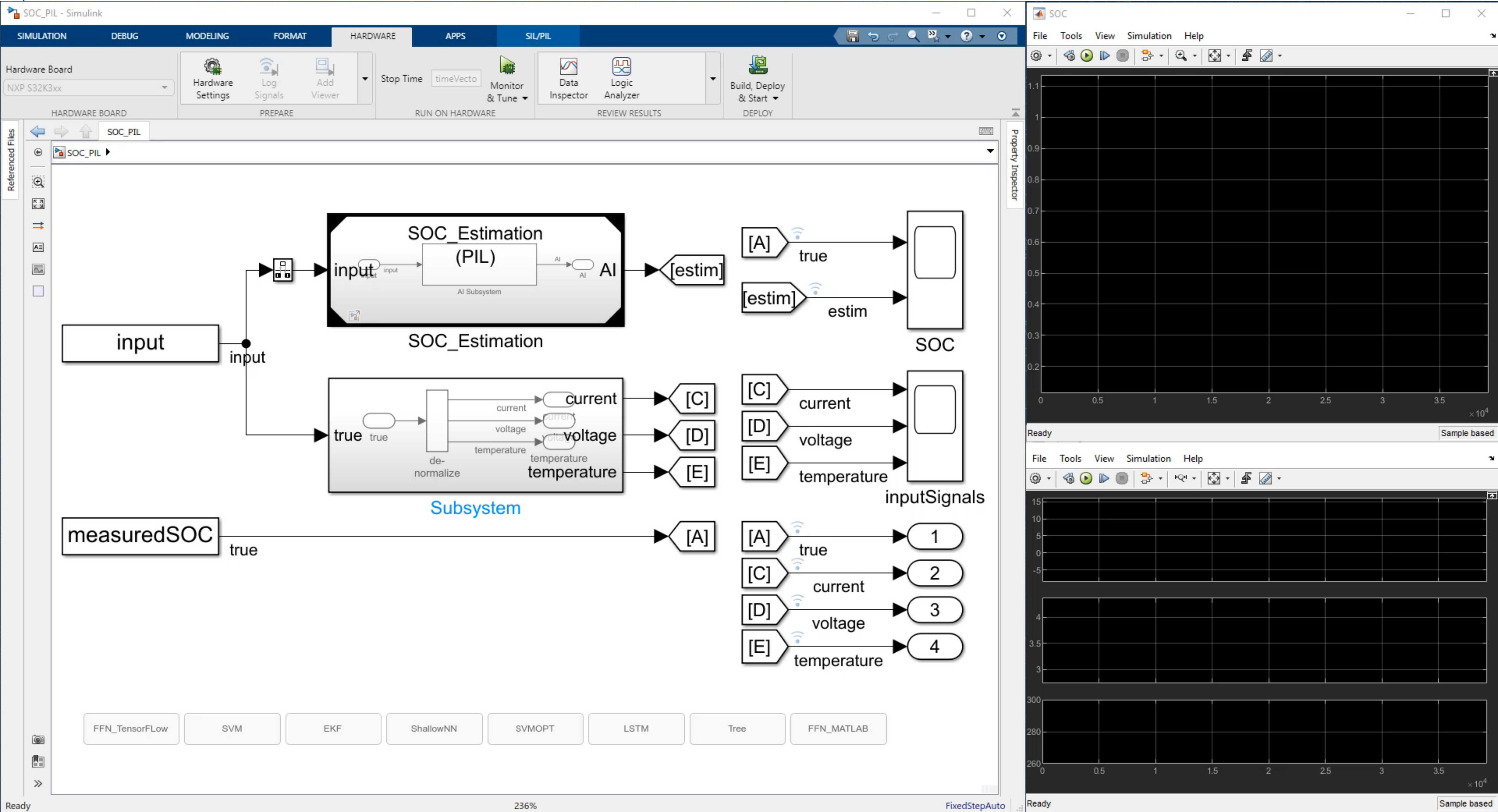
prediction

ground truth

Simulink Integration

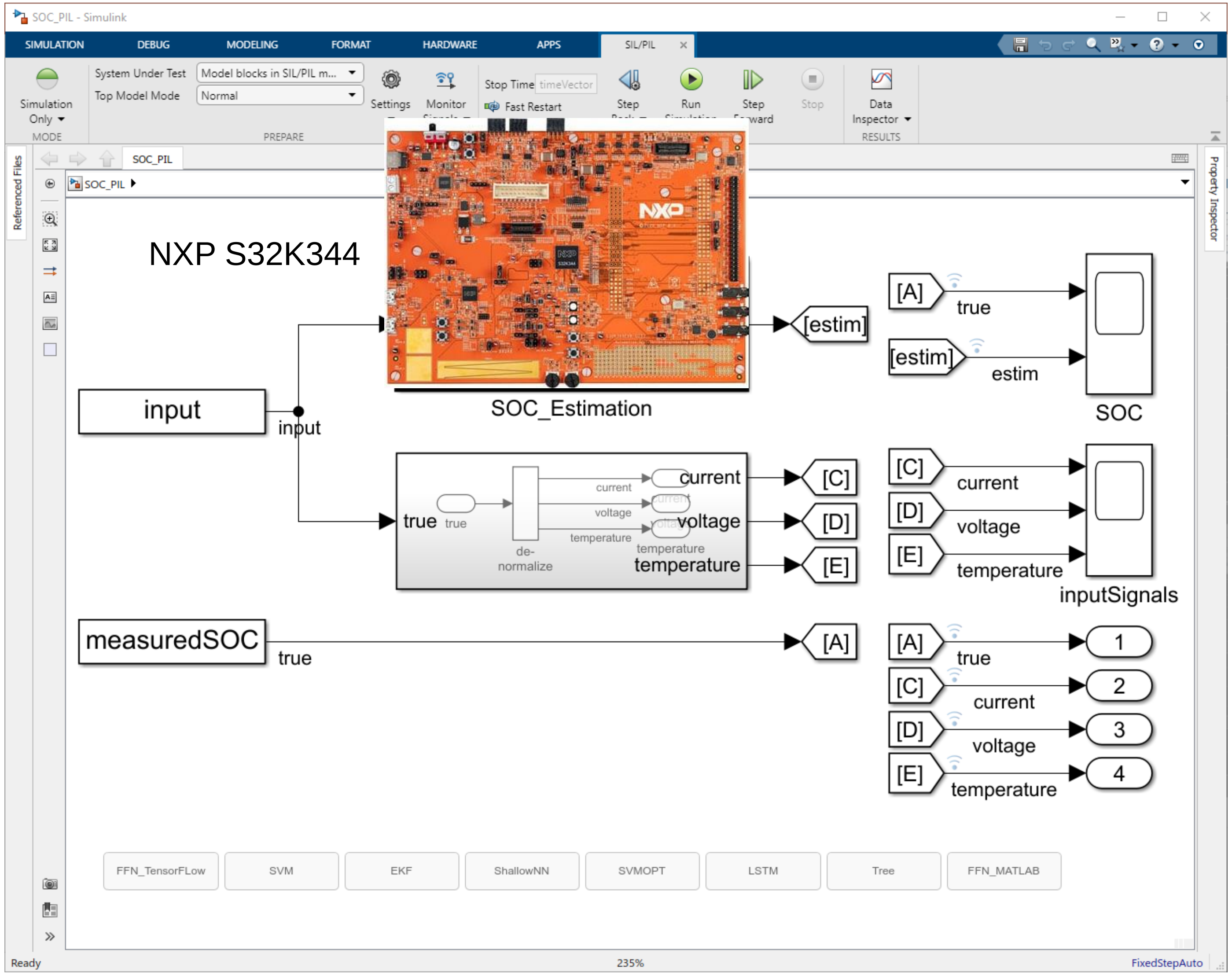
Voltage	Current	Temperature
0.7510	0.3851	0.3031
0.7510	0.3852	0.3046
0.7510	0.3852	0.3061
0.7510	0.3852	0.3076
0.7510	0.3852	0.3091



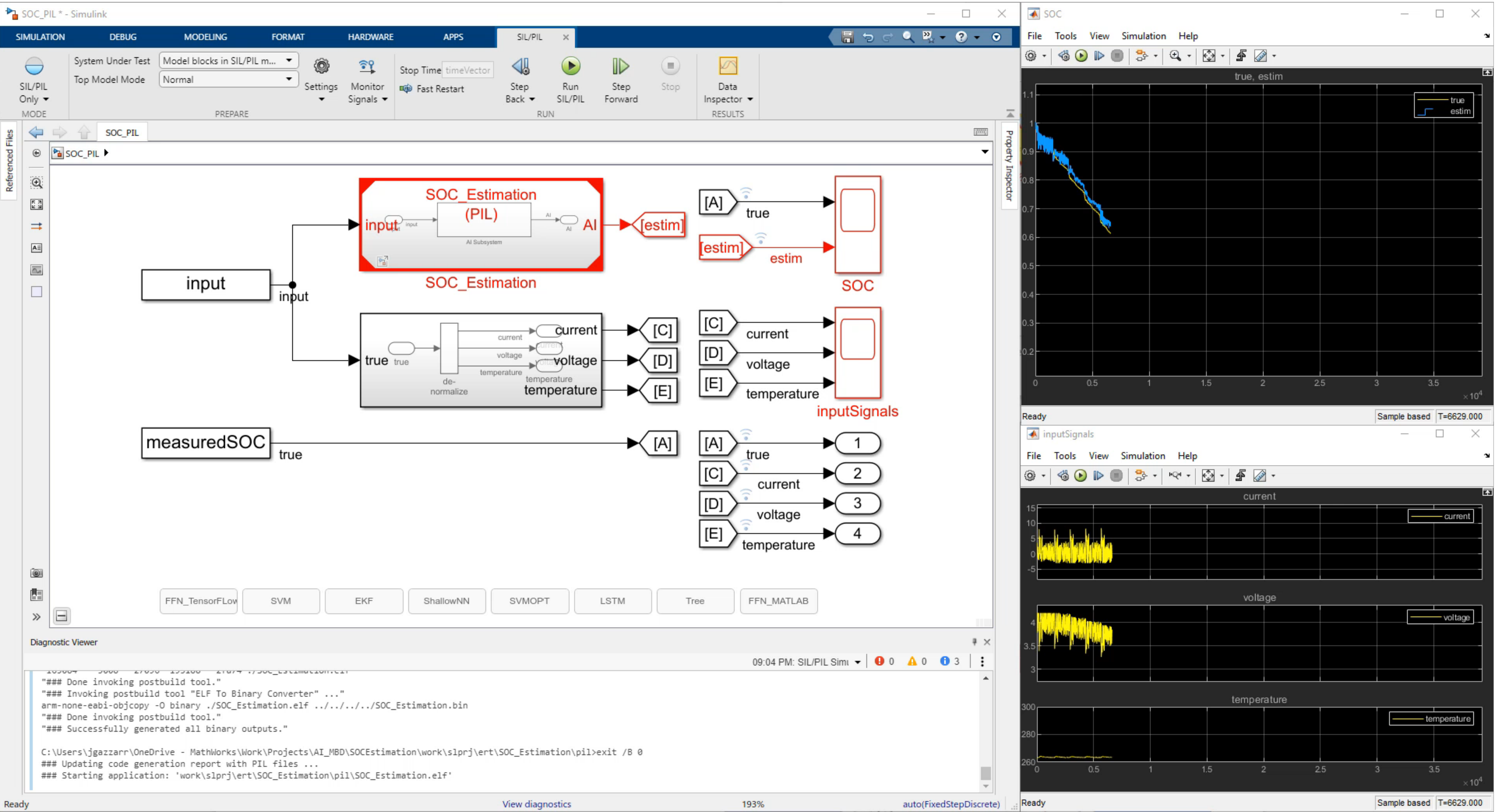

SOC_PIL - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
HARDWARE
APPS
SIL/PIL
Hardware Board
NXP S32K3xx
HARDWARE BOARD
Hardware Settings
Log Signals
Add Viewer
PREPARE
Stop Time
timeVecto
Monitor & Tune
RUN ON HARDWARE
Data Inspector
Logic Analyzer
REVIEW RESULTS
Build, Deploy & Start
DEPLOY
SOC_PIL
SOC_Estimation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

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

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



C Code Generation


SOC_PIL * - Simulink
SIMULATION DEBUG MODELING FORMAT HARDWARE APPS SIL/PIL
System Under Test Model blocks in SIL/PIL m...
Top Model Mode Normal
Settings
Monitor Signals
Stop Time timeVector
Fast Restart
Step Back
Run SIL/PIL
Step Forward
Stop
Data Inspector
MODE PREPARE RUN RESULTS
SOC_PIL
SOC_Estimation (PIL)
input
AI
[estim]
SOC_Estimation
input
true
current
voltage
temperature
de-normalize
[C]
[D]
[E]
[A]
estim
SOC
inputSignals
measuredSOC
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
Sample based T=6629.000
inputSignals
current
voltage
temperature

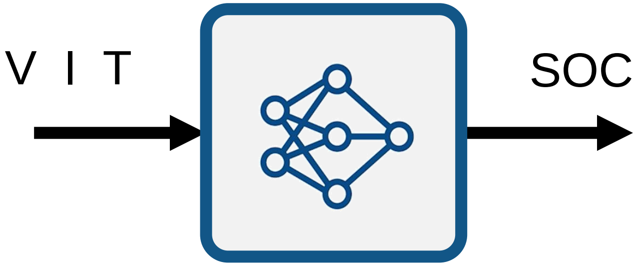
Tradeoffs and Benchmark

	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*

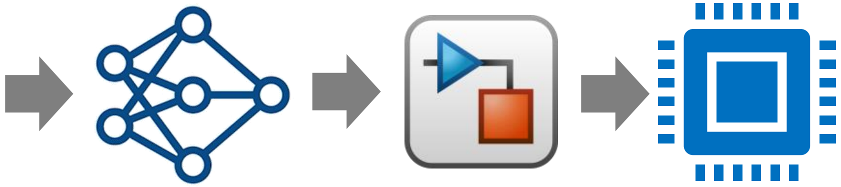
Summary



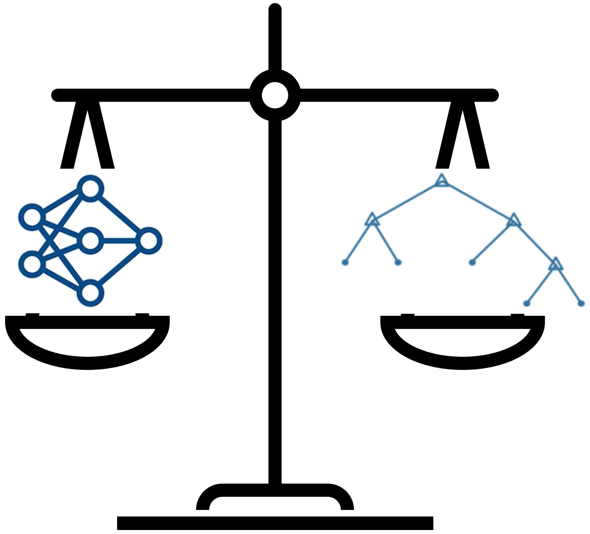
- Develop AI-based Battery SOC Estimation

- 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
0.7510	0.3852	0.3076
0.7510	0.3852	0.3091



- Compare Different Methods AI

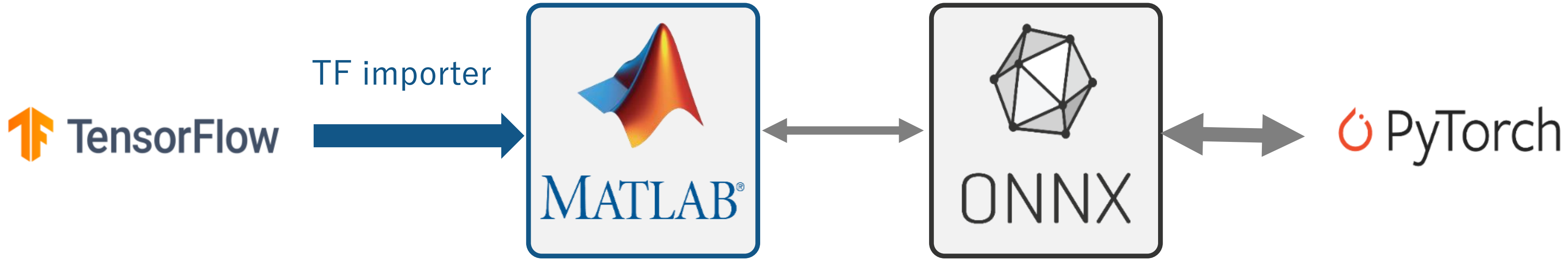


MathWorks
AUTOMOTIVE CONFERENCE 2022
North America

Thank you

MathWorks

Import Pre-Trained Model



Why Virtual Sensors?

1) When a physical sensor is expensive or impractical