智能控制系统的设计、优化与实现

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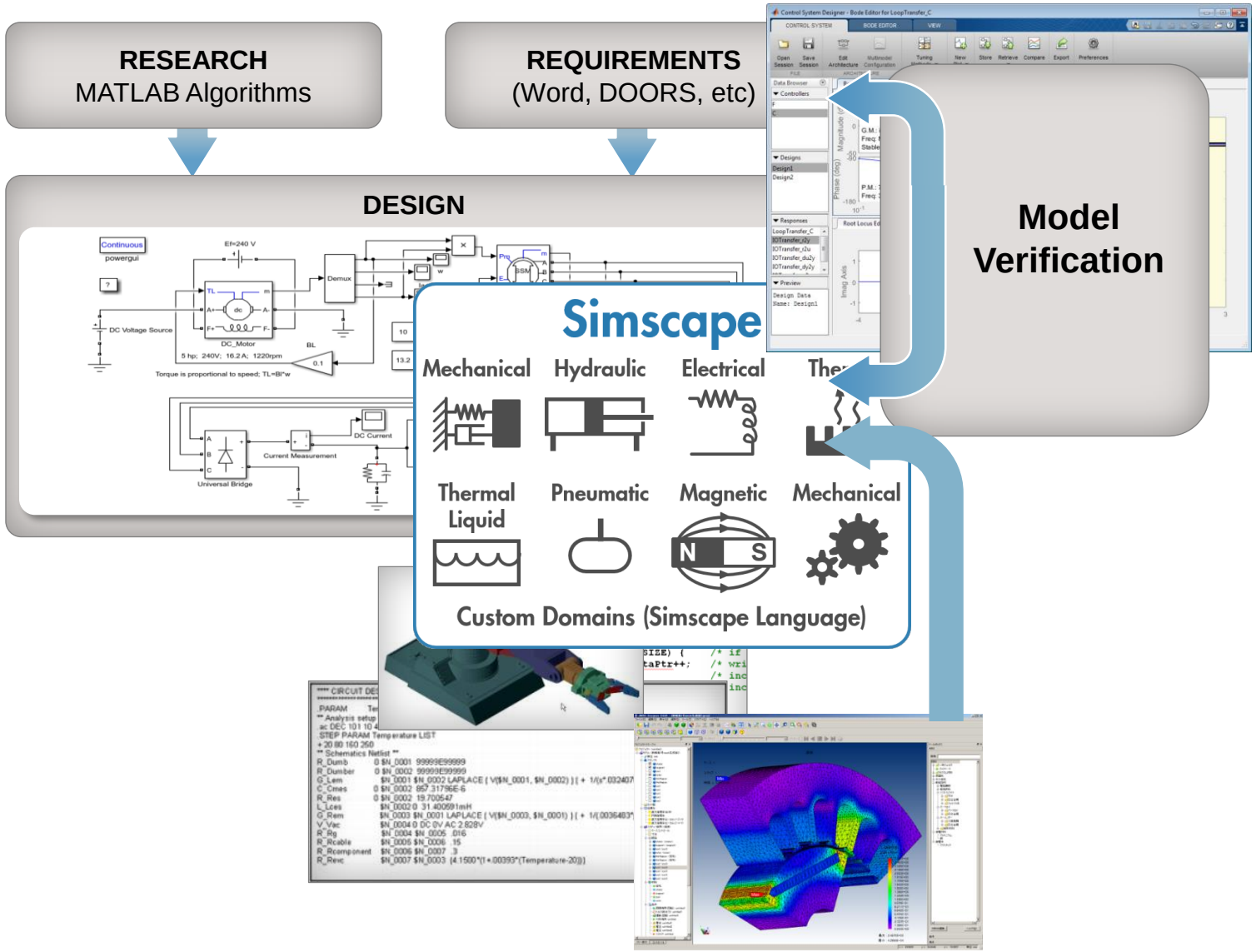
主要内容

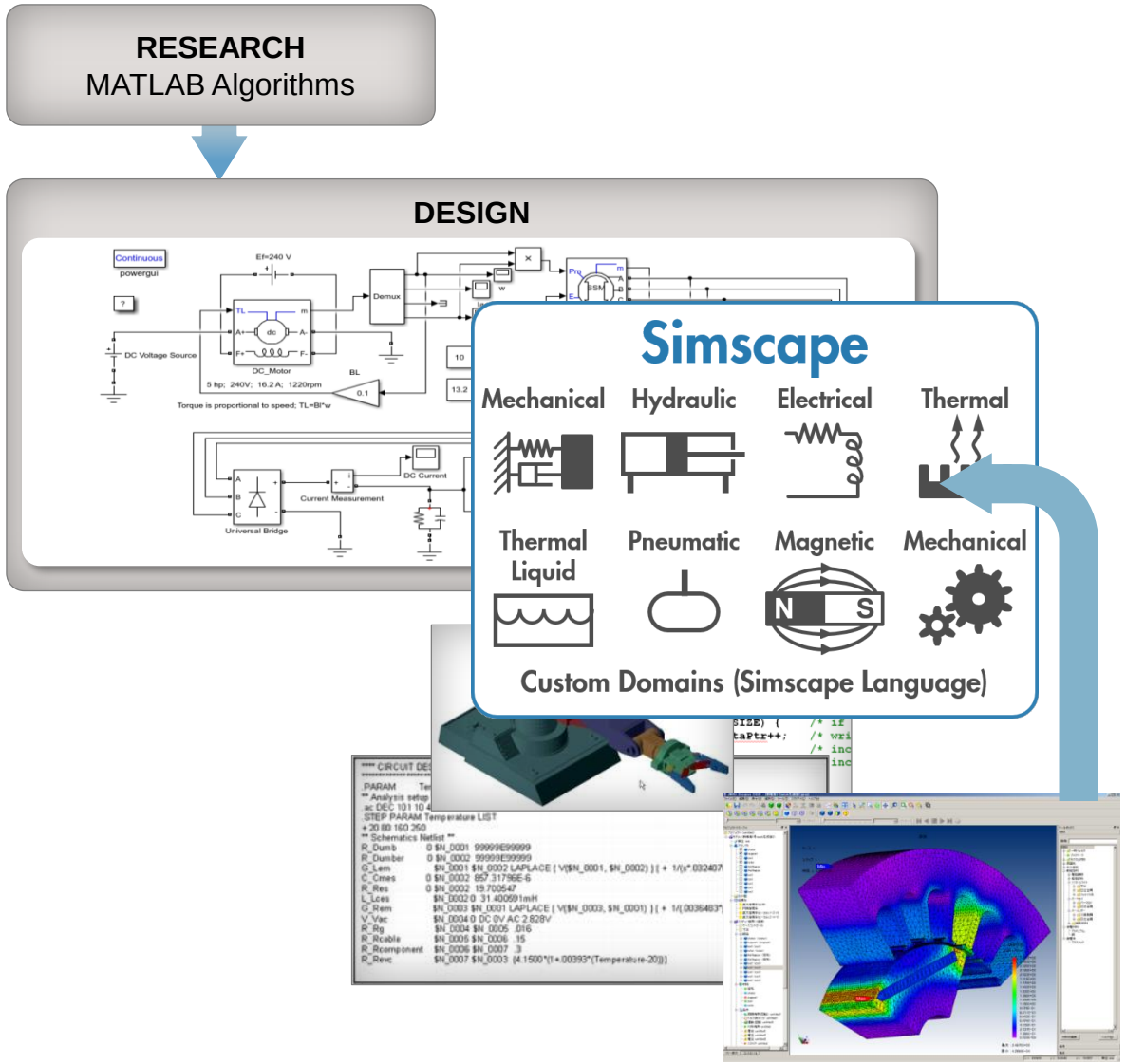
- 基于模型设计—桌面仿真
  - 如何建立高精度的系统模型
  - 快速设计先进控制算法
  - 自动化测试
- 基于模型设计—实时仿真
- 基于模型设计—产品化的代码实现

基于模型设计– 桌面仿真



- 在MATLAB环境中开发控制算法
- 使用Simulink框图搭建模型仿真系统行为
- 细化特定物理域模型优化系统
- 重用CAE工具的设计和工程数据，比如 CAD, FEA 和 SPICE 模型
- 链接需求到设计
- 通过运行仿真持续验证设计是否满足需求

如何建立高精度的系统模型



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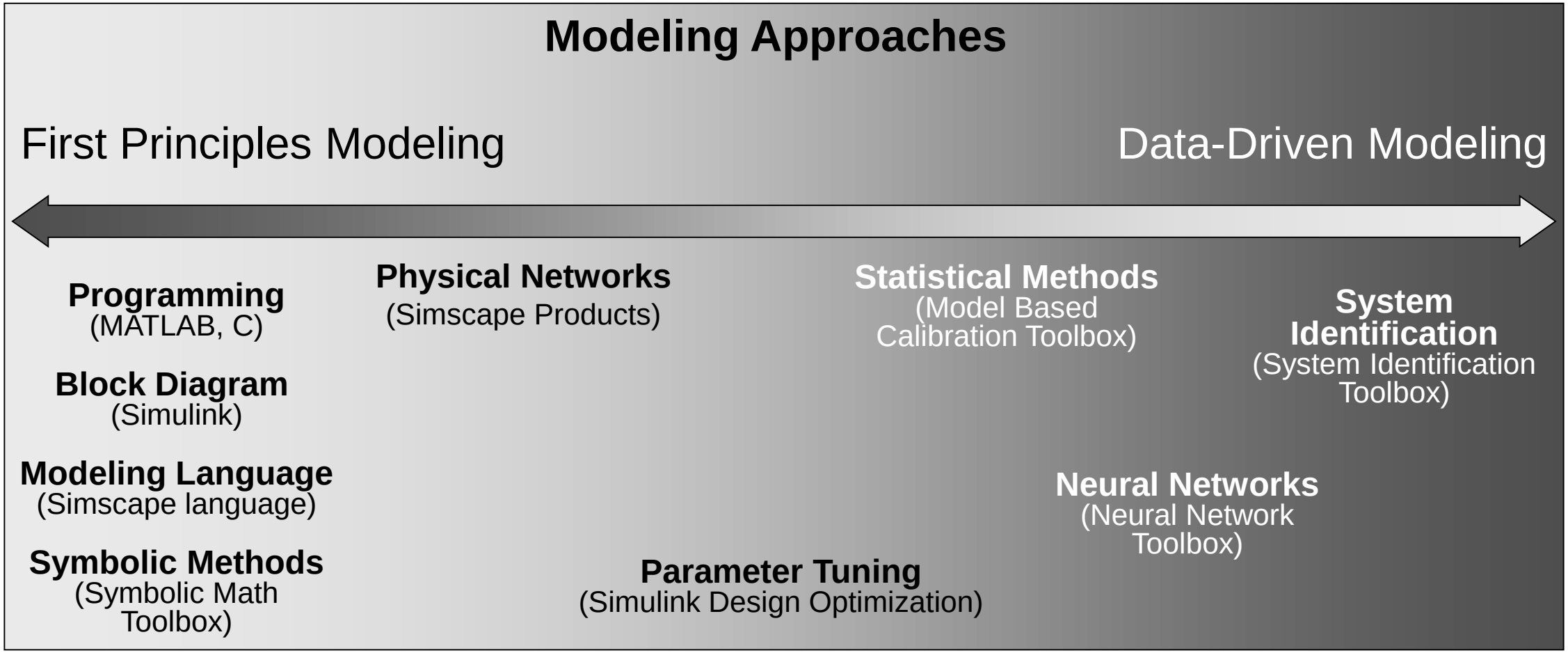
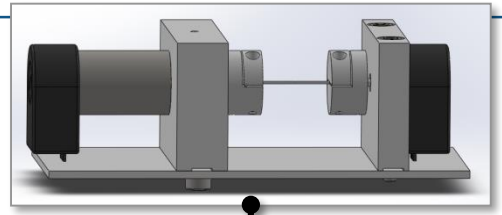
使用MathWorks 产品进行物理系统建模



建模方法



First Principles

Data-Driven

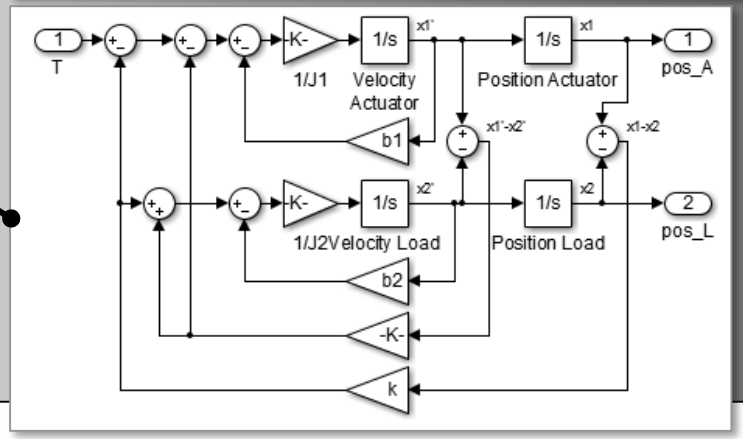
Programming

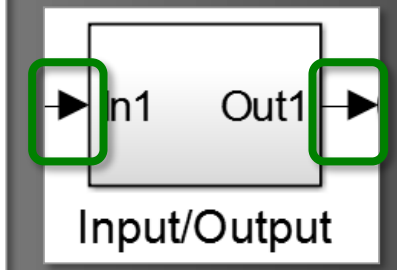
Block Diagram

Modeling Language

Symbolic Methods

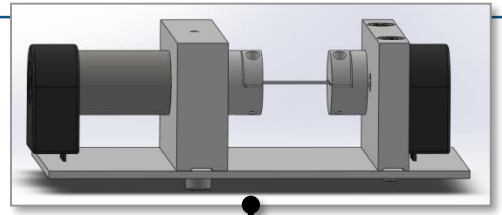
$$J_1 x_1'' = -b_1 x_1' - k(x_1 - x_2) - b_{12}(x_1' - x_2') + T$$
$$J_2 x_2'' = -b_2 x_2' + k(x_1 - x_2) - b_{12}(x_1' - x_2')$$

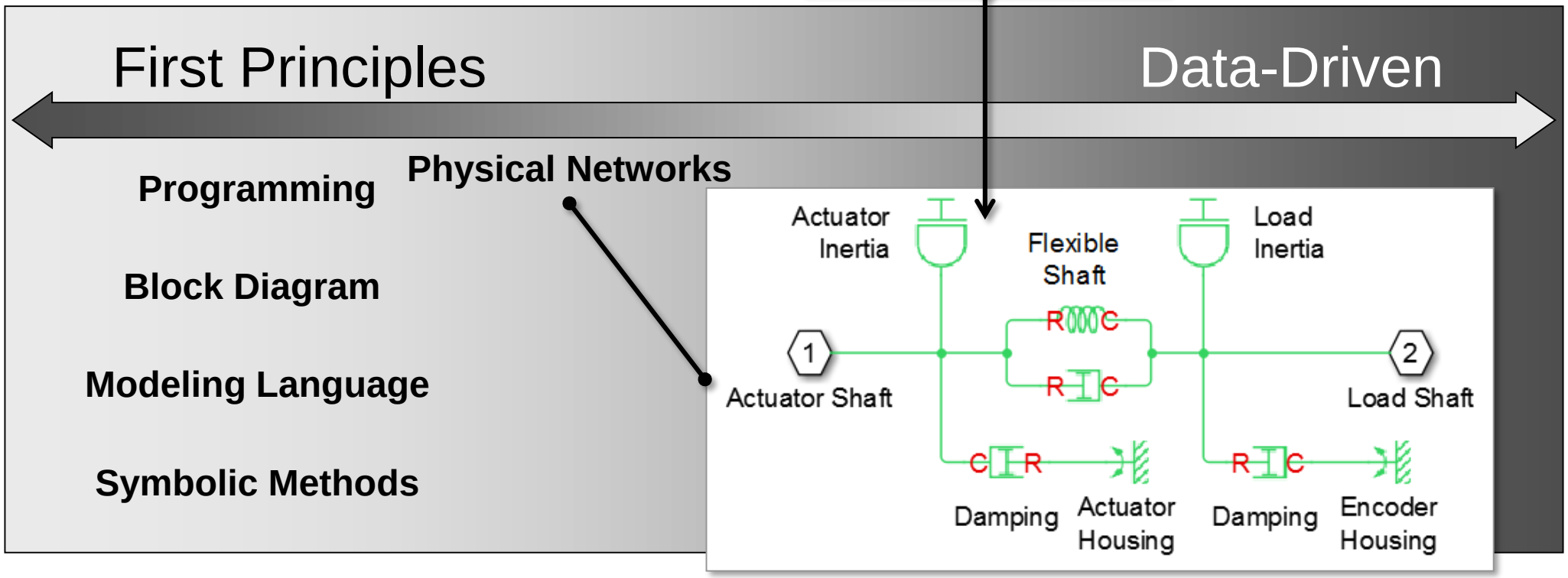




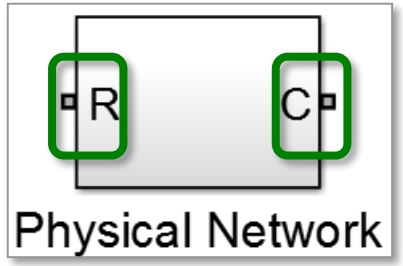
- 目的: 开发设计和物理参数
- 要求:
  - 物理系统是确定的
  - 可以推导系统级方程

建模方法

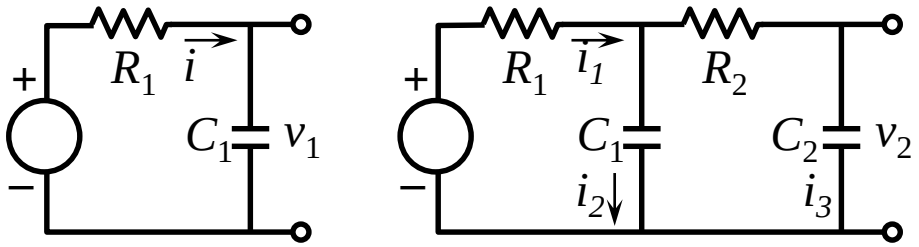




- 目的: 开发设计和物理参数
- 要求:
  - 物理系统是确定的
  - 组件级模型存在或者可以创建

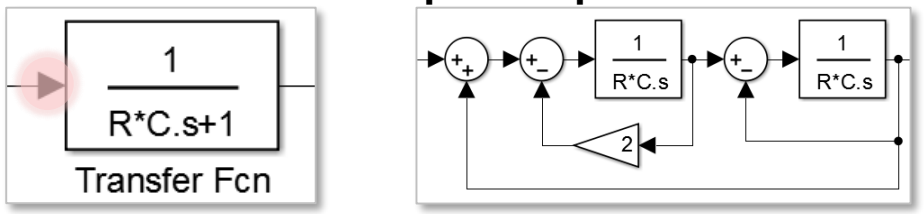


物理建模

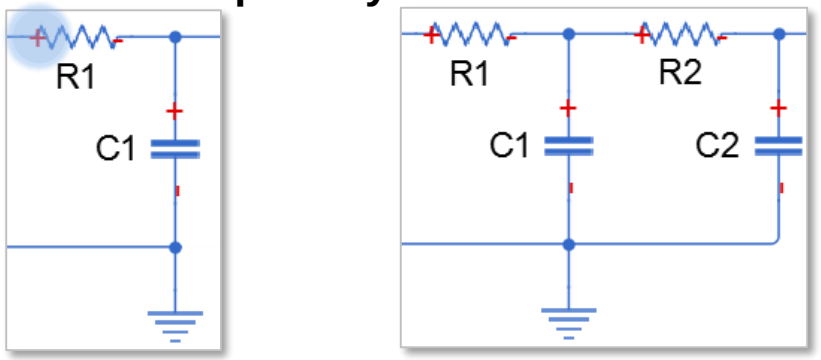


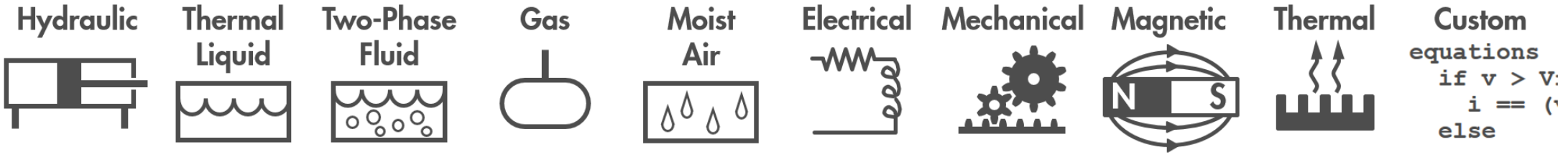
- Simulink 是基于信号流建模
  - 因果关系或输入输出
- Simscape 是组件之间可以双向的能量传递
- 系统级方程:
  - 自动构建方程
  - 同时进行求解
  - 覆盖多物理域

Simulink: Input/Output



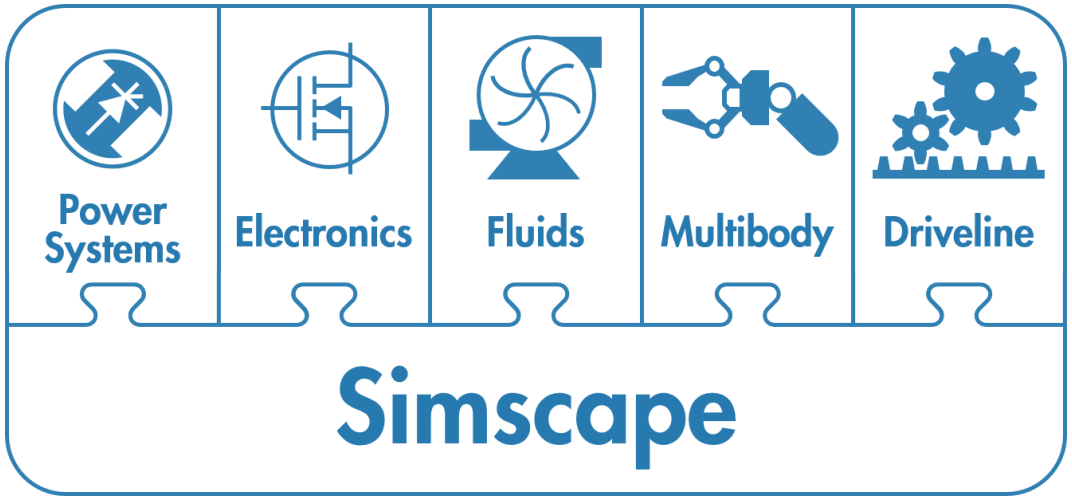
Simscape: Physical Networks

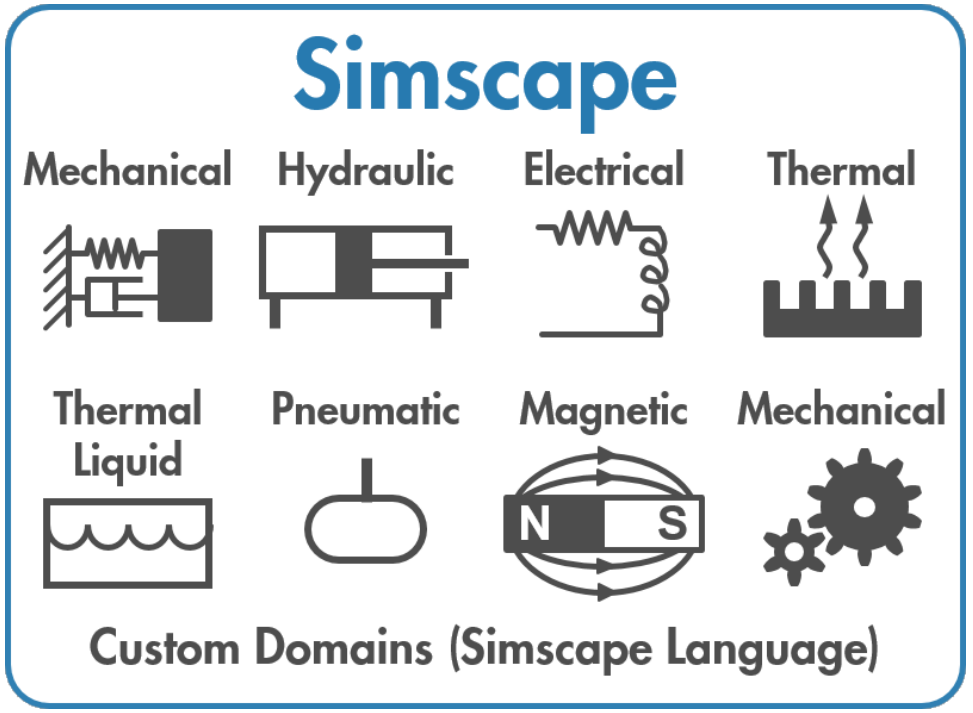




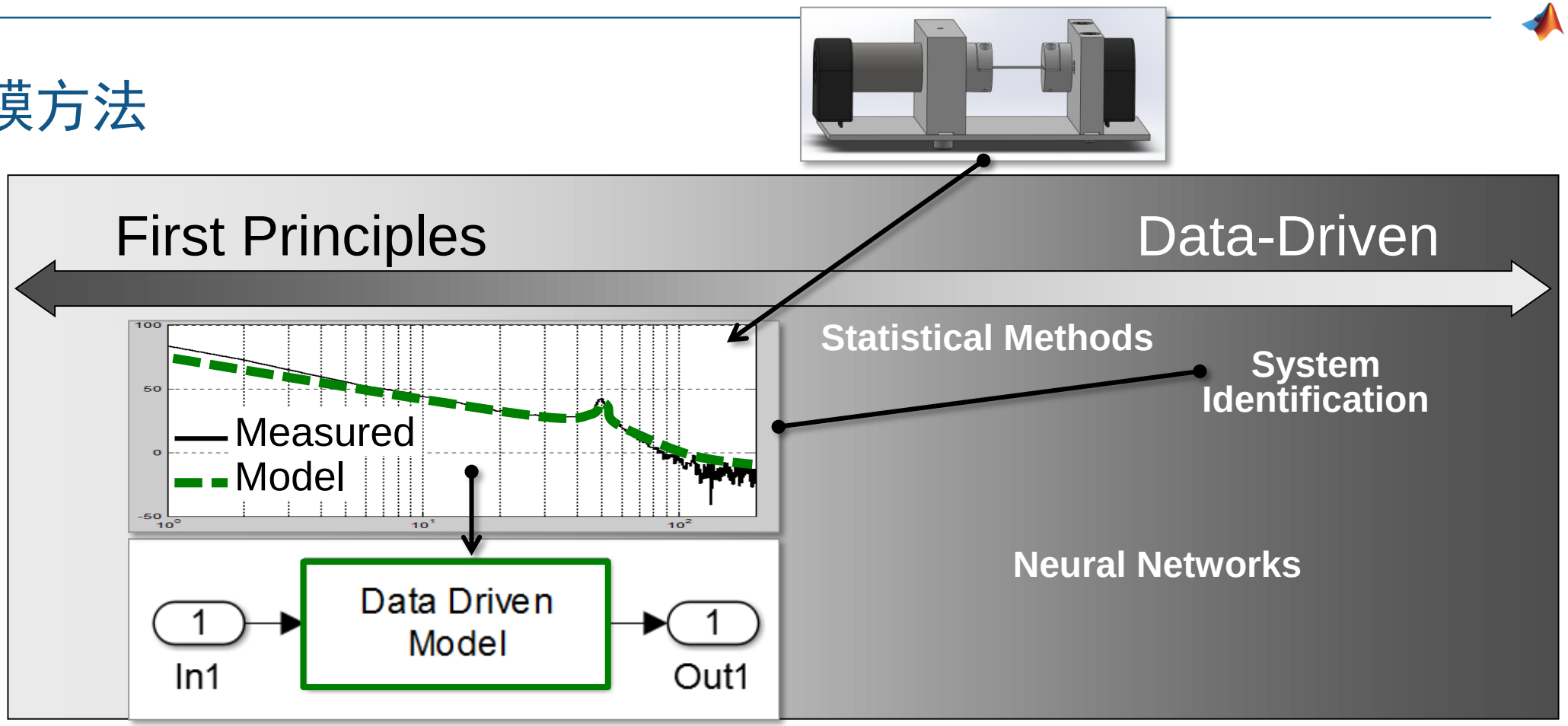
Simscape

- Simscape Power Systems
  - Three-phase electrical networks
- Simscape Electronics
  - Actuators, sensors, and semiconductors
- Simscape Fluids
  - Pumps, actuators, pipelines, valves, tanks
- Simscape Multibody
  - Multibody systems: joints, bodies, frames
- Simscape Driveline
  - Gears, leadscrew, clutches, tires, engines



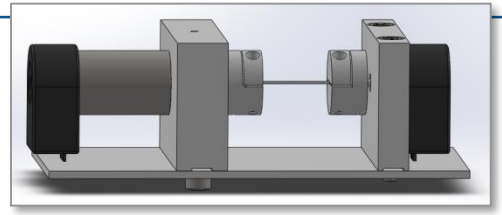


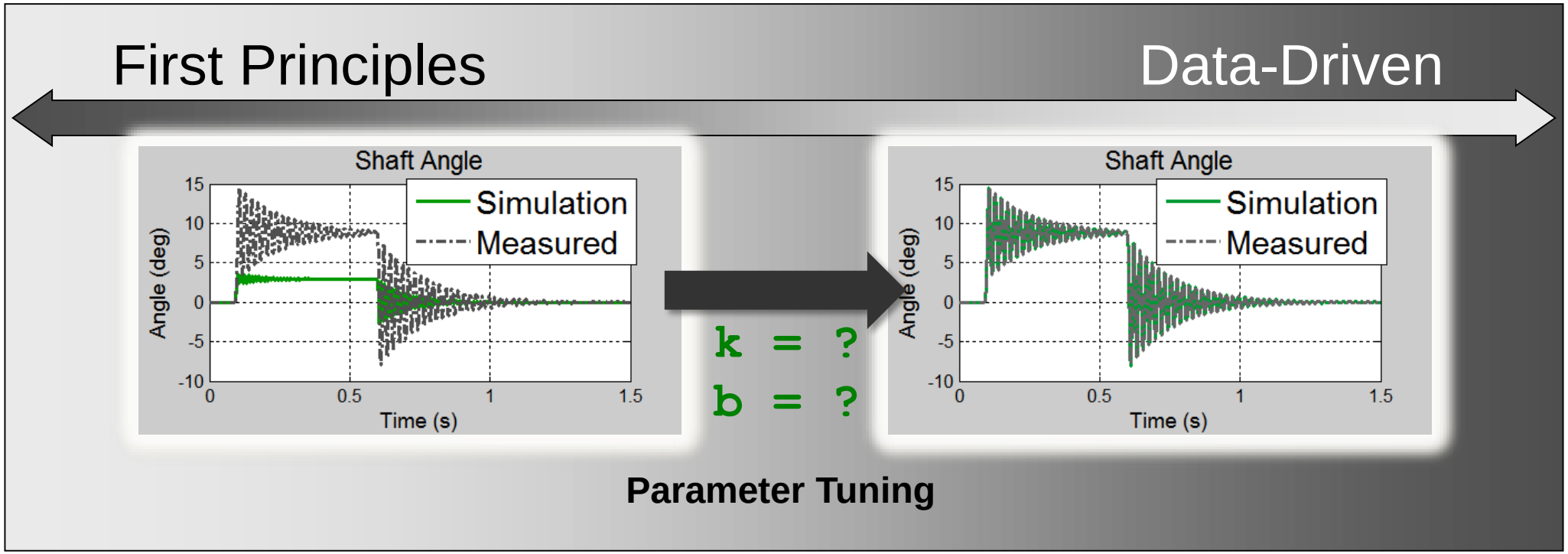
建模方法



- 目的: 模拟现有的设计 (真实或虚拟的)
- 需求:
  - 可以获得相关的测量数据
  - 设计和物理参数不会改变

建模方法

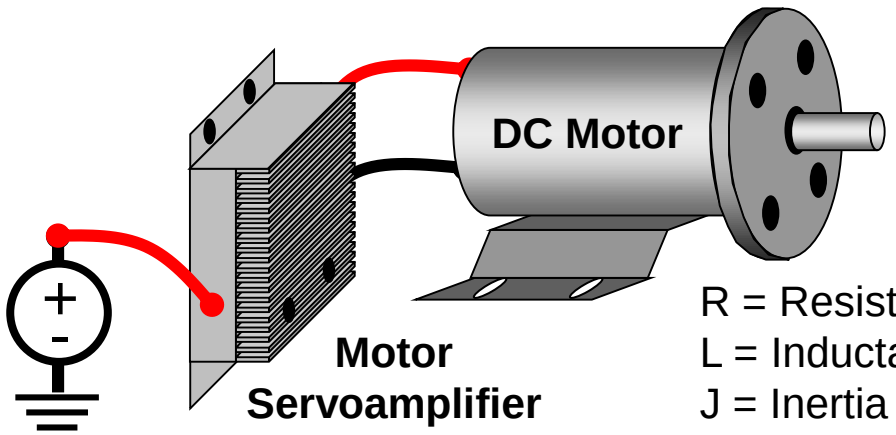




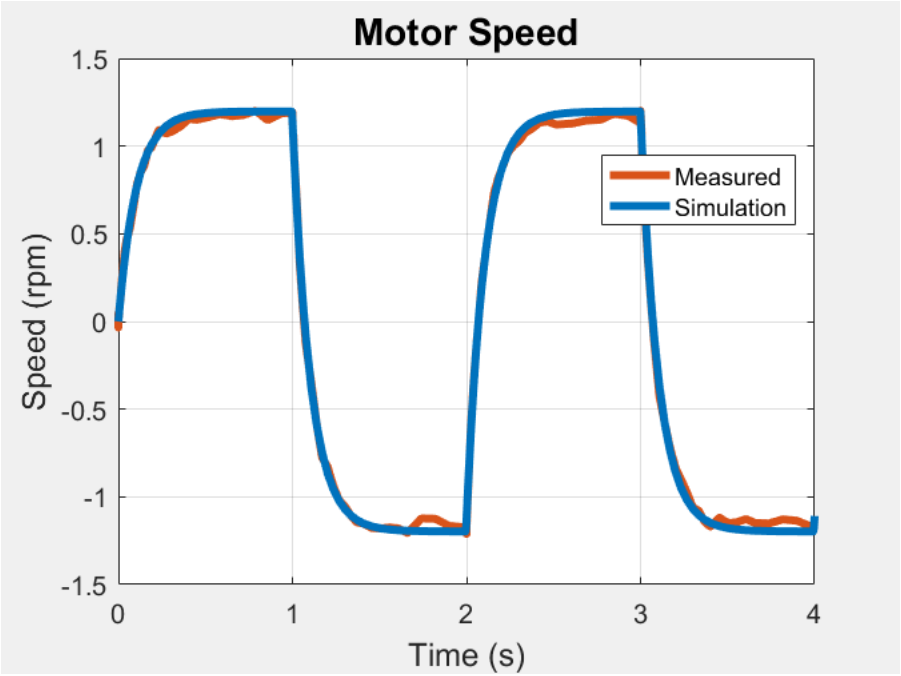
- 目的: 确保参数值是精确的
- 需求:
  - 相关的测量数据可以获
  - 具有物理意义的参数可以自动调节

使用测量数据辨识系统参数

Model:



R = Resistance
L = Inductance
J = Inertia
B = Friction
K = Back EMF Constant



Problem: Simulation results
do not match measured data
because model parameters are incorrect

Solution: Use Simulink Design Optimization
to automatically tune model parameters

R	L	J	K	B
4.03	1e-4	0.11	0.45	1.07

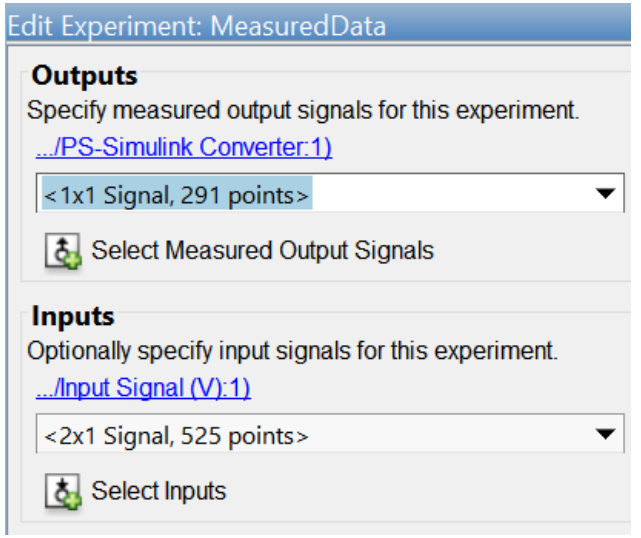
使用测量数据辨识系统参数

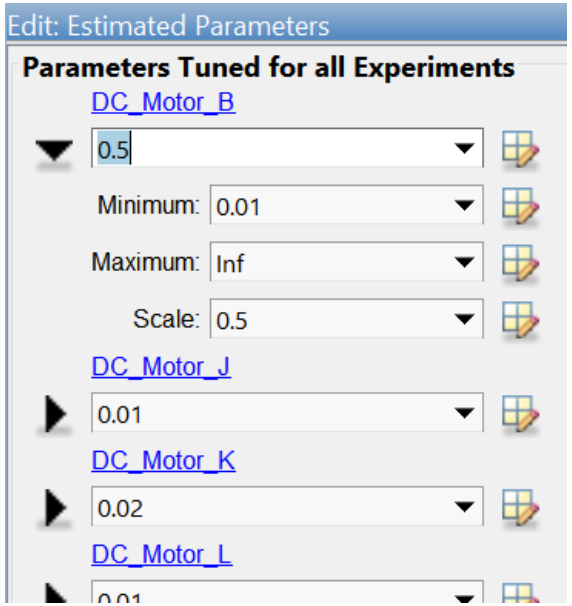
- 参数辨识步骤

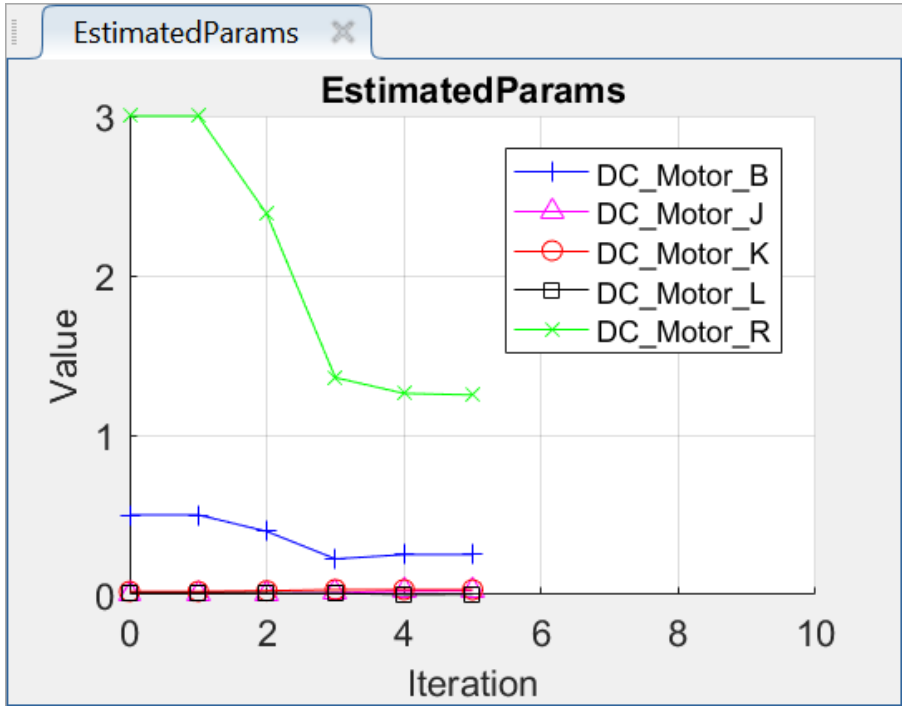
1. 导入测量数据并选择评估数据

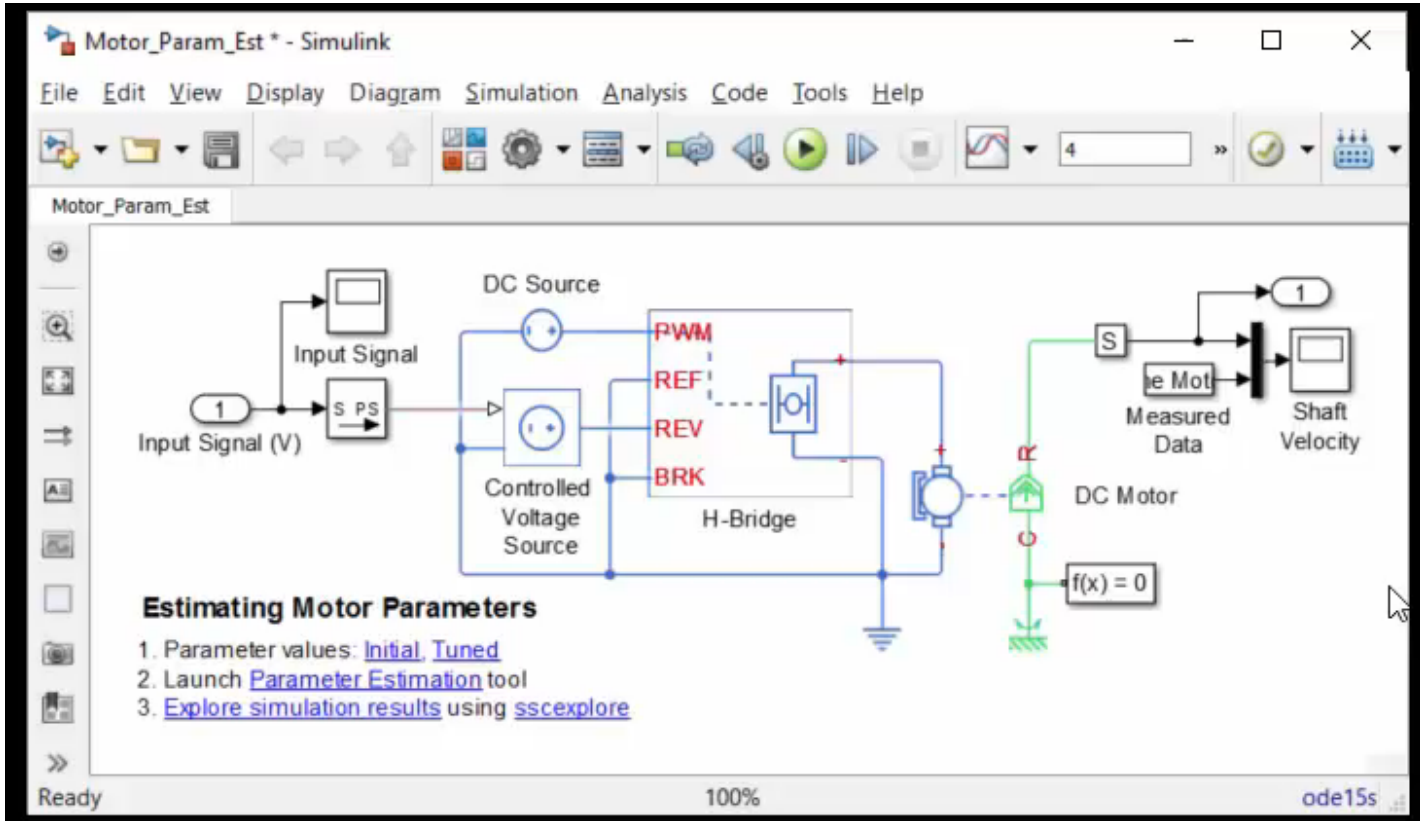
2.指定参数和数据范围

3.执行参数估计

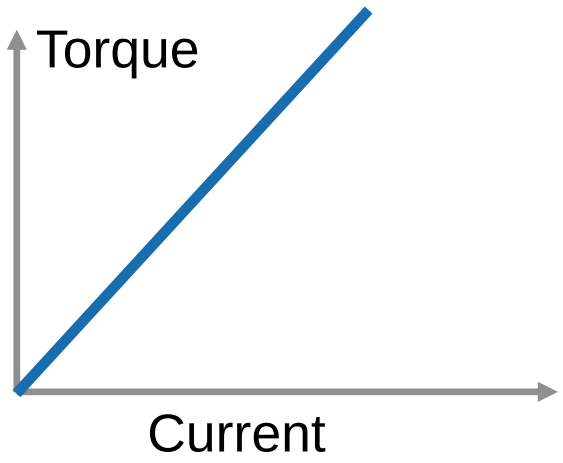




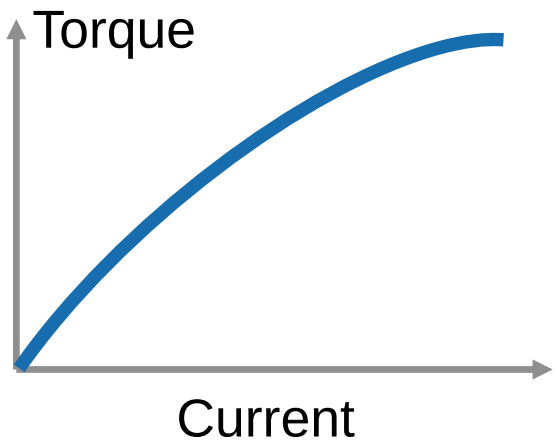



Motor_Param_Est * - Simulink
File Edit View Display Diagram Simulation Analysis Code Tools Help
Motor_Param_Est
DC Source
Input Signal
Input Signal (V)
PWM
REF
REV
BRK
Controlled Voltage Source
H-Bridge
DC Motor
Measured Data
Shaft Velocity
f(x) = 0
Estimating Motor Parameters
1. Parameter values: Initial, Tuned
2. Launch Parameter Estimation tool
3. Explore simulation results using sscexplore
Ready
100%
ode15s

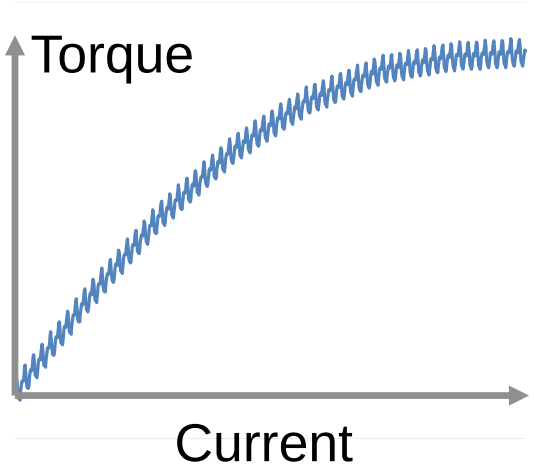
- 三种逼真度的永磁同步电机模型



集总参数模型

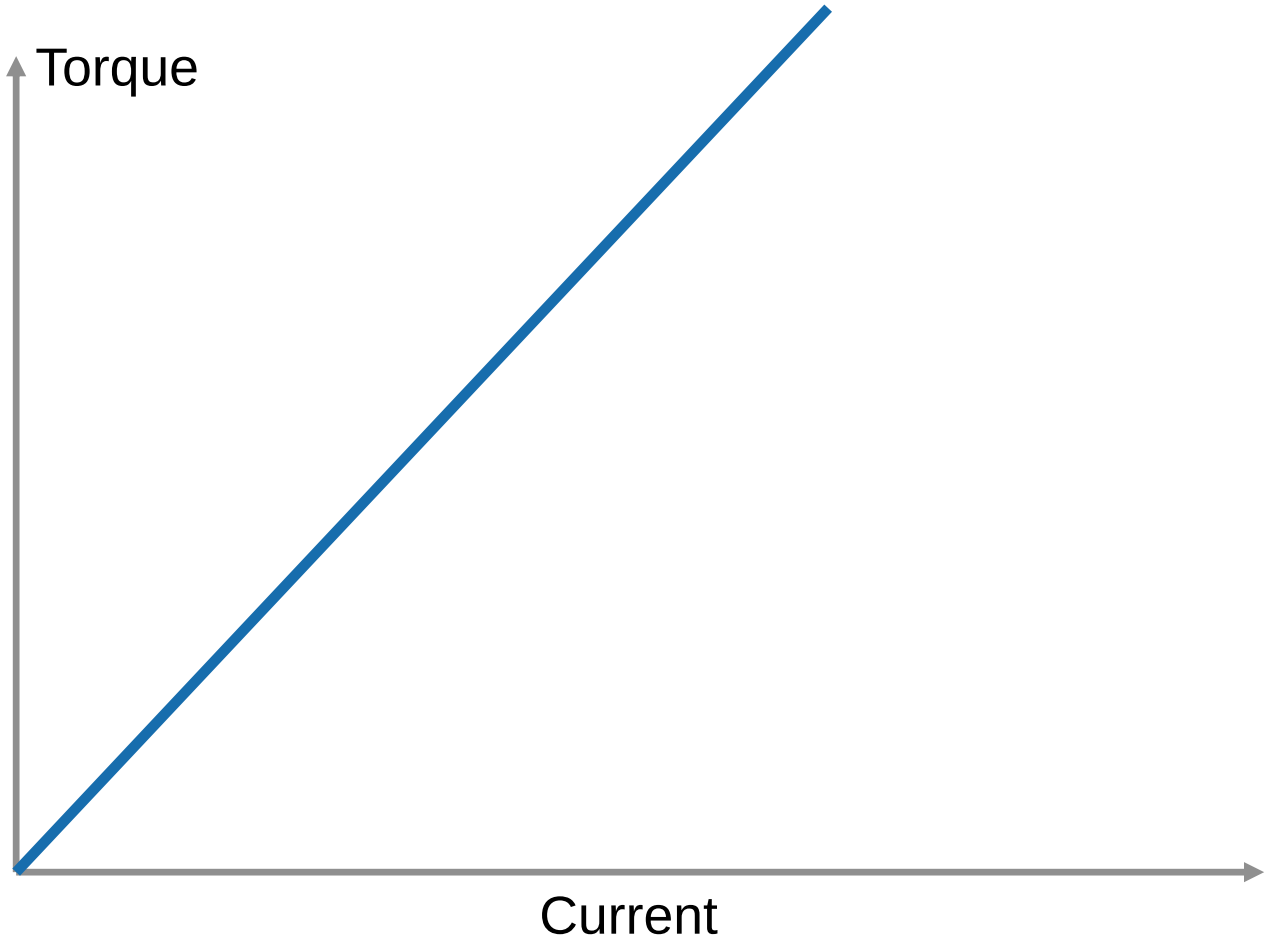


饱和模型



饱和空间谐波模型

集总参数模型



需要的参数

Electrical Model

$$v_d = Ri_d - L_q p\omega_r i_q + L_d \frac{d}{dt} i_d$$

$$v_q = Ri_q + p\omega_r (L_d i_d + \lambda) + L_q \frac{d}{dt} i_q$$

$$\omega_e = p\omega_r$$

$$T_e = 1.5p\left[\lambda i_q + (L_d - L_q) i_d i_q\right]$$

$$T_e = K_t i_q \ (assumes\ round\ rotor, L_d = L_q)$$

Mechanical Model

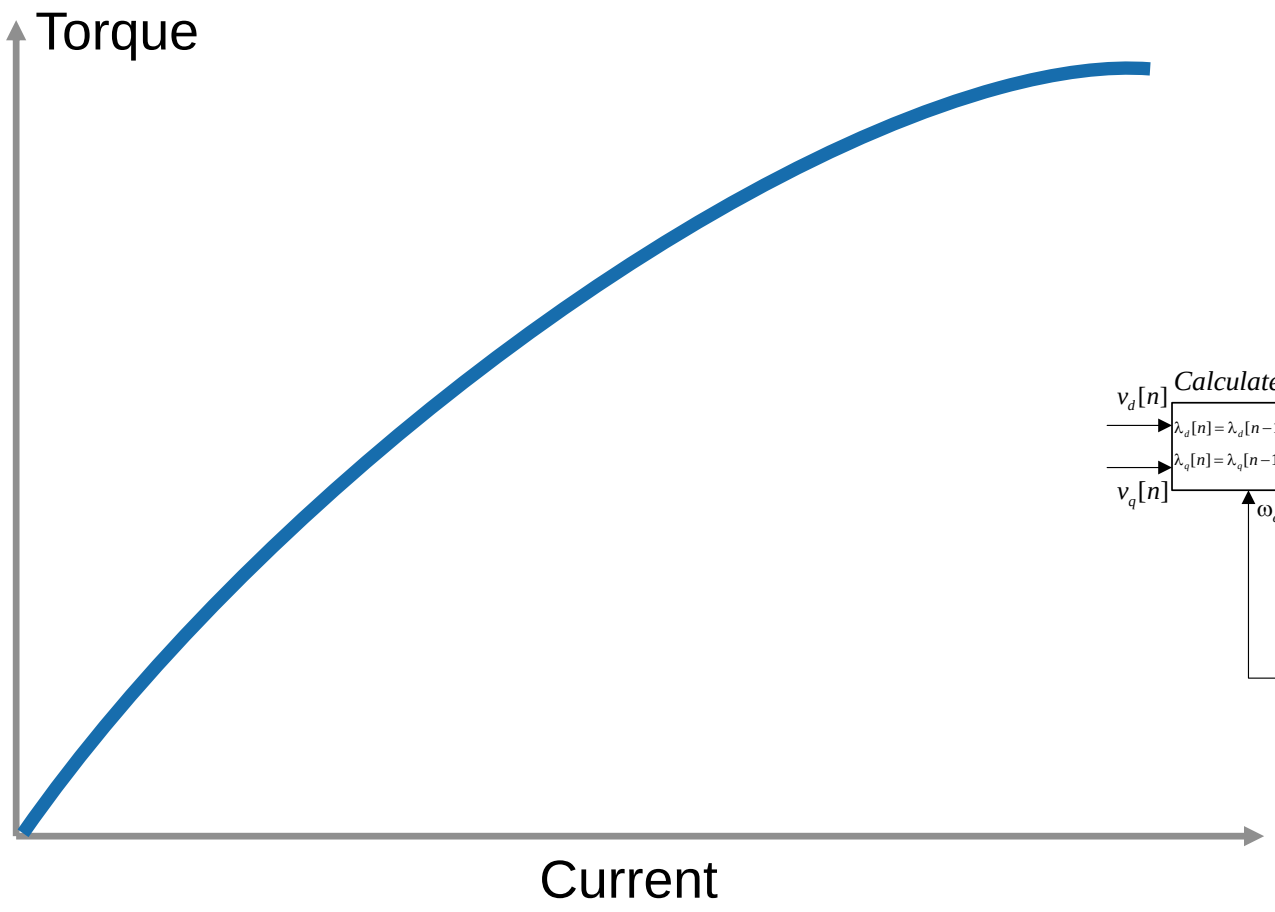
$$\frac{d}{dt}\omega_r = \frac{1}{J}(T_e - sgn(\omega_r) J_0 - b\omega_r - T_{load})$$

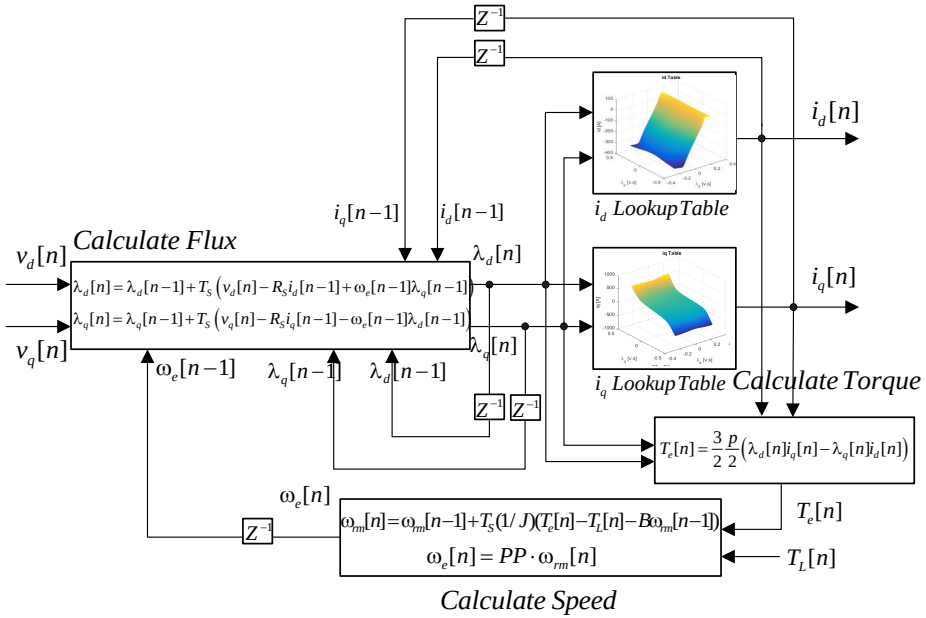
如何获得这些参数

电机测试	参数识别	识别方法
Back EMF Test	Number of Pole Pairs (p) Flux Linkage Constant (λ) Torque Constant (K_t)	Calculation
Friction Test	Viscous Damping Coefficient (b) Coulomb Friction (J_0)	Curve fitting
Coast Down Test	Rotor Inertia (J)	Curve fitting
DC Voltage Step Test	Resistance (R) Inductance (L)	Parameter estimation

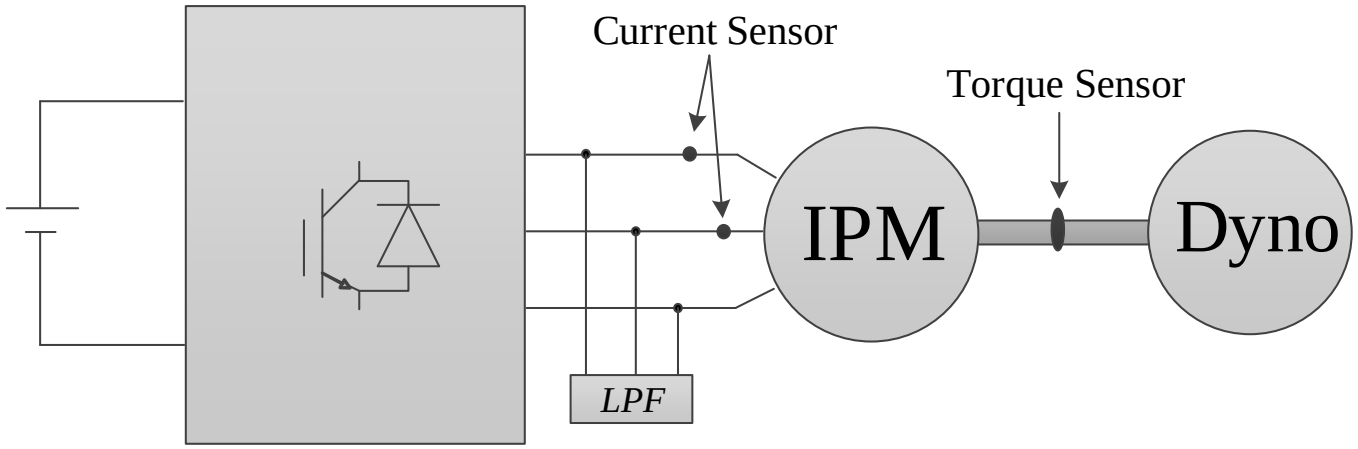
https://www.mathworks.com/company/newsletters/articles/creating-a-high-fidelity-model-of-an-electric-motor-for-control-system-design-and-verification.html

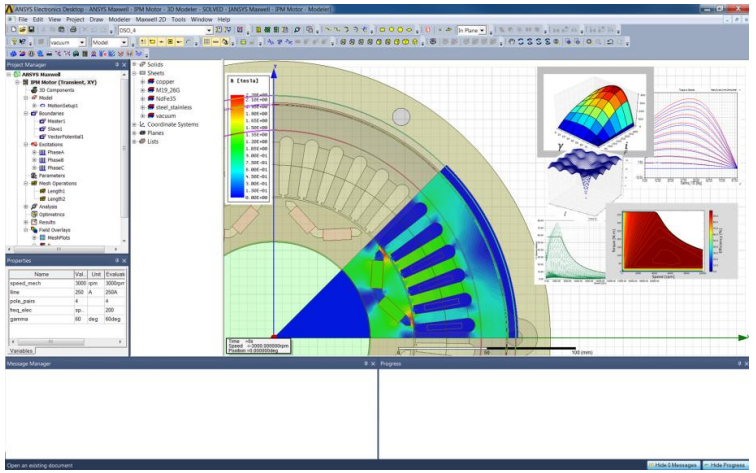
饱和模型


Torque
Current


Calculate Flux
$v_d[n]$
$v_q[n]$
$\lambda_d[n]=\lambda_d[n-1]+T_S\left(v_d[n]-R_S i_d[n-1]+\omega_e[n-1]\lambda_q[n-1]\right)$
$\lambda_q[n]=\lambda_q[n-1]+T_S\left(v_q[n]-R_S i_q[n-1]-\omega_e[n-1]\lambda_d[n-1]\right)$
$\lambda_d[n]$
$\lambda_q[n]$
$i_q[n-1]$
$i_d[n-1]$
$\omega_e[n-1]$
$\lambda_q[n-1]$
$\lambda_d[n-1]$
Z^{-1}
i_d Lookup Table
i_q Lookup Table
$i_d[n]$
$i_q[n]$
Calculate Torque
$T_e[n]=\frac{3}{2}\frac{p}{2}\left(\lambda_d[n]i_q[n]-\lambda_q[n]i_d[n]\right)$
$\omega_e[n]$
$\omega_m[n]=\omega_m[n-1]+T_S(1/J)(T_e[n]-T_L[n]-B\omega_m[n-1])$
$\omega_e[n]=PP\cdot\omega_{rm}[n]$
$T_e[n]$
$T_L[n]$
Calculate Speed

两种方式获得饱和模型

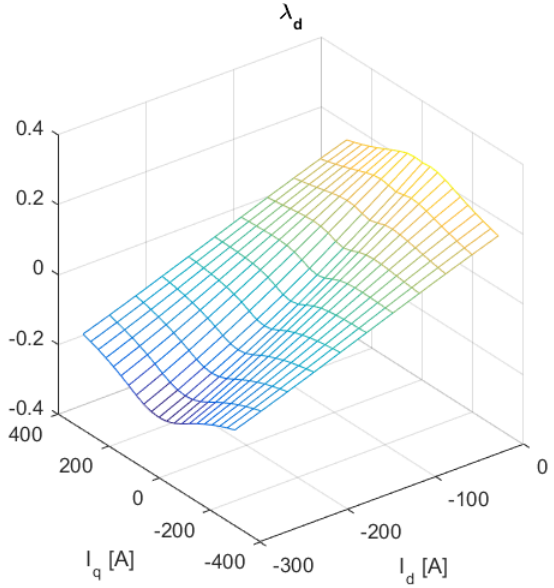


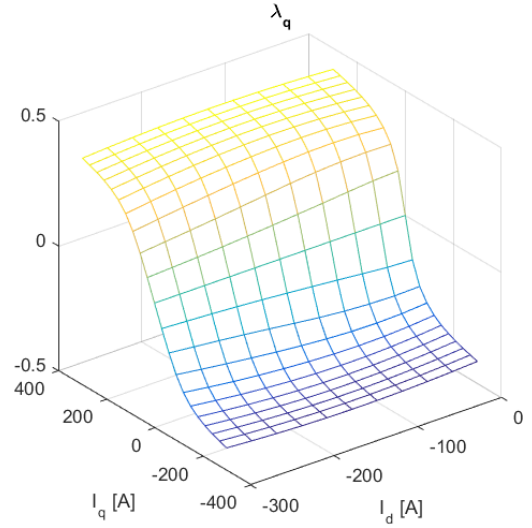


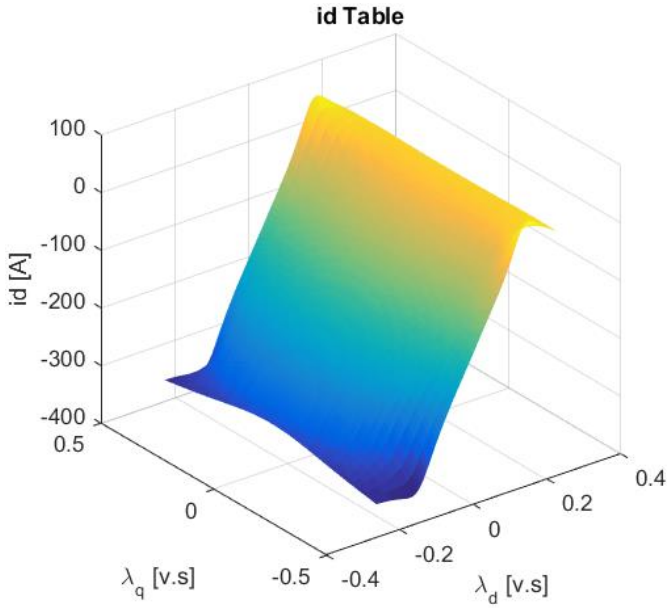
Dyno testing

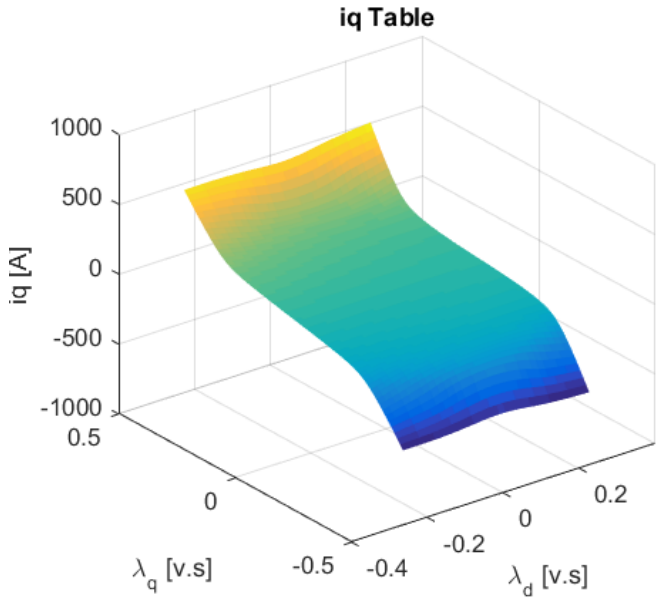
FEA

非线性通量和电流表

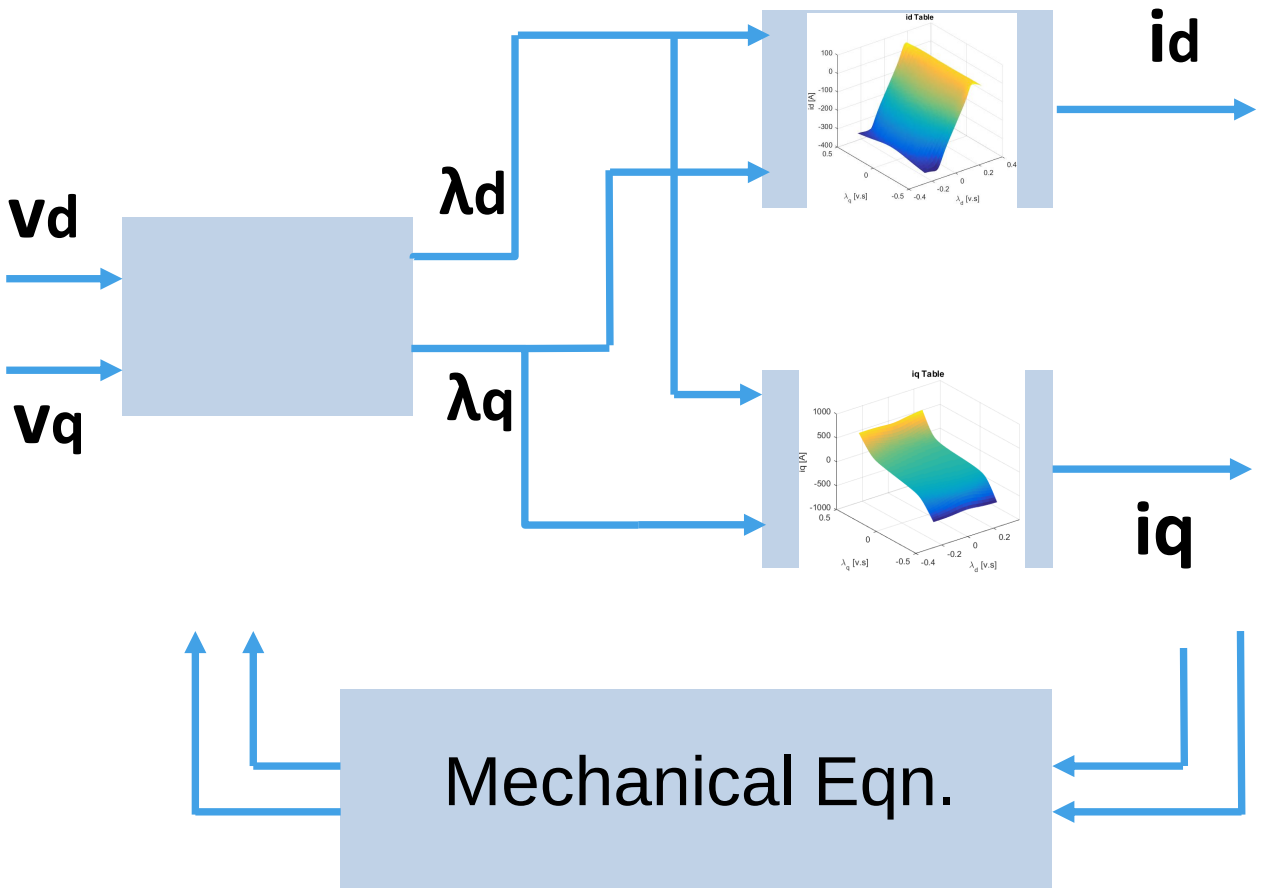

λ_d
0.4
0.2
0
-0.2
-0.4
400
200
0
-200
-400
I_q [A]
0
-100
-200
-300
I_d [A]

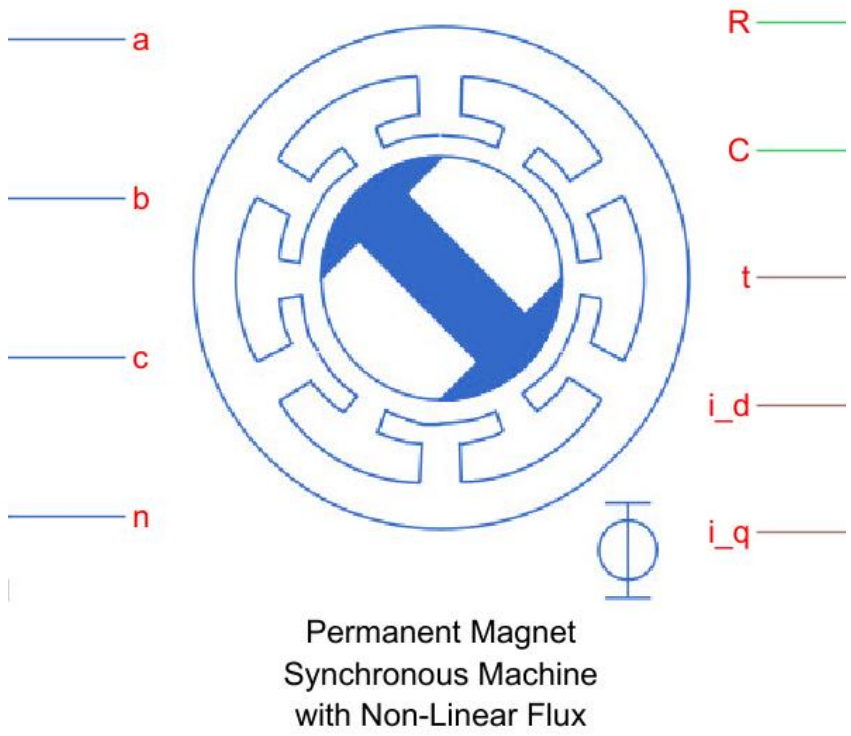

λ_q
0.5
0
-0.5
400
200
0
-200
-400
I_q [A]
0
-100
-200
-300
I_d [A]


id Table
100
0
-100
-200
-300
-400
id [A]
0.5
0
-0.5
λ_q [v.s]
-0.4
-0.2
0
0.2
0.4
λ_d [v.s]

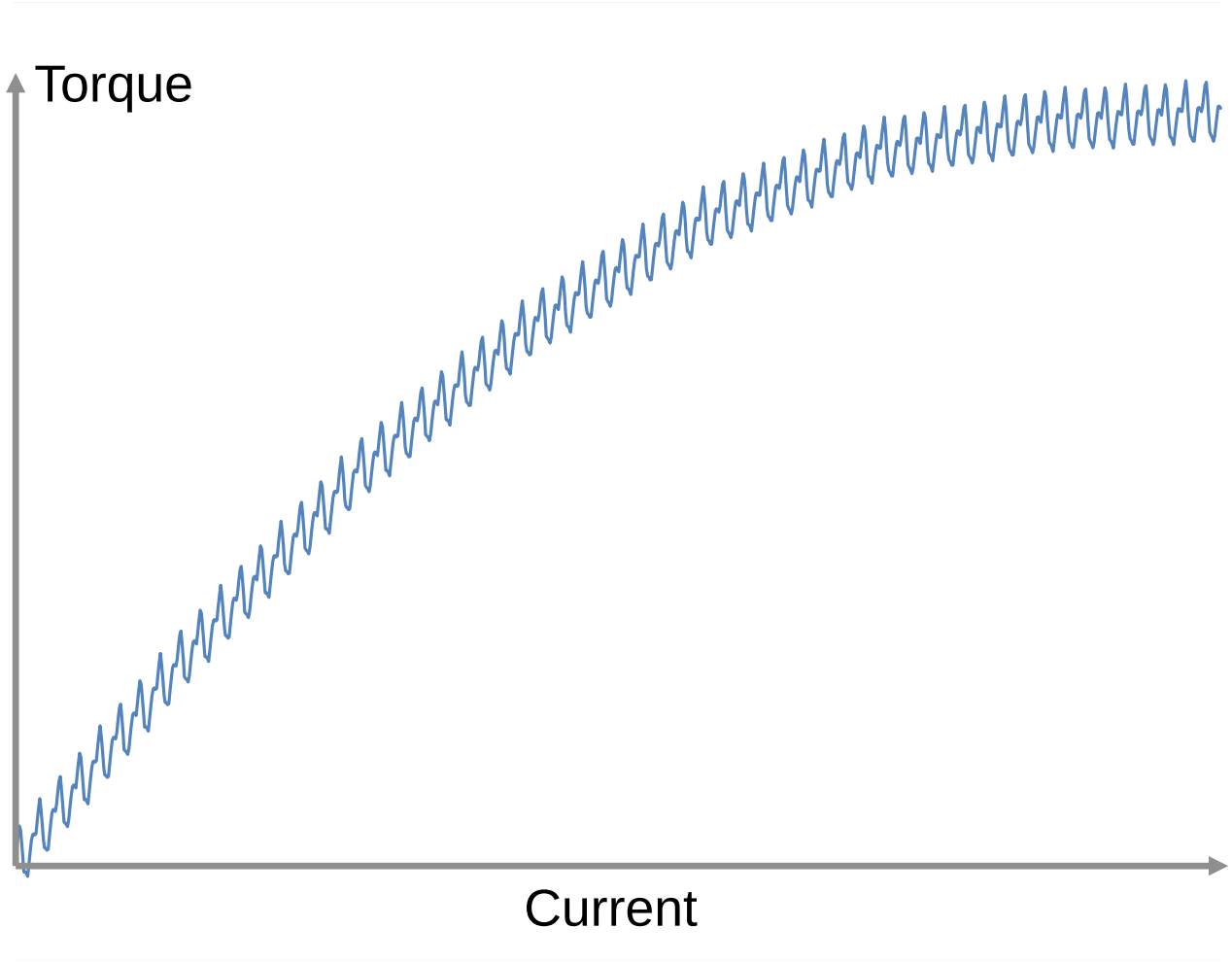

iq Table
1000
500
0
-500
-1000
iq [A]
0.5
0
-0.5
λ_q [v.s]
-0.4
-0.2
0
0.2
λ_d [v.s]

Simscape中的饱和PMSM模型

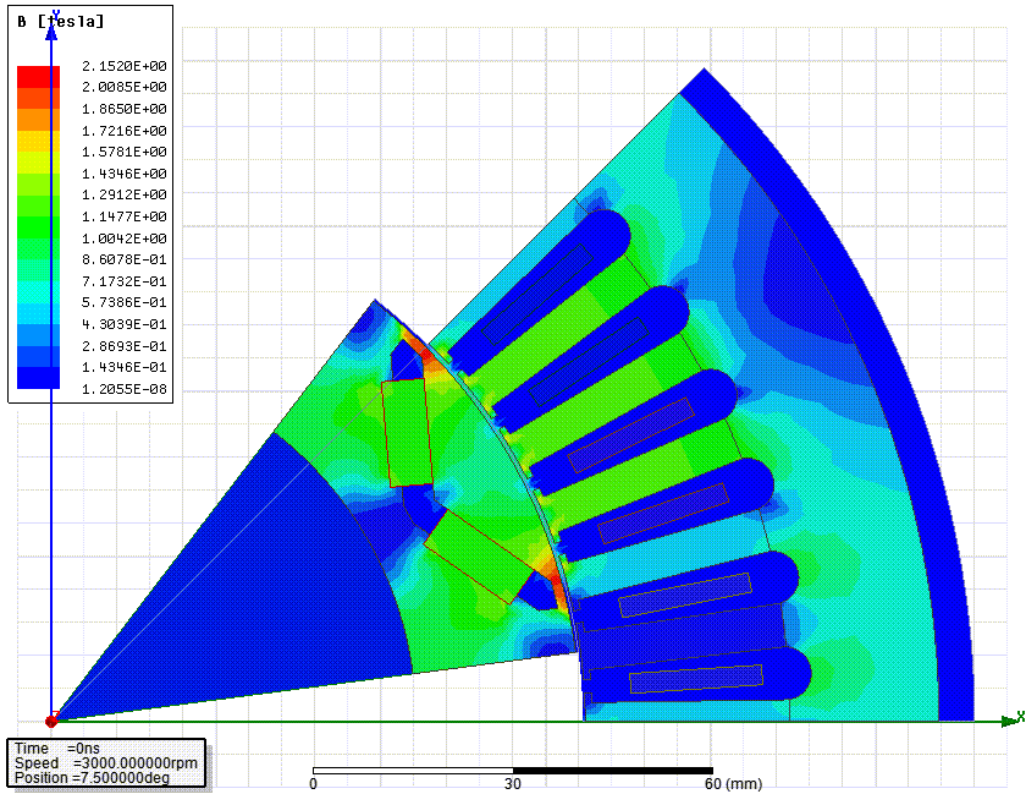


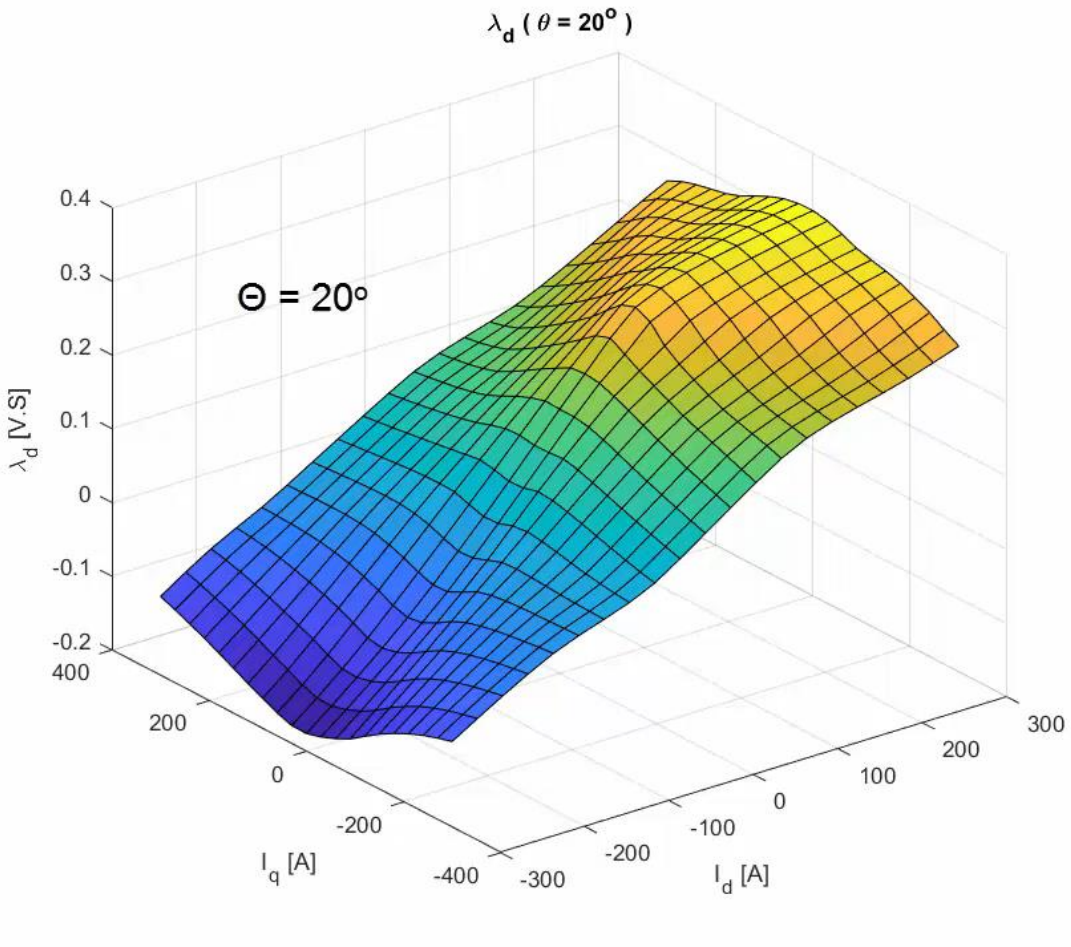


饱和空间谐波模型



转子位置的关系



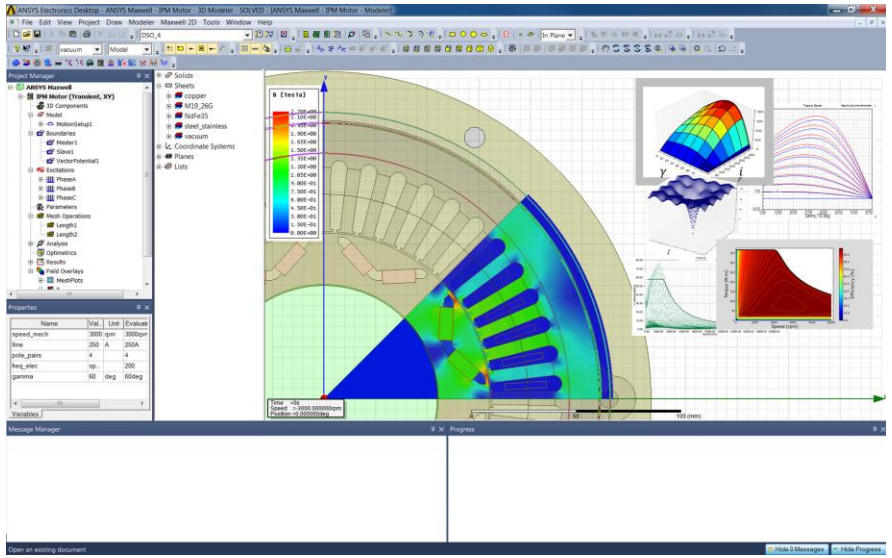


Animation: flux variation at different rotor position

如何获得饱和和空间谐波数据

Current

Rotor Position

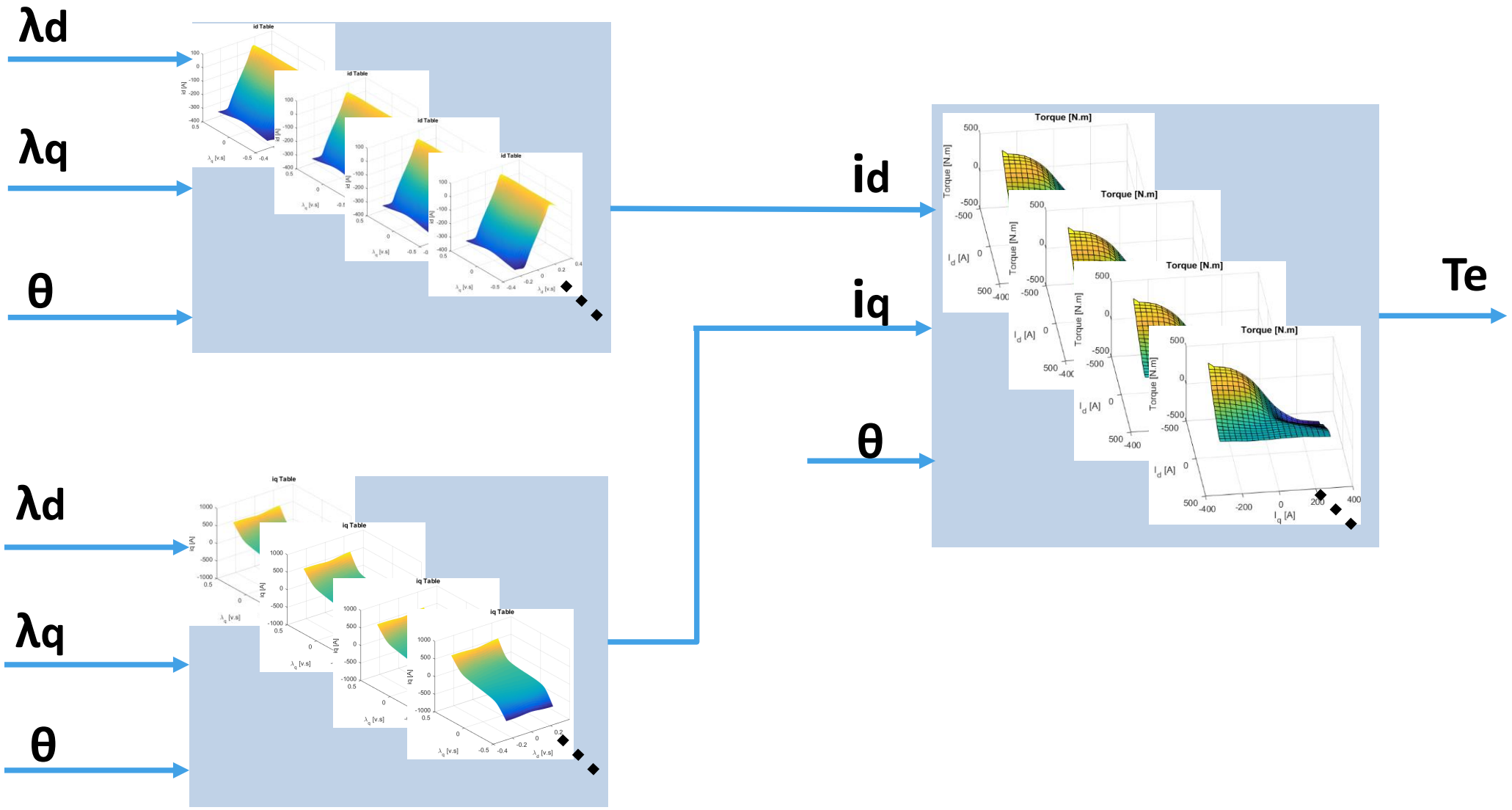


Flux Linkage

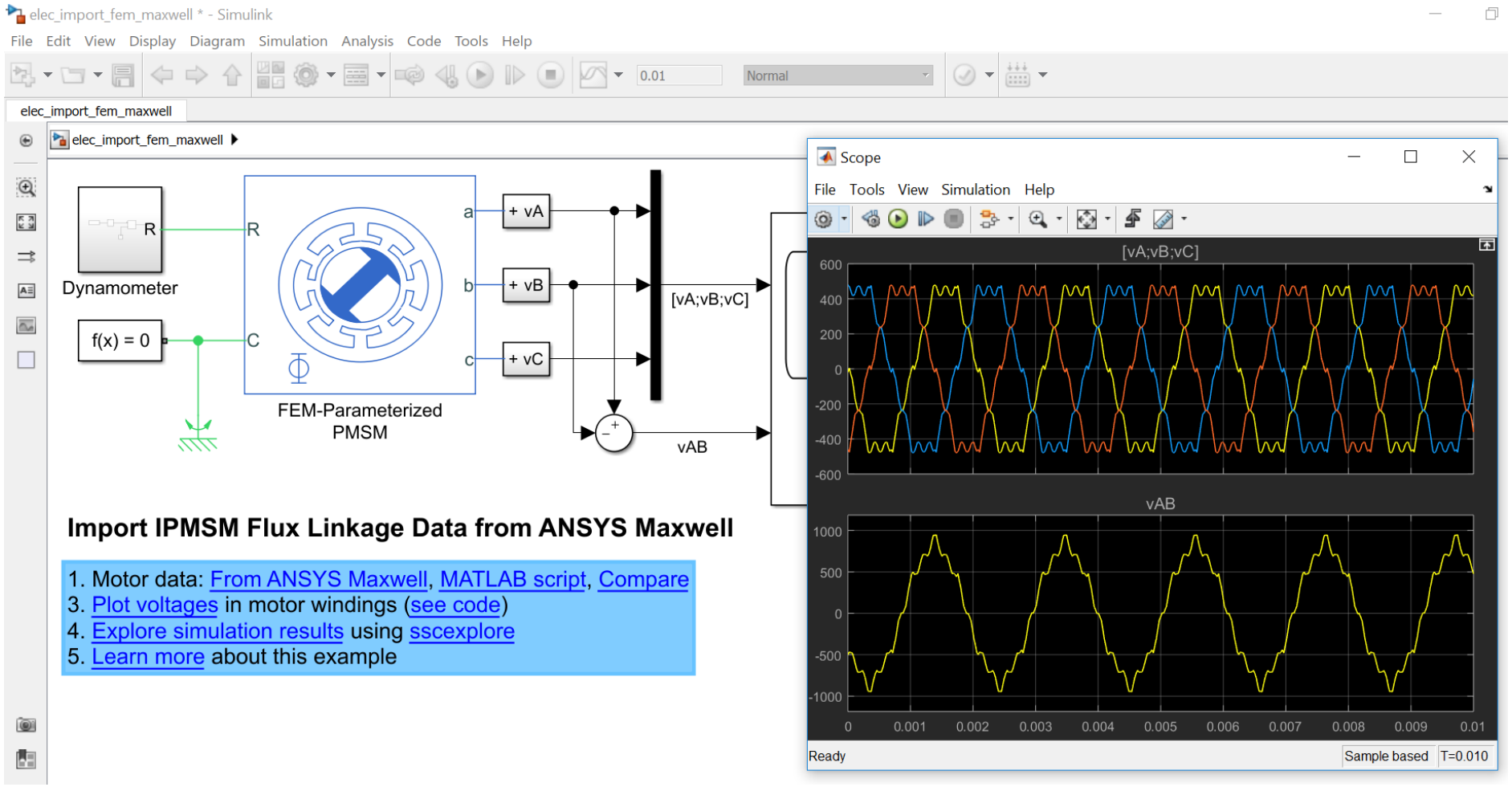
Torque

Sweep in FEA Tool

Simulink中饱和和空间谐波模型的结构



Simulink中饱和和空间谐波模型的结构

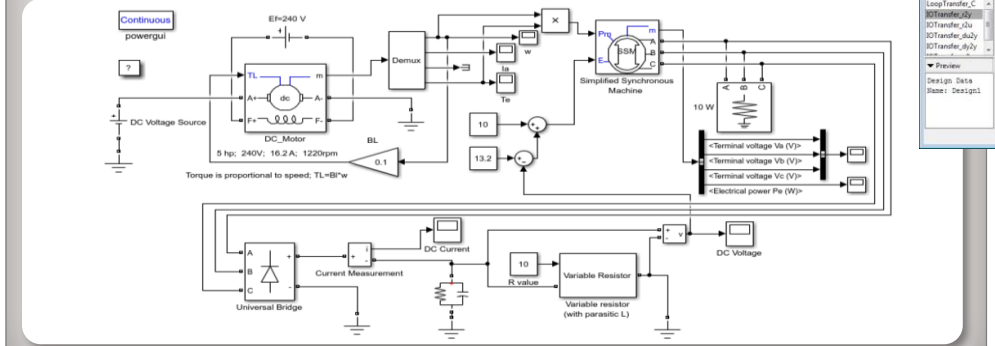


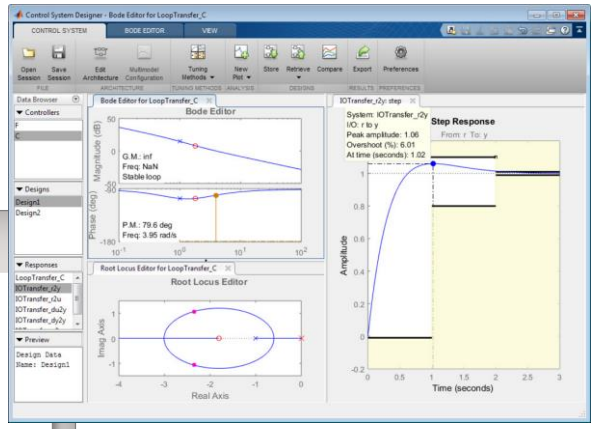
Demo: elec_import_fem_maxwell

快速设计先进控制算法

RESEARCH
MATLAB Algorithms

DESIGN

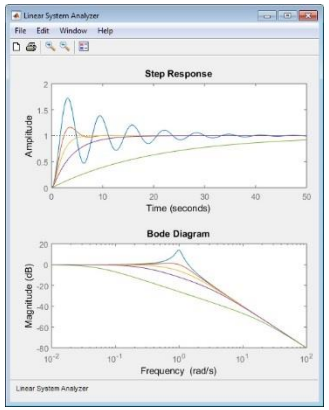


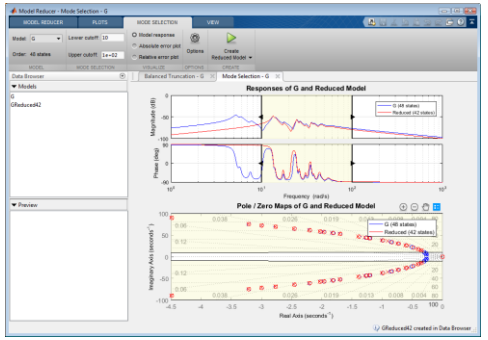


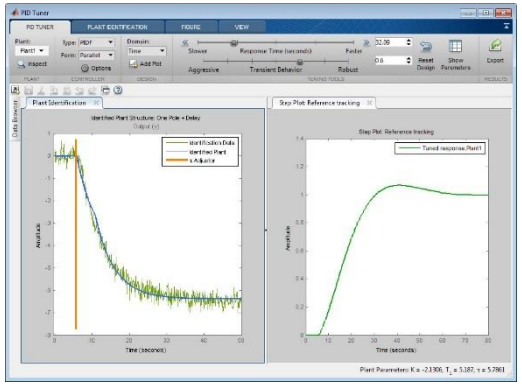
- 在MATLAB环境中开发控制算法
- 使用Simulink框图搭建模型仿真系统行为
- 细化特定物理域模型优化系统
- 重用CAE工具的设计和工程数据，比如 CAD, FEA 和 SPICE模型
- 链接需求到设计
- 通过运行仿真持续验证设计是否满足需求

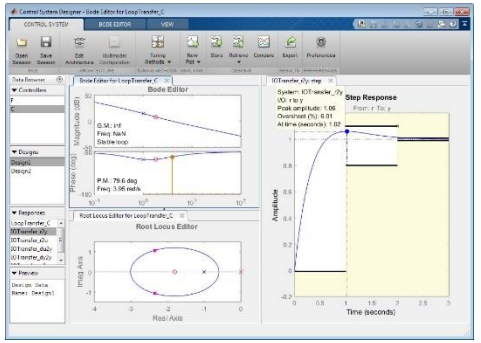
控制系统工具箱

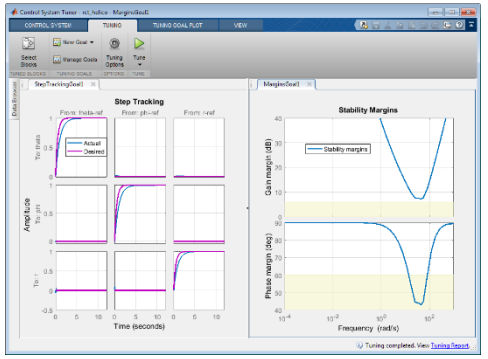
- 使用算法和应用程序进行分析、设计并调节控制系统
- 创建、操作并分析线性模型
- 设计并调节SISO 和 MIMO控制器





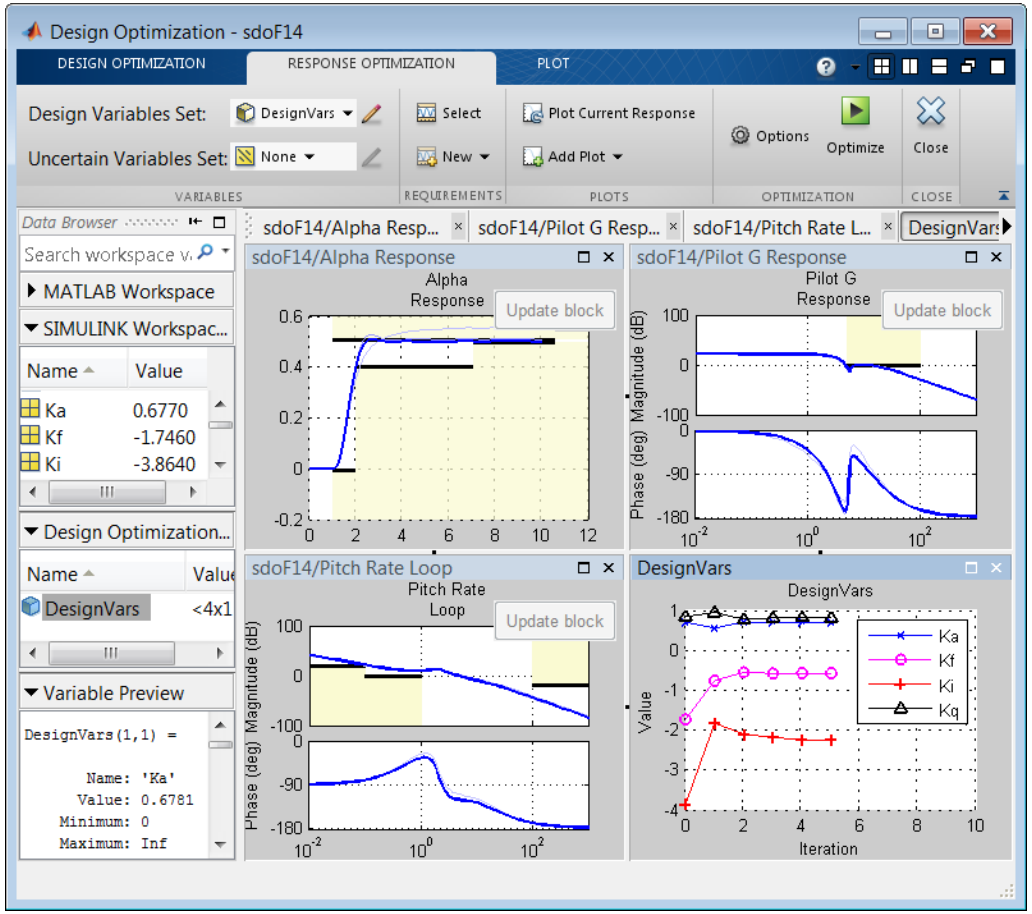


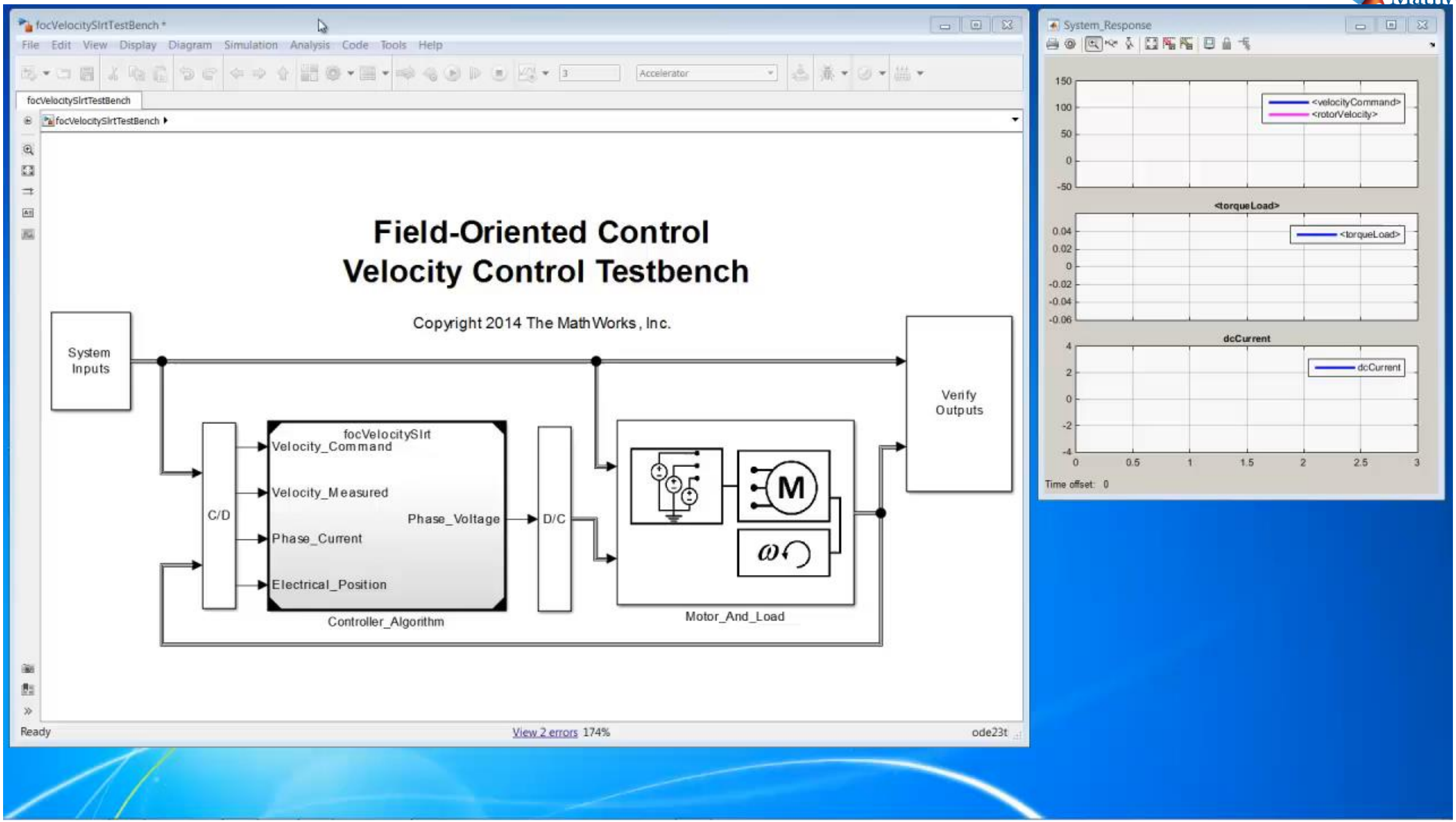




优化Simulink模型的时域和频域响应

- 通过图形画出期望的响应或输入数值来指定期望的行为
- 指定频域需求：
  - 幅值的上下限
  - 增益和相位裕度的边界
  - 自然频率和阻尼系数的边界
- 添加设计需求而不需要更改模型
- 同时优化频域和时域响应

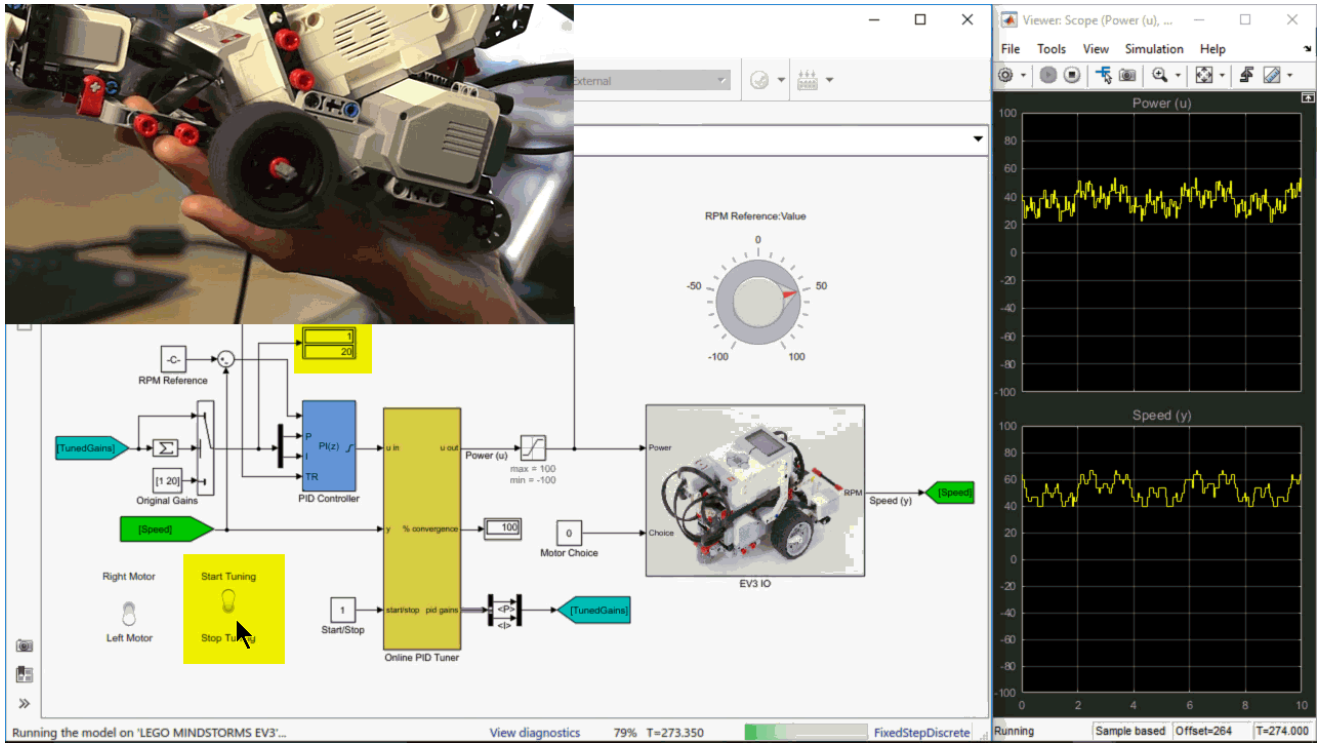



focVelocitySlrtTestBench *
File Edit View Display Diagram Simulation Analysis Code Tools Help
Accelerator
focVelocitySlrtTestBench
Field-Oriented Control
Velocity Control Testbench
Copyright 2014 The MathWorks, Inc.
System Inputs
C/D
focVelocitySlrt
Velocity_Command
Velocity_Measured
Phase_Current
Electrical_Position
Phase_Voltage
Controller_Algorithm
D/C
M
Motor_And_Load
Verify Outputs
Ready
View 2 errors 174%
ode23t
System_Response
<velocityCommand>
<rotorVelocity>
<torqueLoad>
dcCurrent
Time offset: 0

PID 实时自动调节

部署PID自动调节的算法到嵌入式软件

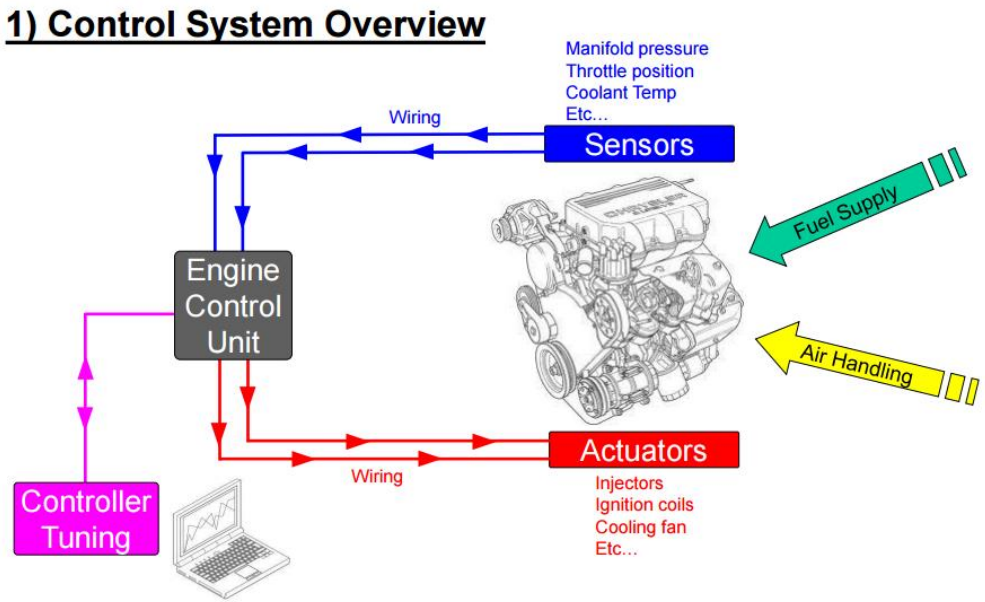
- 使用 Online PID Tuner 模块产生自动调节的代码并部署到嵌入式软件
- PID自动调节不依赖于被控对象模型
- PID自动调节产生的代码可以完全独立于Simulink使用或通过外部模式



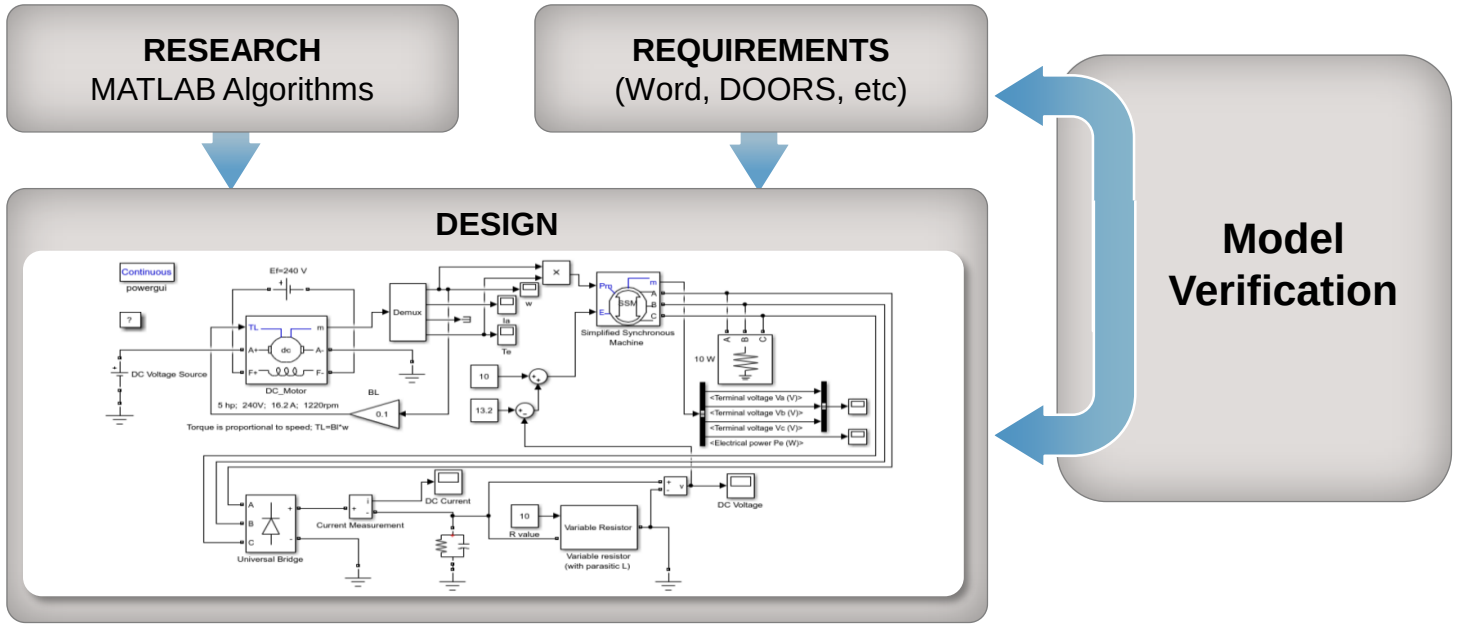
PID自动调节应用场景

- 调节运行在目标计算机上的PID，来控制安装在机器人关节上的直流电机，PC上的MATLAB/Simulink 与目标机通讯，在MATLAB/Simulink中通过外部模式调优

- 标定过程中调节运行在ECU上的PID控制器， ECU与标定平台通讯，通过平台内置的app调节PID参数



自动化测试



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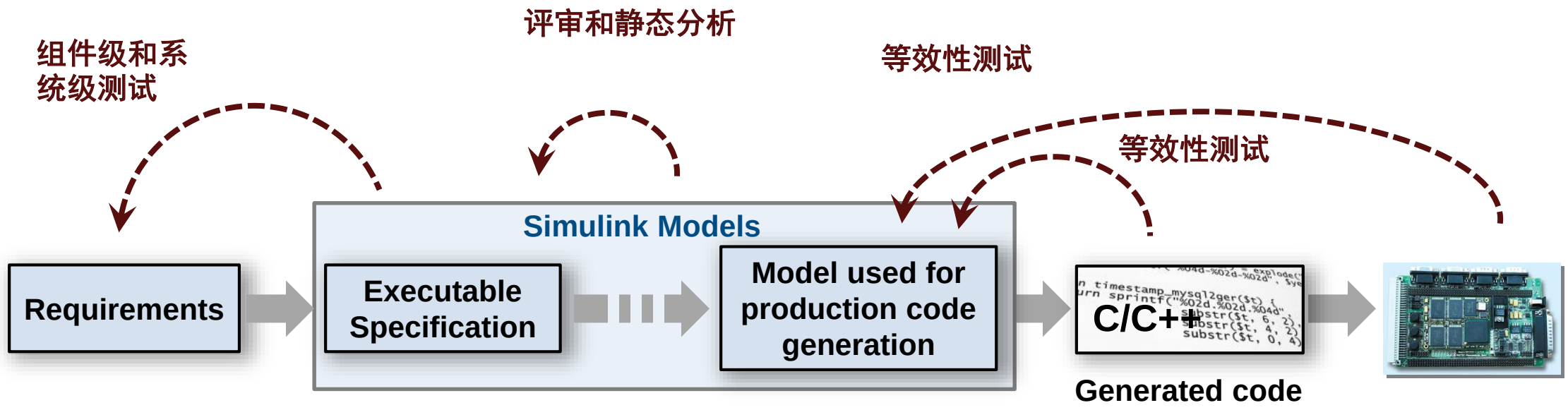
基于模型设计的验证流程

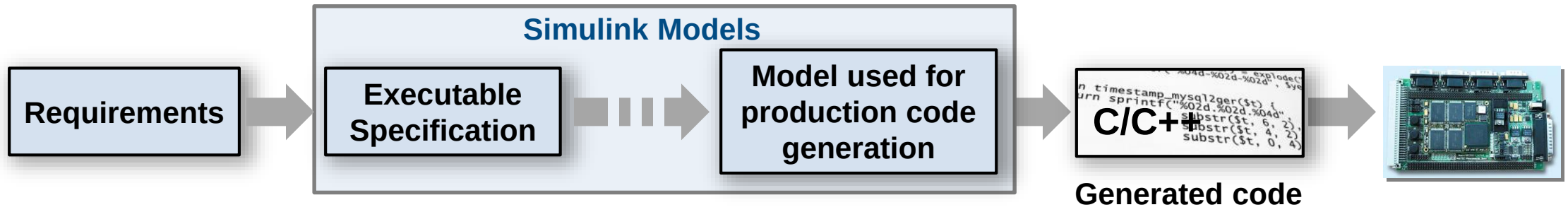


需求的挑战

需求在哪里实现?

设计和需求是否一致?

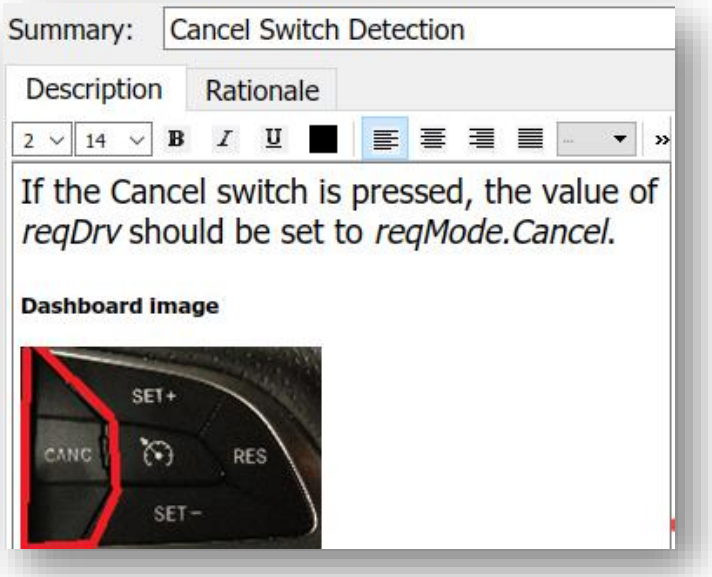
如何测试?

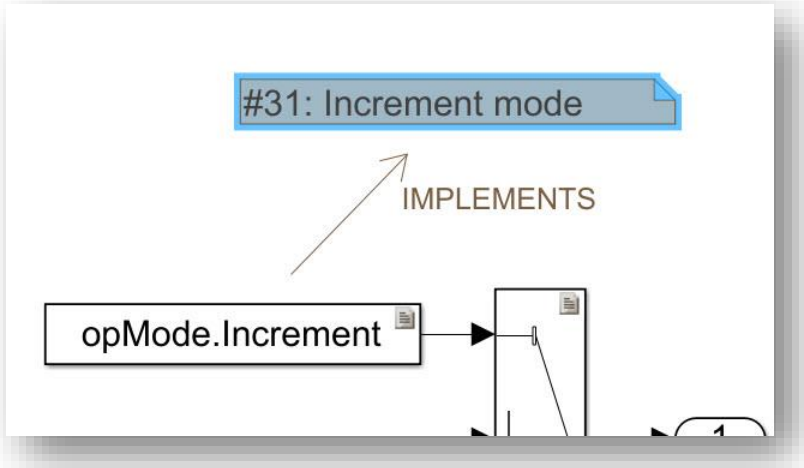


Simulink Requirements

R2017b

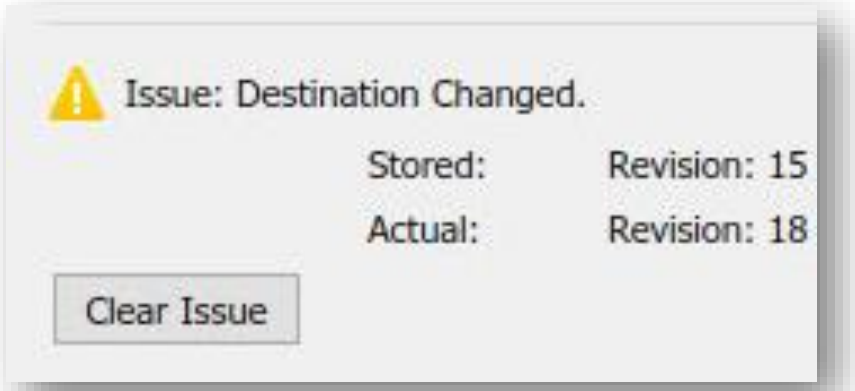
编写



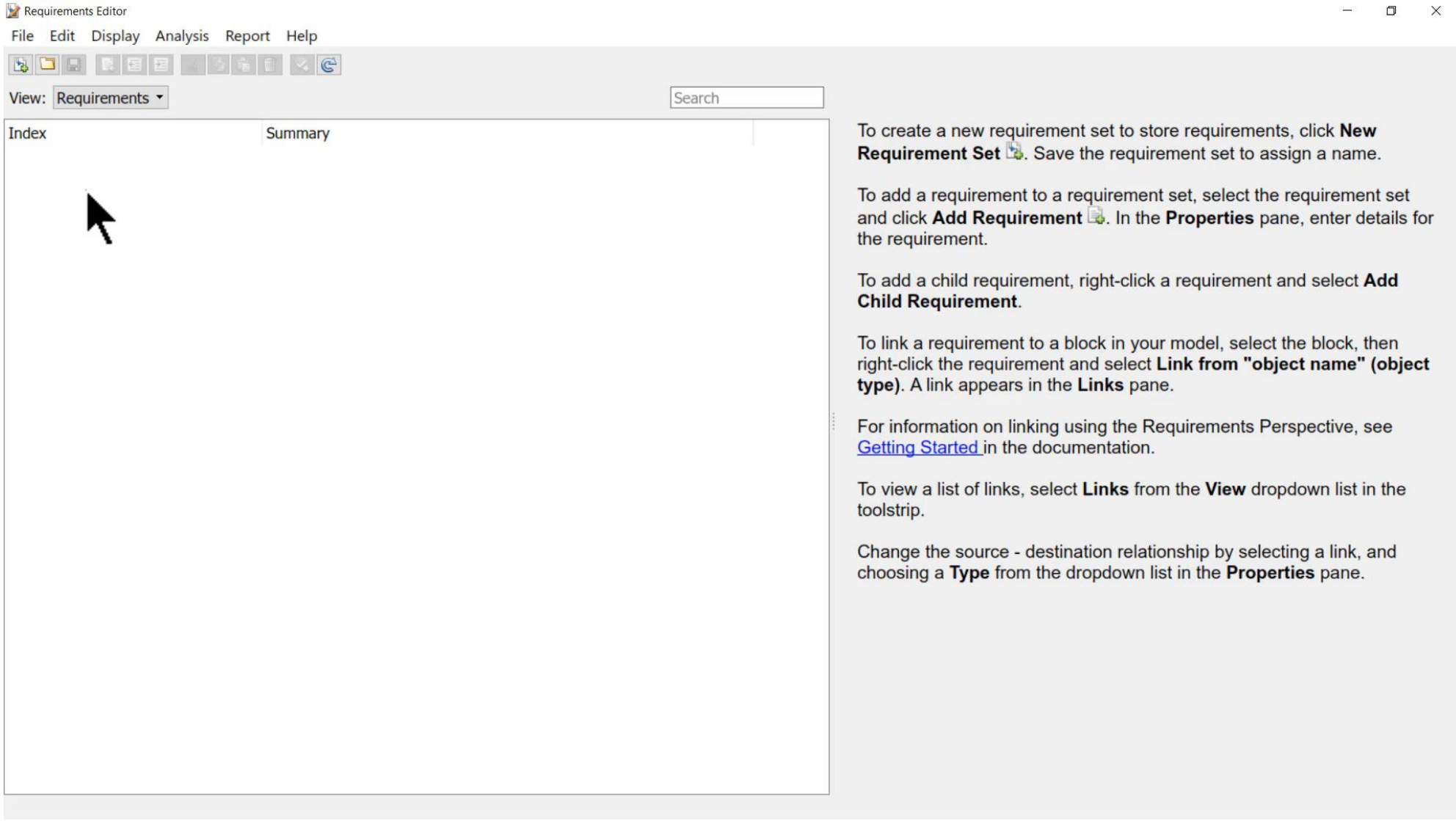


跟踪

管理



需求编辑器


Requirements Editor
File Edit Display Analysis Report Help
View: Requirements
Search
Index
Summary
To create a new requirement set to store requirements, click New Requirement Set. Save the requirement set to assign a name.
To add a requirement to a requirement set, select the requirement set and click Add Requirement. In the Properties pane, enter details for the requirement.
To add a child requirement, right-click a requirement and select Add Child Requirement.
To link a requirement to a block in your model, select the block, then right-click the requirement and select Link from "object name" (object type). A link appears in the Links pane.
For information on linking using the Requirements Perspective, see Getting Started in the documentation.
To view a list of links, select Links from the View dropdown list in the toolstrip.
Change the source - destination relationship by selecting a link, and choosing a Type from the dropdown list in the Properties pane.

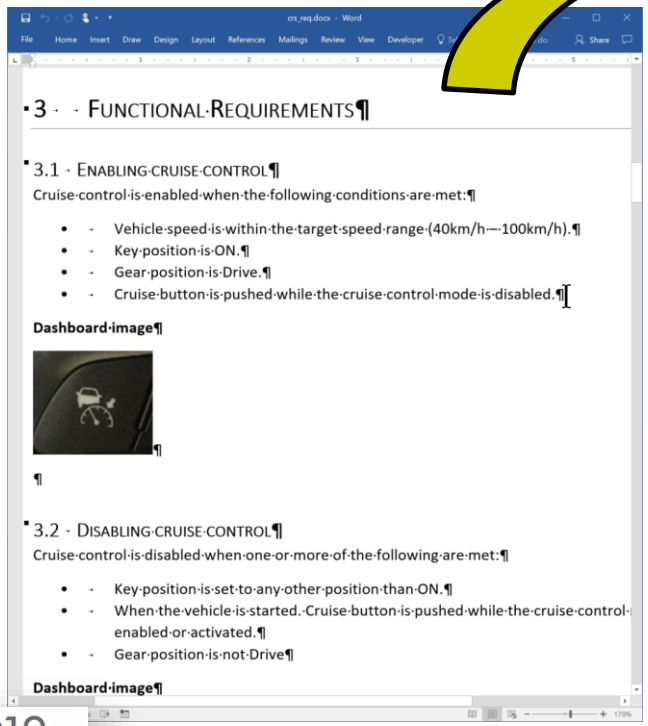
从外部导入需求

IBM Rational DOORS

ReqIF Requirements Interchange Format

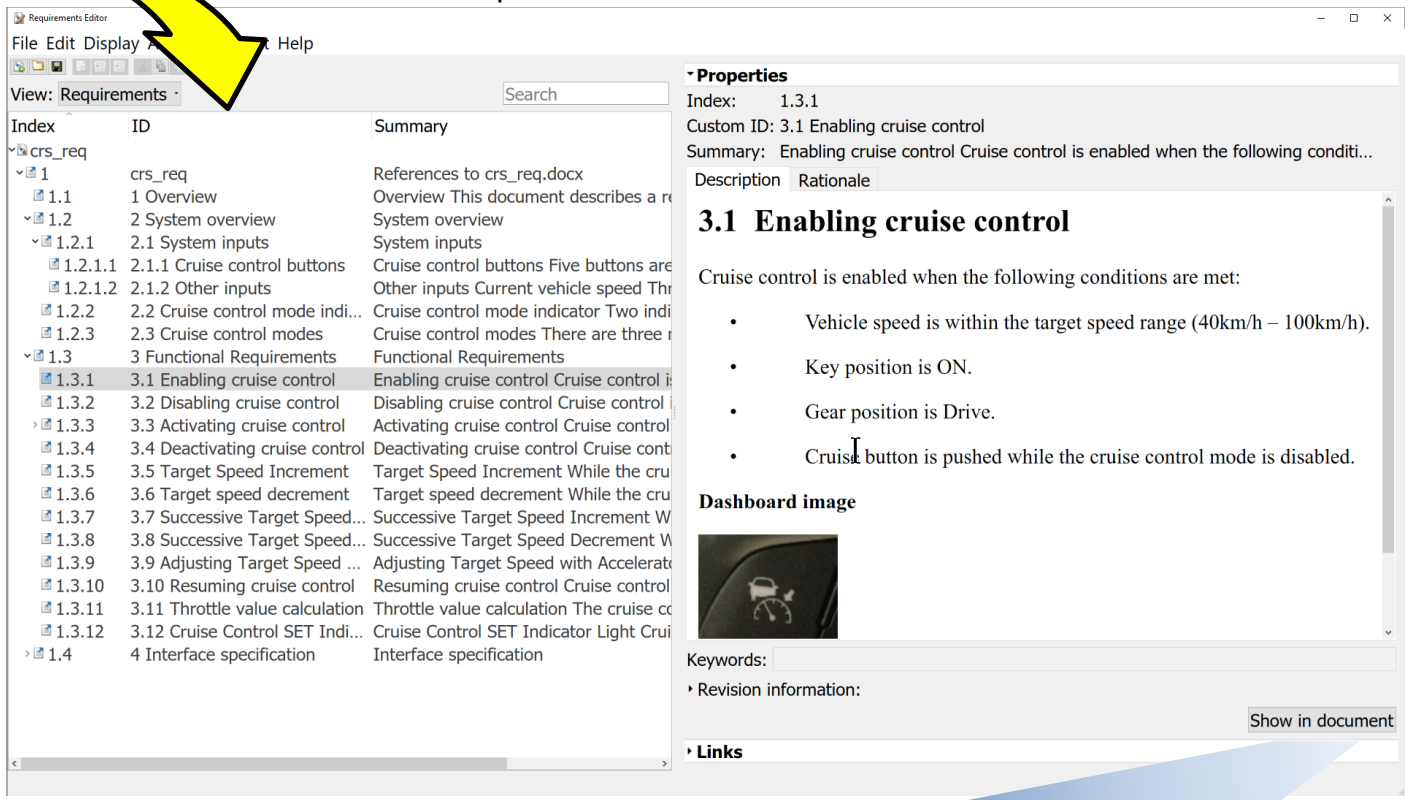
Import

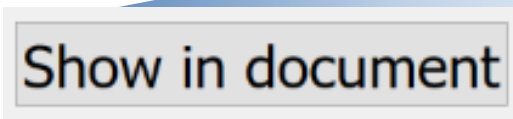
Microsoft Word



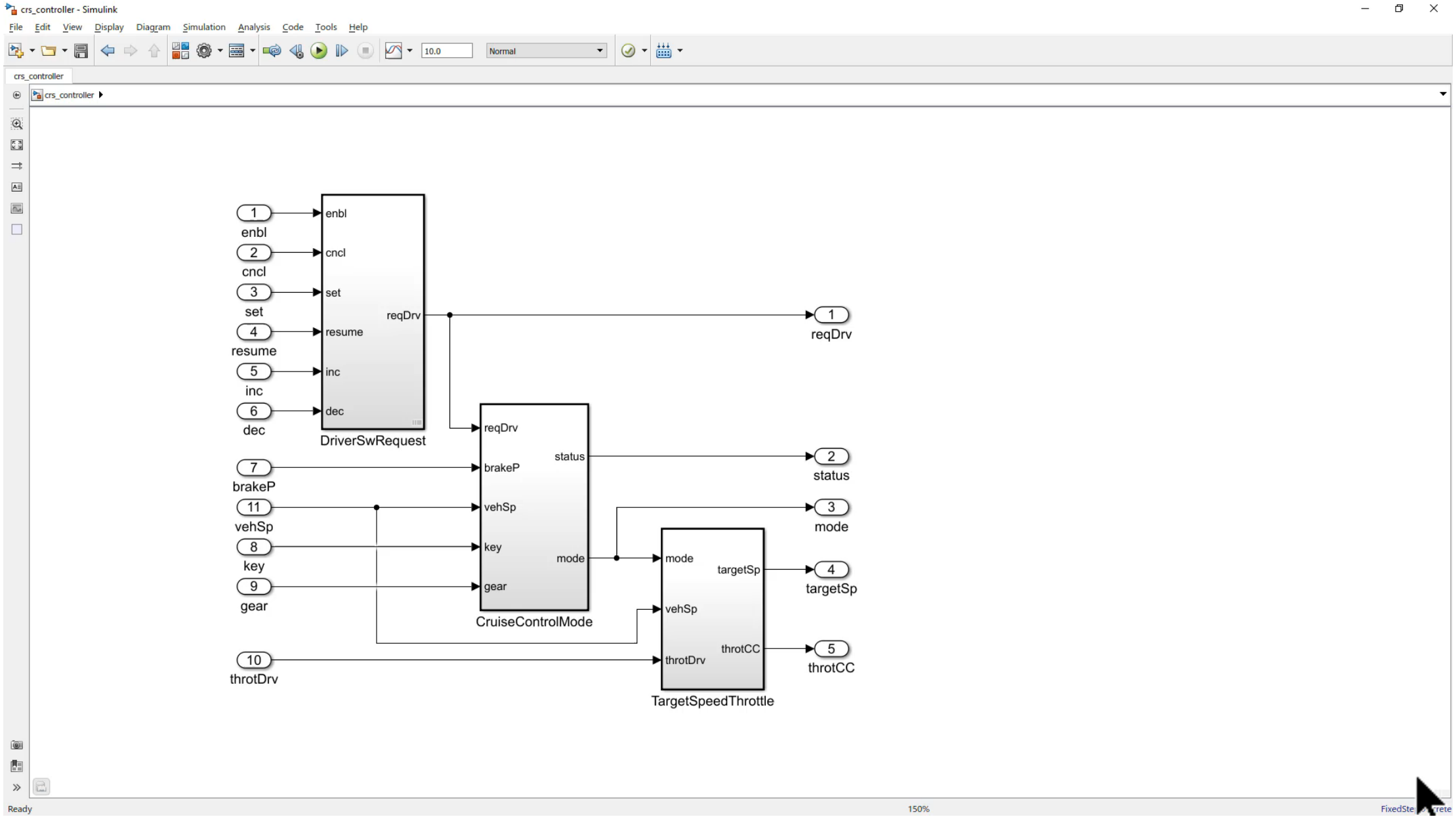
R2018a

Simulink Requirements Editor

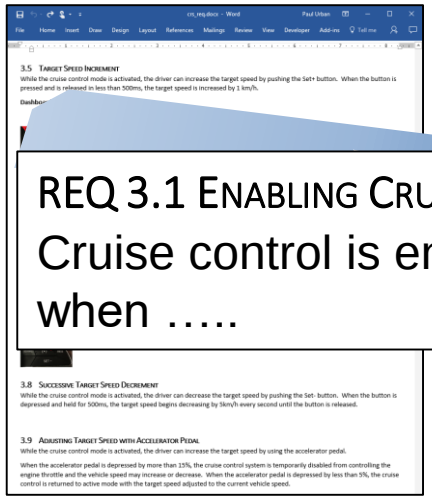




需求的浏览


crs_controller - Simulink
File Edit View Display Diagram Simulation Analysis Code Tools Help
10.0
Normal
crs_controller
crs_controller
1
enbl
2
cncl
3
set
4
resume
5
inc
6
dec
enbl
cncl
set
resume
inc
dec
reqDrv
DriverSwRequest
1
reqDrv
reqDrv
brakeP
vehSp
key
gear
status
mode
CruiseControlMode
7
brakeP
11
vehSp
8
key
9
gear
2
status
3
mode
mode
vehSp
throtDrv
targetSp
throtCC
TargetSpeedThrottle
10
throtDrv
4
targetSp
5
throtCC
Ready
150%

需求链接、设计和测试



3.5 Target Speed Increment

While the cruise control mode is activated, the driver can increase the target speed by pushing the Set+ button. When the button is pressed and is released in less than 500ms, the target speed is increased by 1 km/h.

3.8 Successive Target Speed Decrement

While the cruise control mode is activated, the driver can decrease the target speed by pushing the Set- button. When the button is depressed and held for 500ms, the target speed begins decreasing by 5km/h every second until the button is released.

3.9 Adjusting Target Speed with Accelerator Pedal

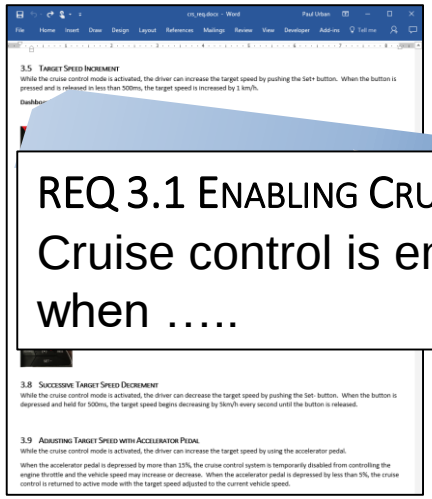
While the cruise control mode is activated, the driver can increase the target speed by using the accelerator pedal.

When the accelerator pedal is depressed by more than 15%, the cruise control system is temporarily disabled from controlling the engine throttle and the vehicle speed may increase or decrease. When the accelerator pedal is depressed by less than 5%, the cruise control is returned to active mode with the target speed adjusted to the current vehicle speed.

REQ 3.1 Enabling Cruise Control

Cruise control is enabled when …..

需求链接、设计和测试

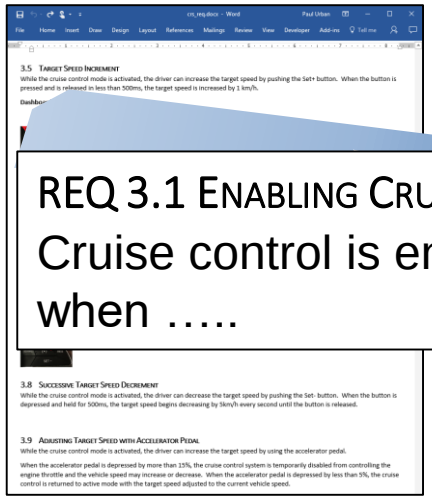


REQ 3.1 ENABLING CRUISE CONTROL
Cruise control is enabled when …..

Derives

ENABLE SWITCH DETECTION
If the Enable switch is pressed ……

需求链接、设计和测试

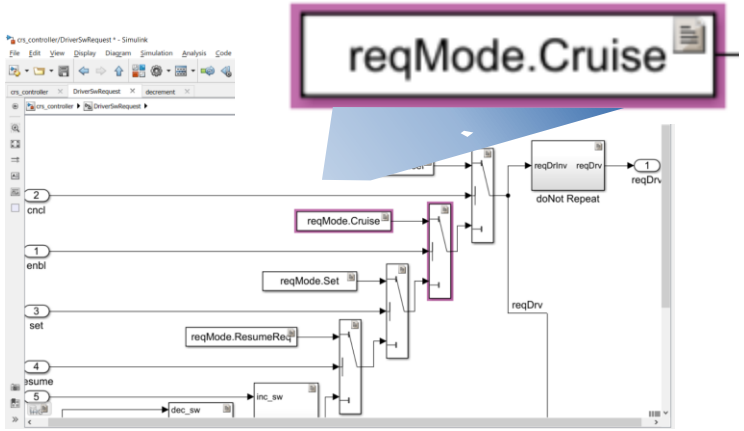


REQ 3.1 ENABLING CRUISE CONTROL
Cruise control is enabled when …..

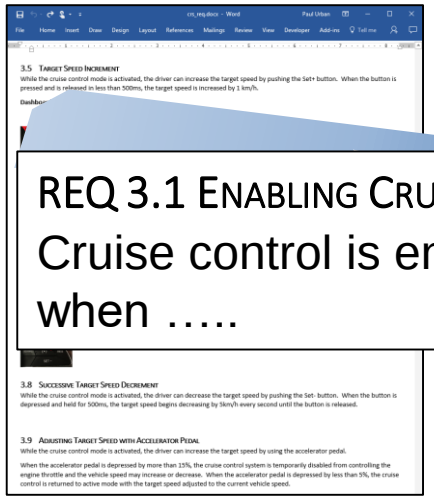
Derives

ENABLE SWITCH DETECTION
If the Enable switch is pressed ……

Implemented By



需求链接、设计和测试

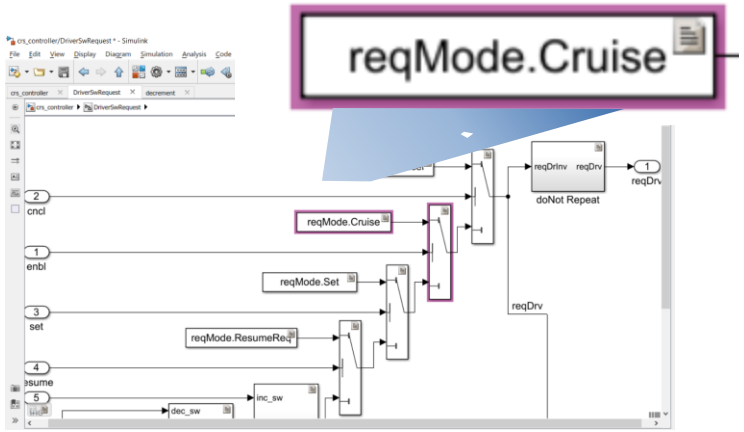


REQ 3.1 ENABLING CRUISE CONTROL
Cruise control is enabled when …..

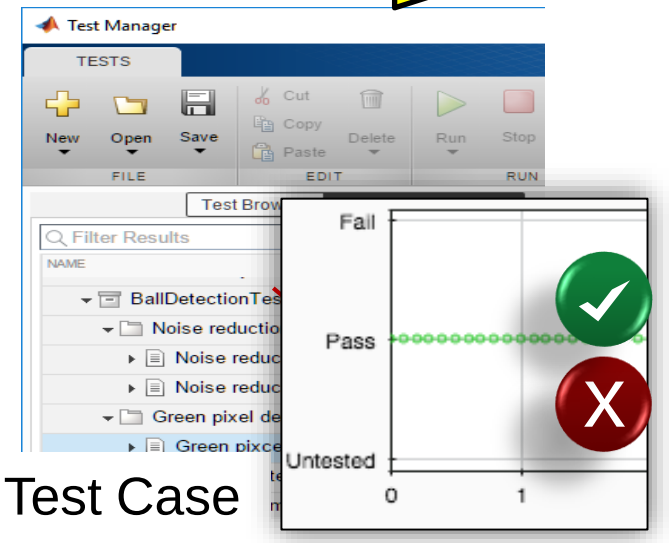
Derives

ENABLE SWITCH DETECTION
If the Enable switch is pressed ……

Implemented By

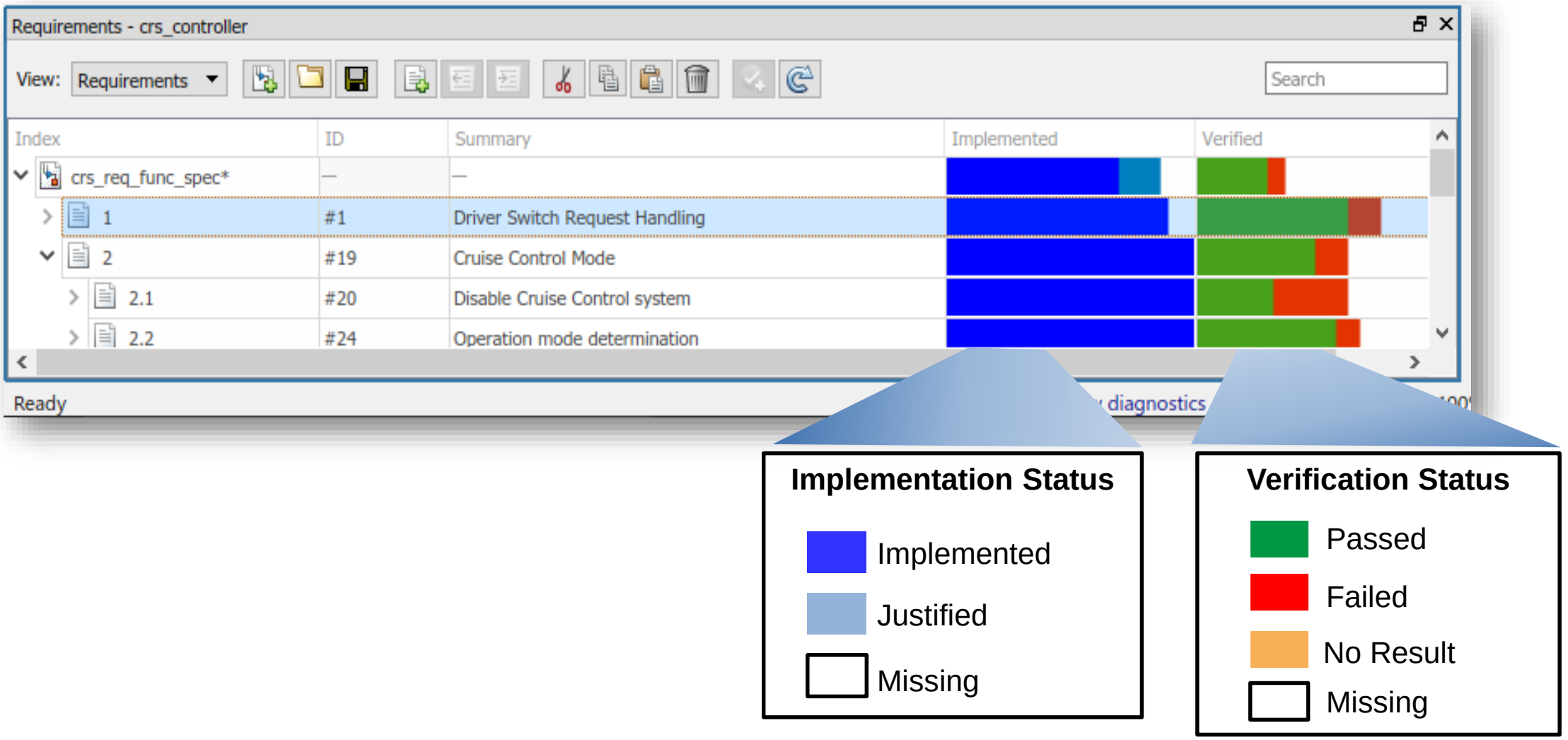


Verified By



Test Case

跟踪实现和验证


Requirements - crs_controller
View: Requirements
Search
Index
ID
Summary
Implemented
Verified
crs_req_func_spec*
1
#1
Driver Switch Request Handling
2
#19
Cruise Control Mode
2.1
#20
Disable Cruise Control system
2.2
#24
Operation mode determination
Ready
diagnostics
Implementation Status
Implemented
Justified
Missing
Verification Status
Passed
Failed
No Result
Missing

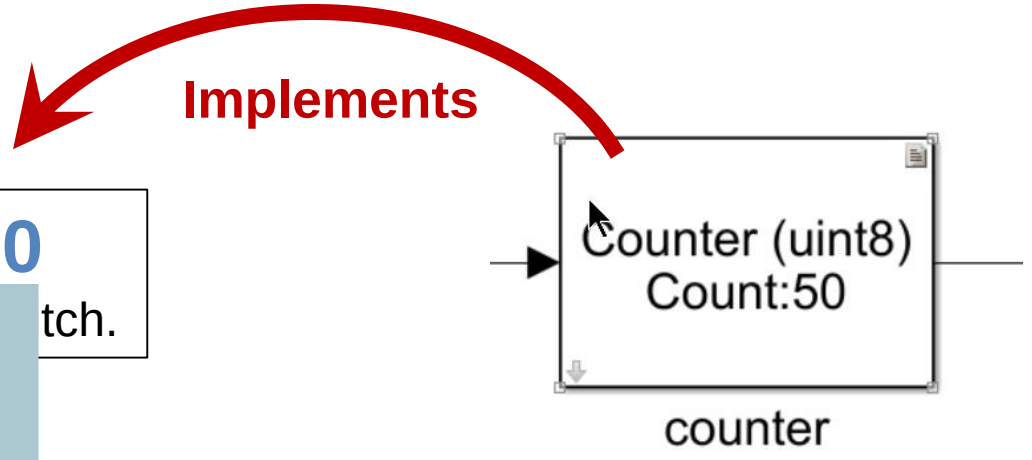
需求变更

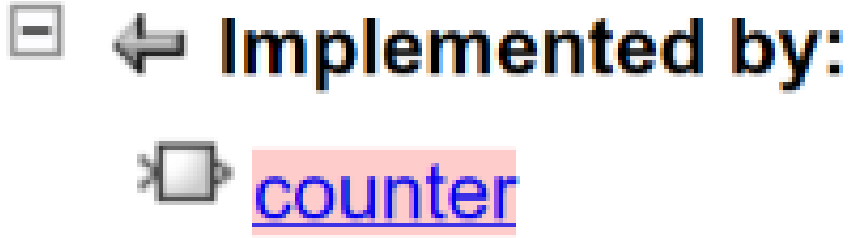
Original Requirement

If the switch is pressed and the counter reaches **50** then it shall be recognized as a long press of the switch.

Updated Requirement

If the switch is pressed and the counter reaches **75** then it shall be recognized as a long press of the switch.





验证设计的规范性

设计是否
正确?

是否
太复杂?

是否可以
代码生成

Review and
static analysis

Simulink Models

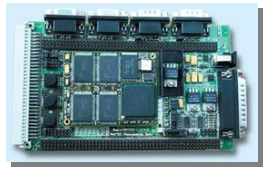
Requirements

Executable
Specification

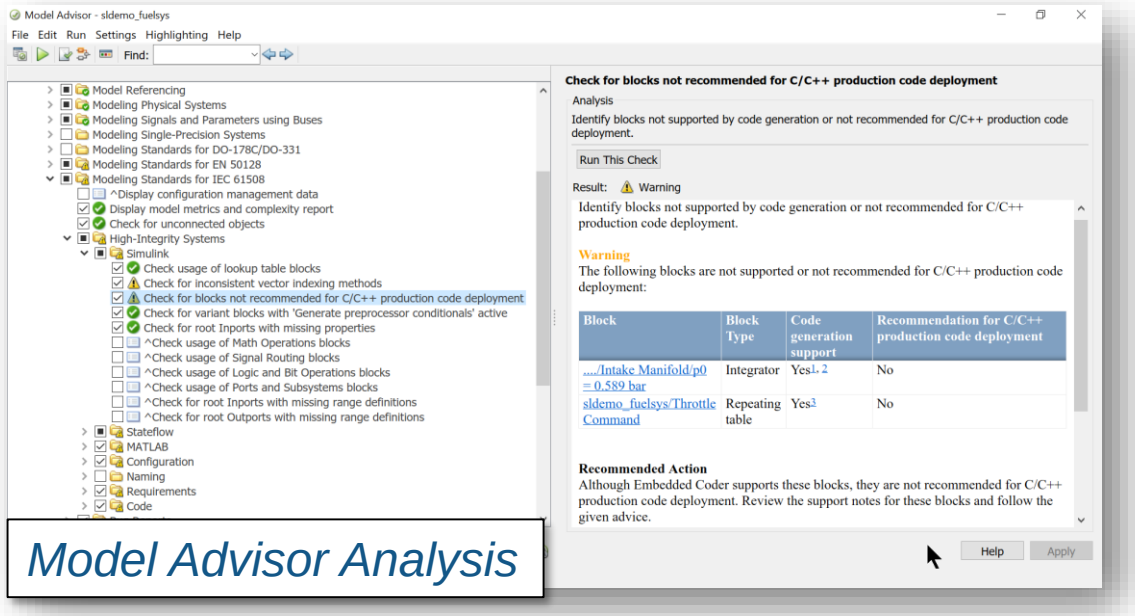
Model used for
production code
generation

C/C++

Generated code



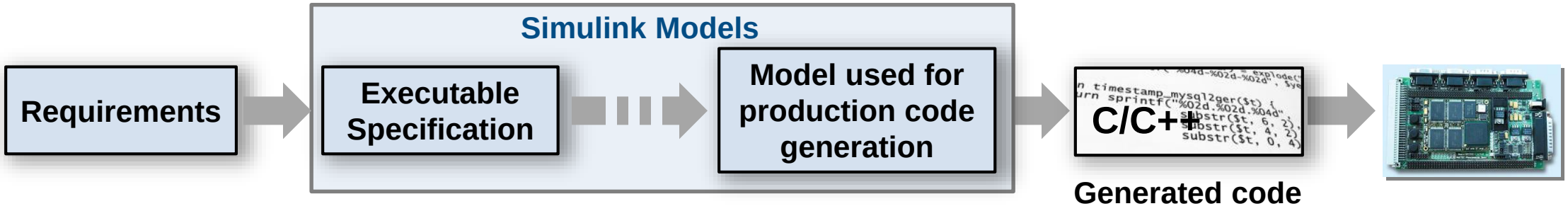
静态分析自动化验证



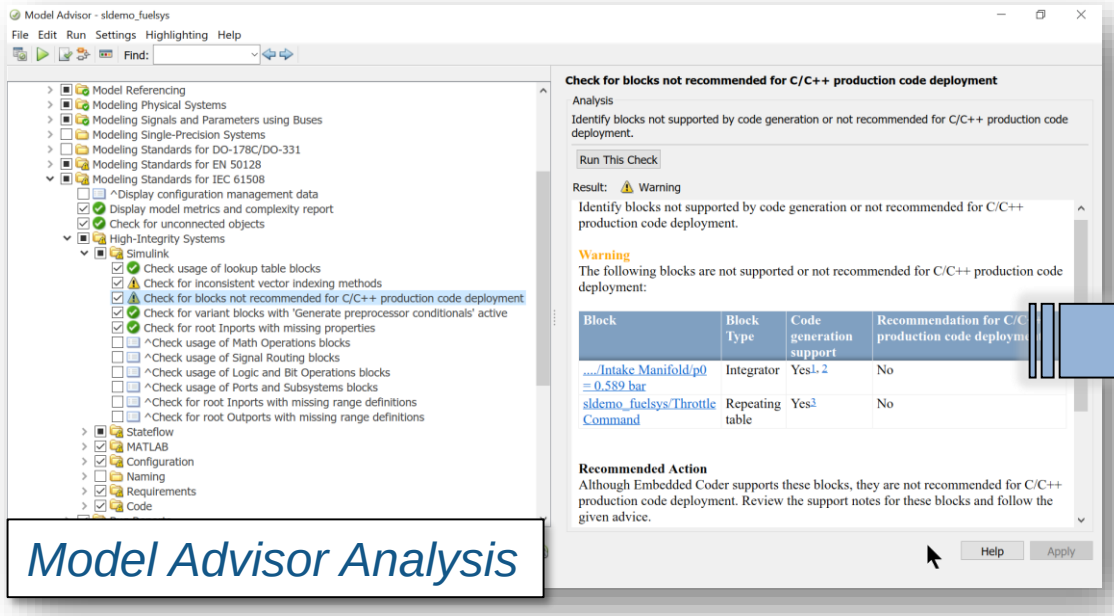
Model Advisor Analysis

Check for:

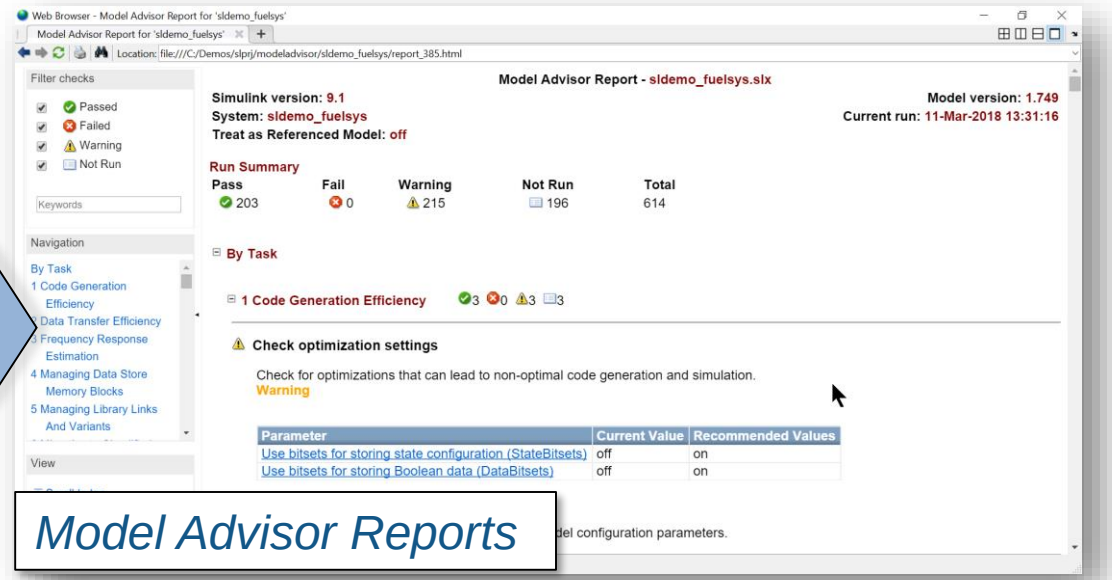
- Readability and Semantics
- Performance and Efficiency
- Clones
- And more……



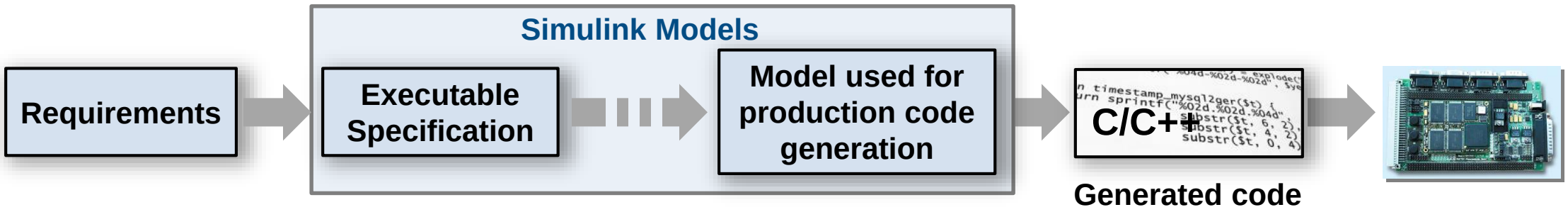
自动产生评审报告



Model Advisor Analysis

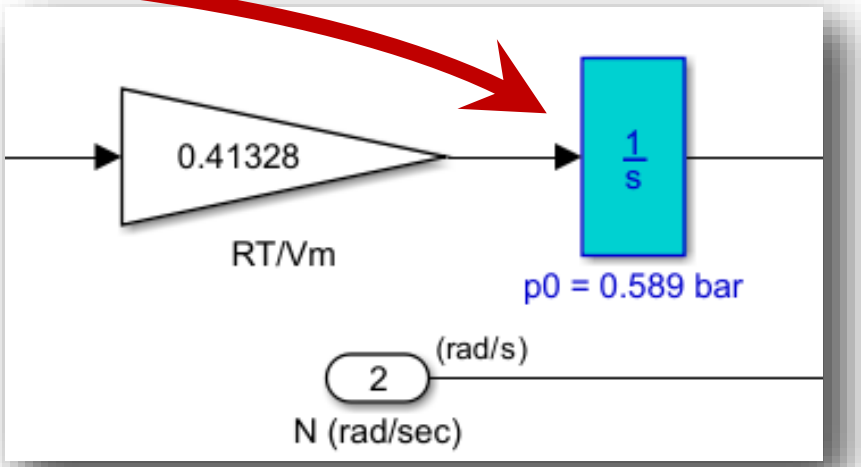


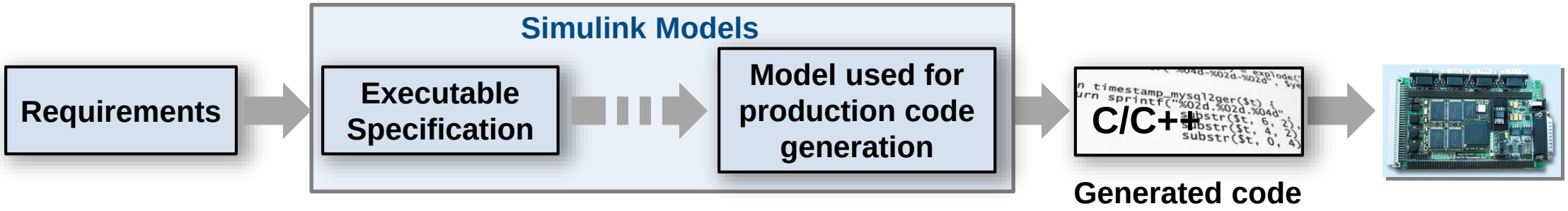
Model Advisor Reports



导航到有问题的模块

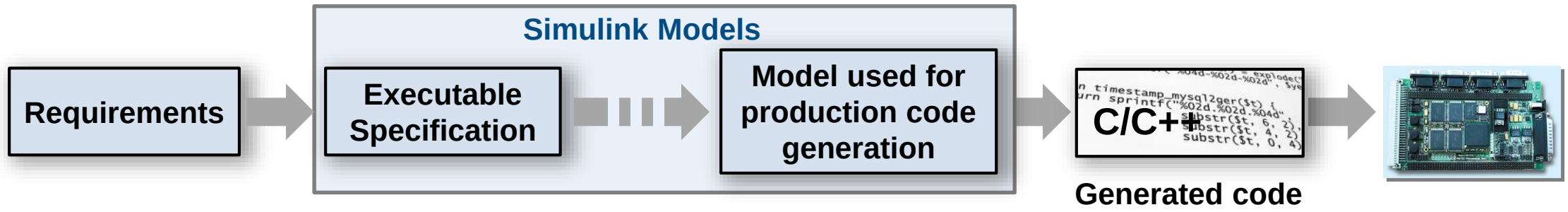
Block	Block Type	Code generation support	Recommendation for C/C++ production code deployment
..../Intake Manifold/p0 = 0.589 bar	Integrator	Yes[1], [2]	No
sldemo_fuelsys/Throttle Command	Repeating table	Yes[3]	No





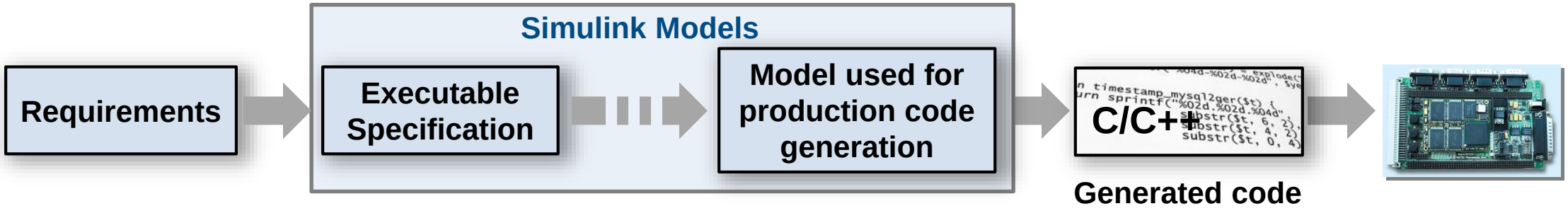
给出改进建议或自动修正

Recommended Action
Although Embedded Coder supports these blocks, they are not recommended for C/C++ production code deployment. Review the support notes for these blocks and follow the given advice.

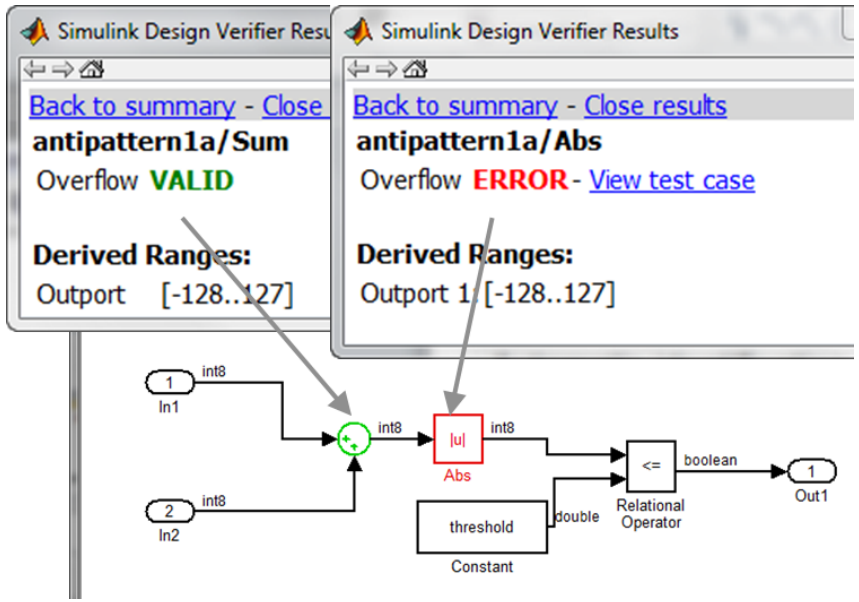


内置行业标准和建模指导的检查

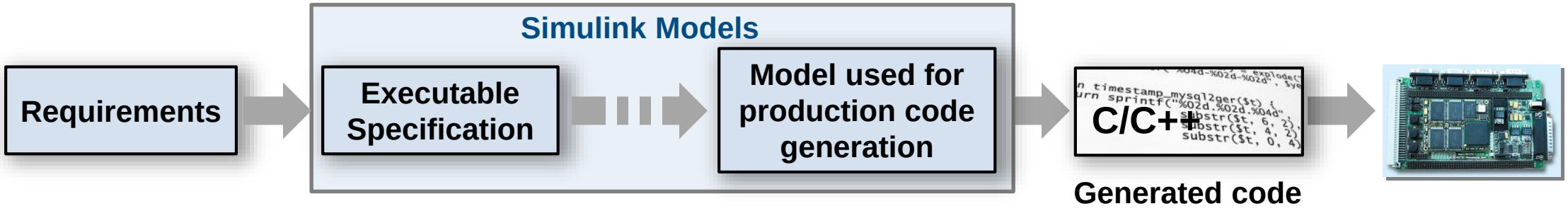
- DO-178/DO-331
- ISO 26262
- IEC 61508
- IEC 62304
- EN 50128
- MISRA C:2012
- CERT C, CWE, ISO/IEC TS 17961
- MAAB (MathWorks Automotive Advisory Board)
- JMAAB (Japan MATLAB Automotive Advisory Board)



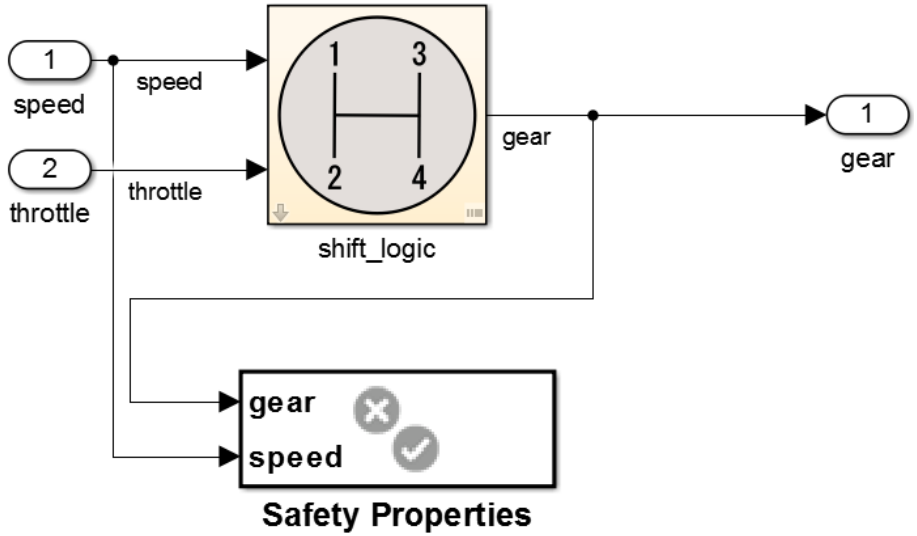
形式化方法发现设计错误



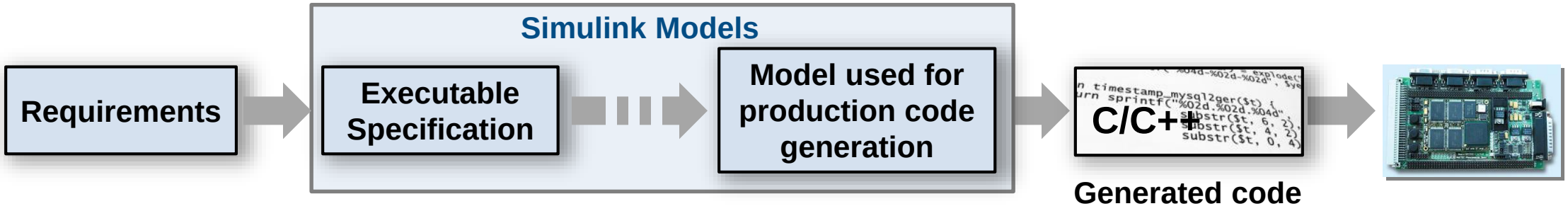
- Find run-time design errors:
  - Integer overflow
  - Dead Logic
  - Division by zero
  - Array out-of-bounds
  - Range violations
- Generate counter example to reproduce error



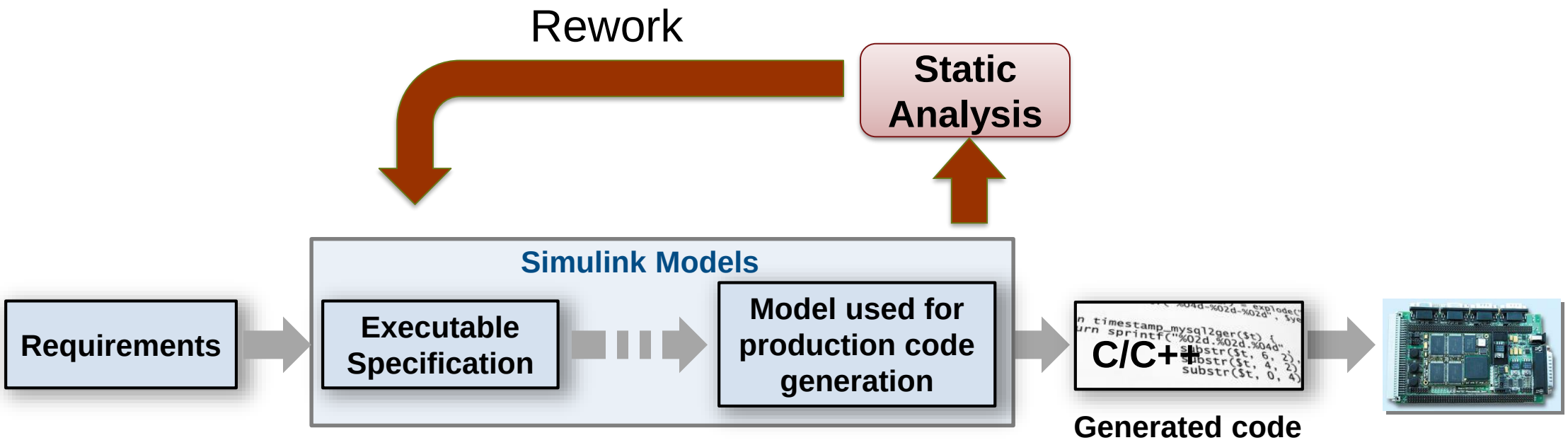
证明设计满足需求



- Prove design properties using formal requirement models
- Model functional and safety requirements
- Generates counter example for analysis and debugging

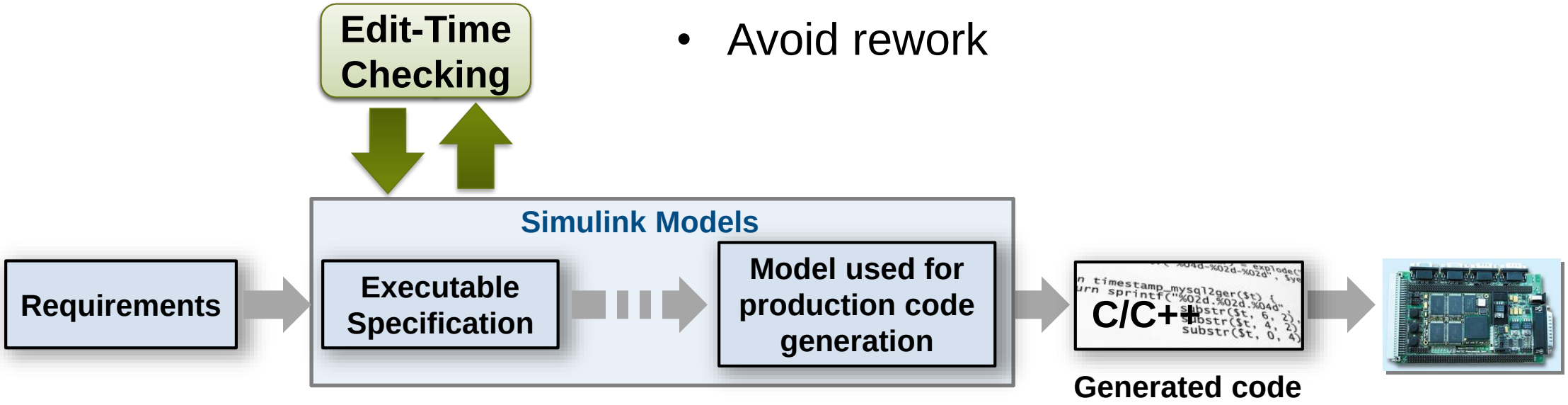


建模标准的检查通常会比较后期

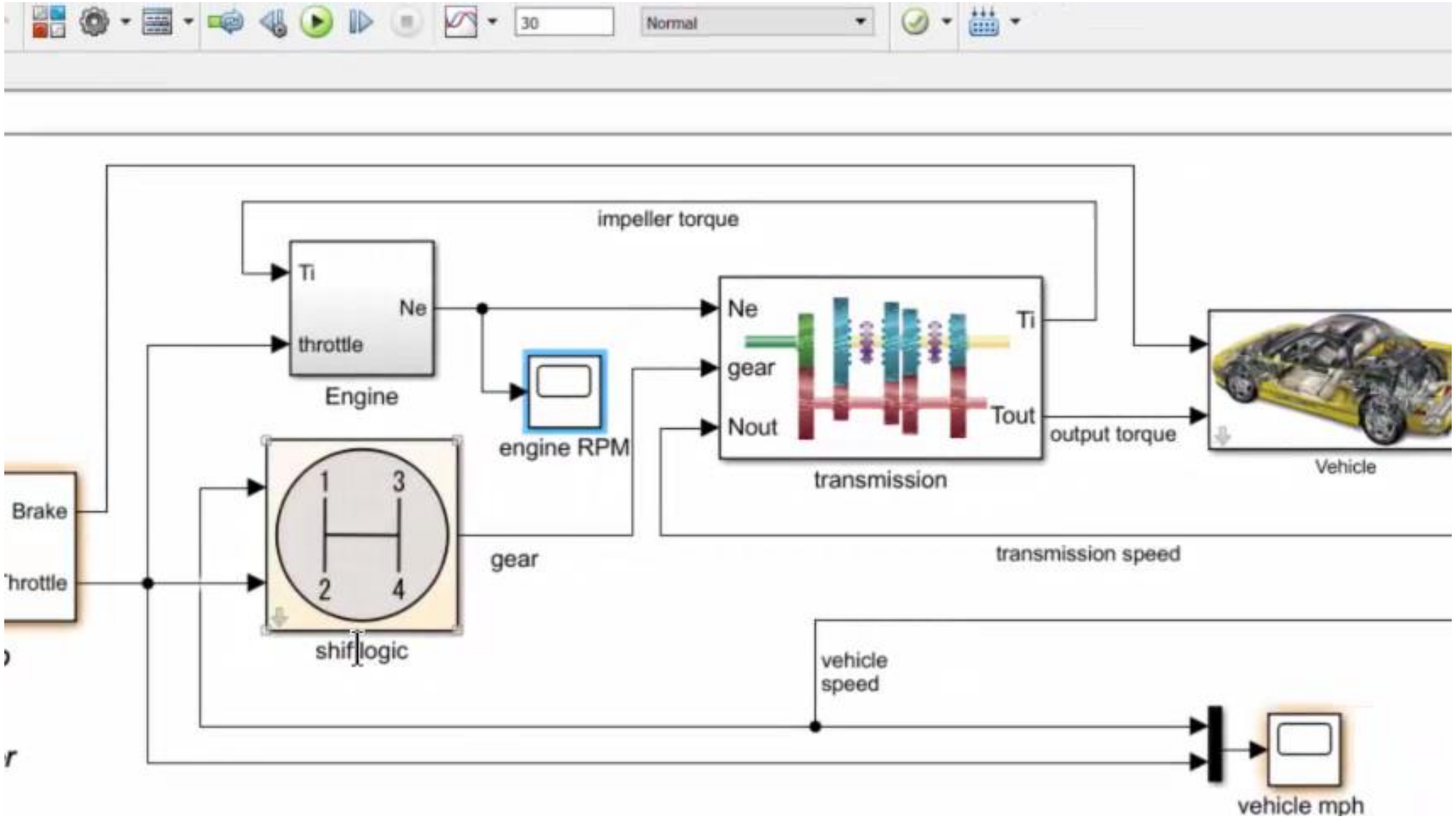


即时编辑检查实现更早期验证

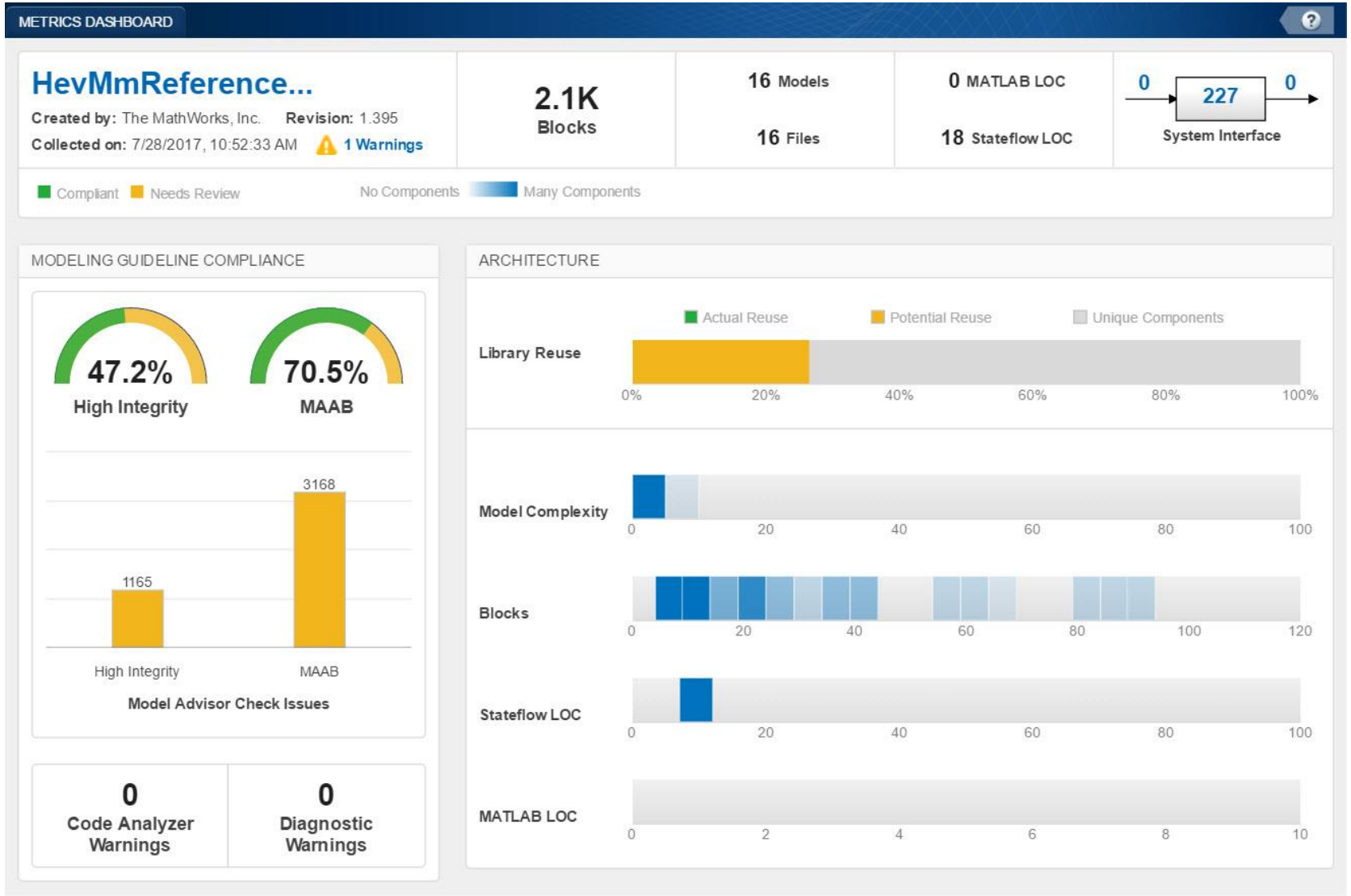
- Highlight violations as you edit
- Fix issues earlier
- Avoid rework



编辑过程中检查合规问题



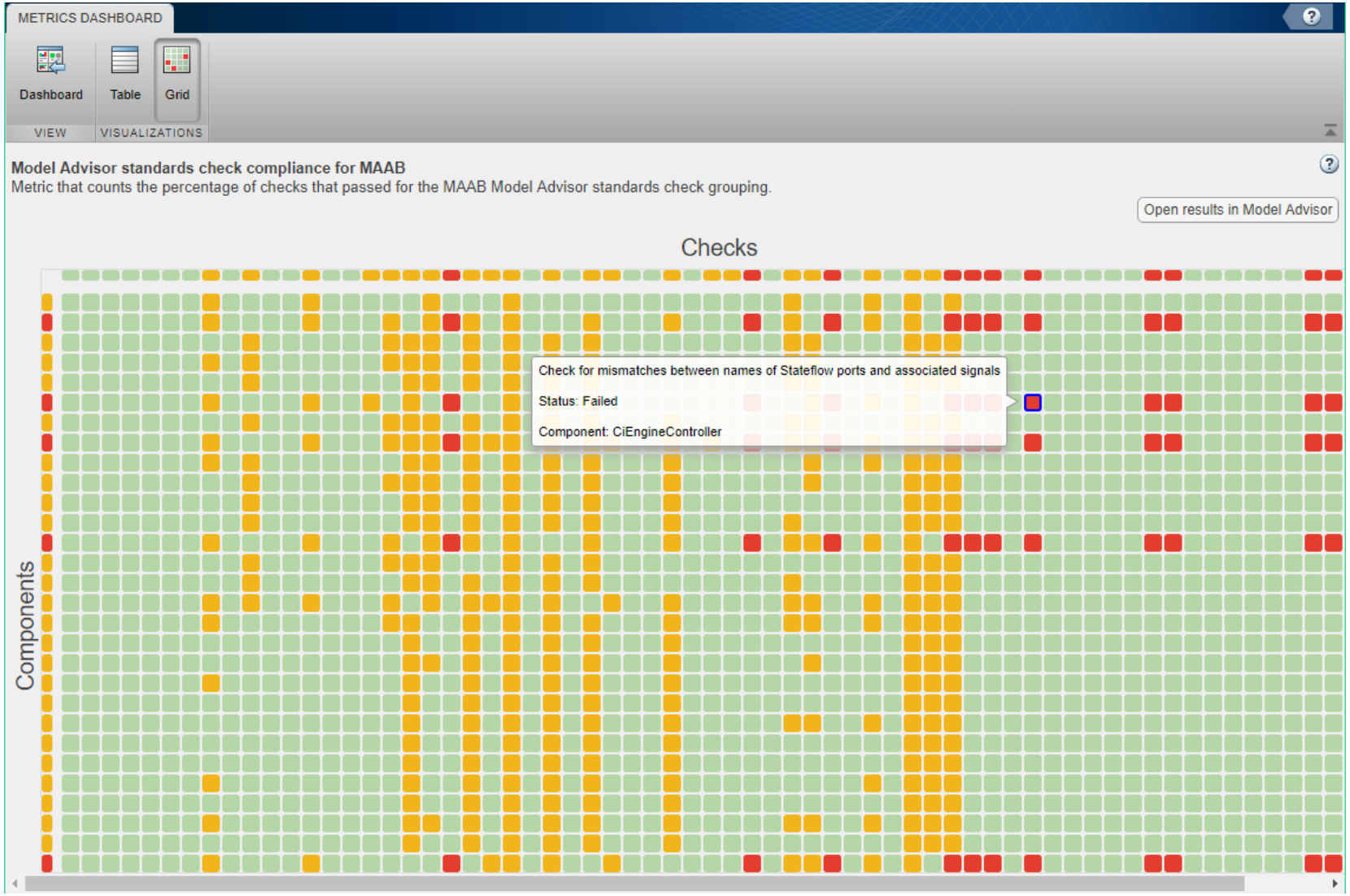
使用度量仪表板评估质量



- Consolidated view of metrics
  - Size
  - Compliance
  - Complexity
- Identify where problem areas may be

指标网格可视化

R2018a



- Visualize Standards Check Compliance
  - Find Issues
  - Identify patterns
  - See hot spots

Legend:

Red:	Fail
Orange:	Warning
Green:	Pass
Gray:	Not run

功能测试

设计是否满足需求?

功能是否正确?

充分测试?

Simulink Models

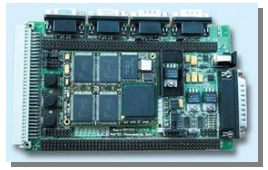
Requirements

Executable Specification

Model used for production code generation

C/C++

Generated code



系统化功能测试

Test Case

Inputs

MAT file (input)

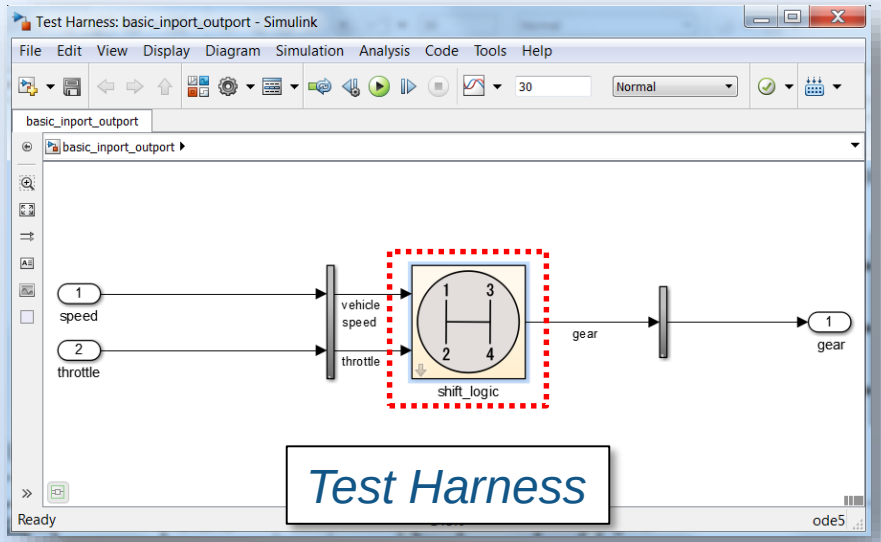
Signal Builder

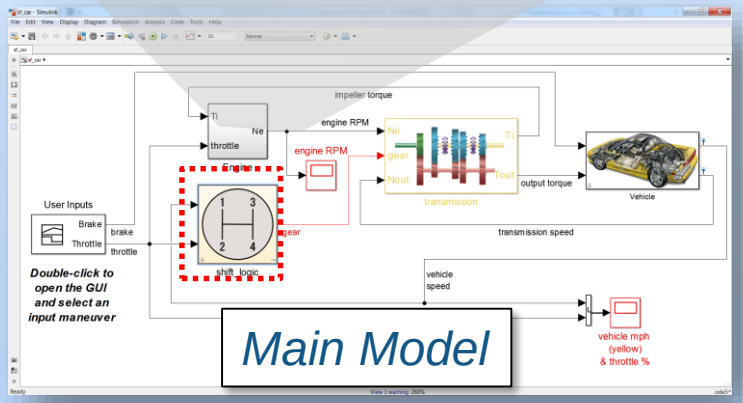
Test Sequence

and more!

Excel file (input)

R2017b





Assessments

MAT file (baseline)

```
function customCriteria
Perform custom criteria
1 test.verifyThat(test.sl
```

MATLAB Unit Test

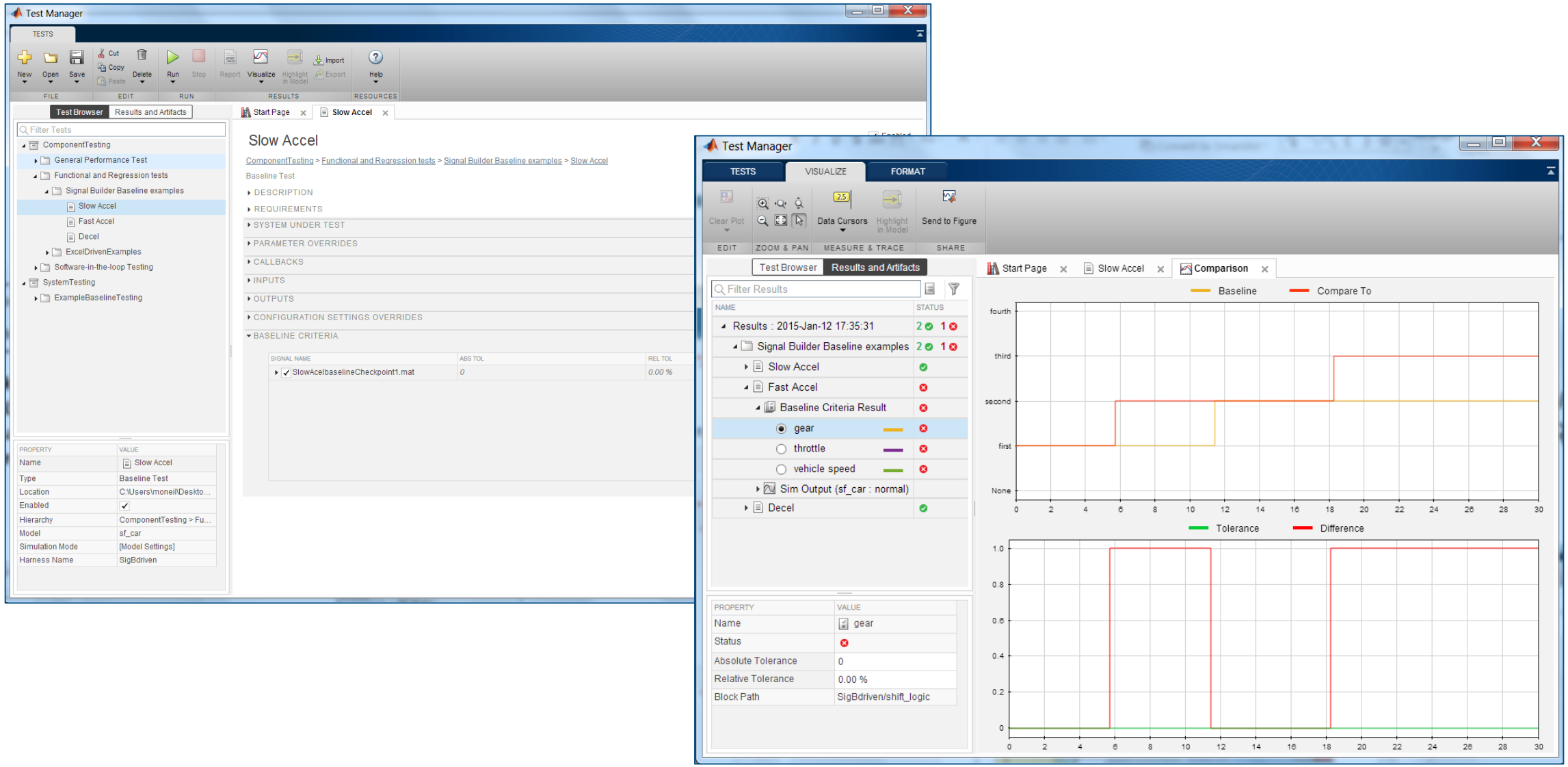
Test Assessment

and more!

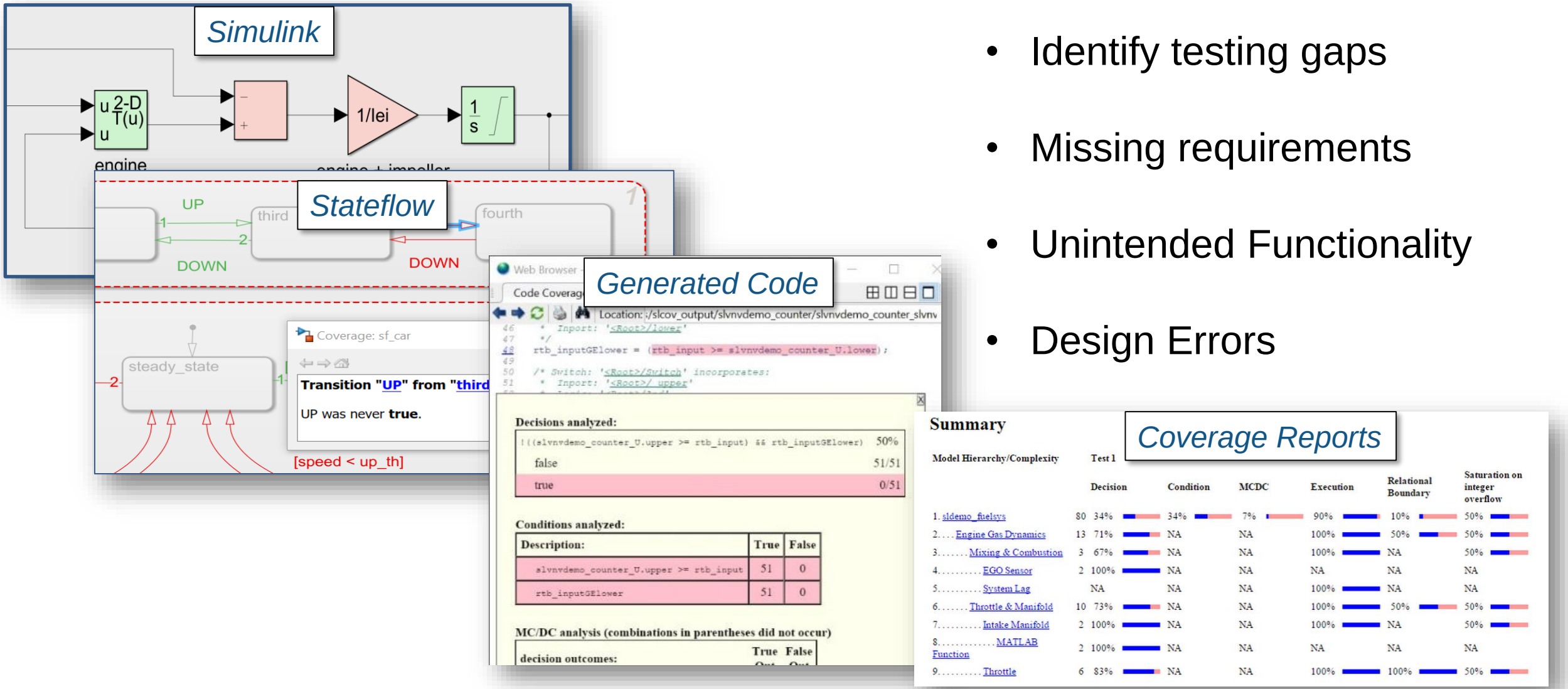
Excel file (baseline)

R2017b

管理测试和测试结果

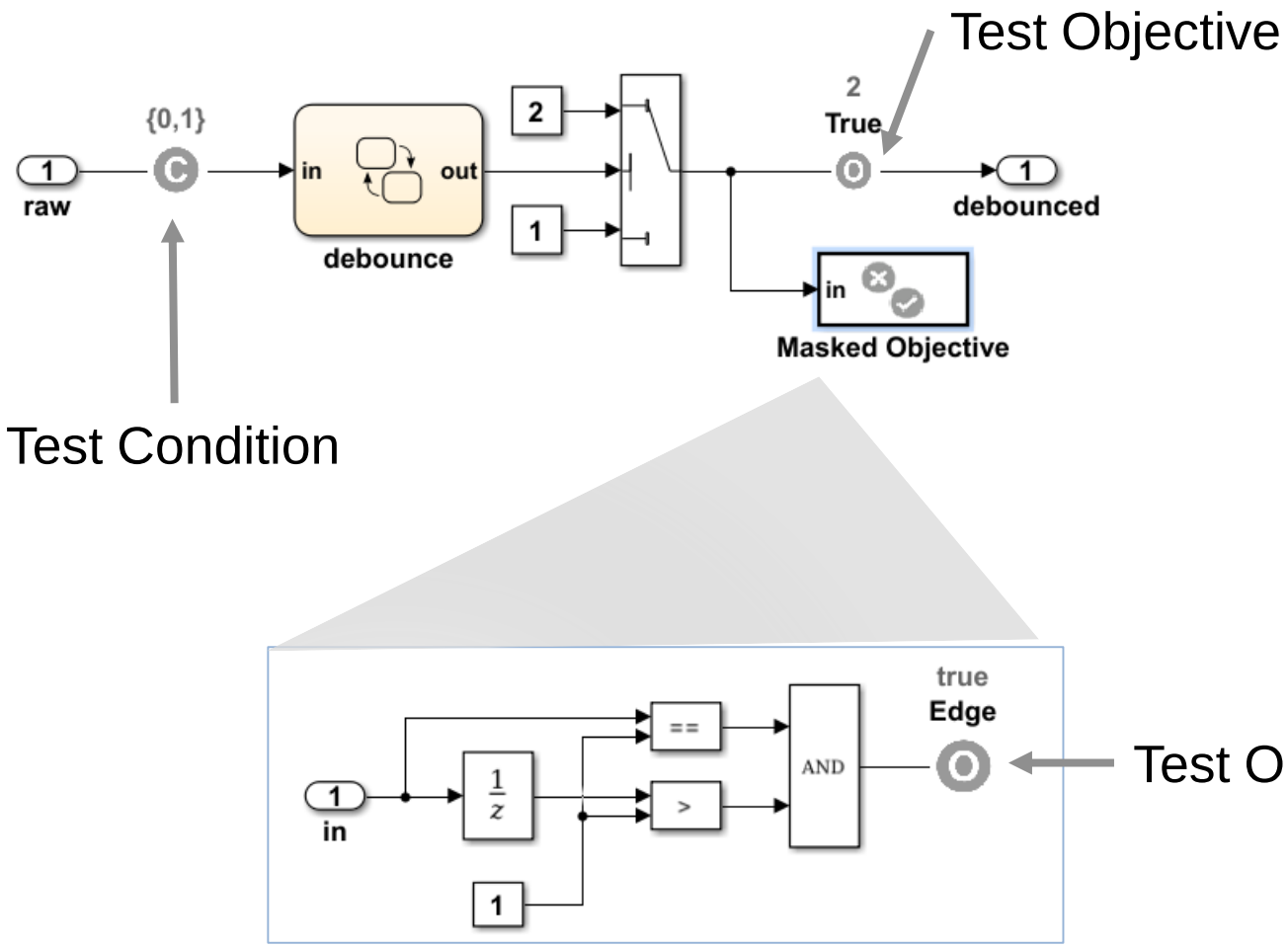

Test Manager
TESTS
New
Open
Save
Cut
Copy
Paste
Delete
Run
Stop
Report
Visualize
Highlight in Model
Import
Export
Help
FILE
EDIT
RUN
RESULTS
RESOURCES
Test Browser
Results and Artifacts
Filter Tests
ComponentTesting
General Performance Test
Functional and Regression tests
Signal Builder Baseline examples
Slow Accel
Fast Accel
Decel
ExcelDrivenExamples
Software-in-the-loop Testing
SystemTesting
ExampleBaselineTesting
Start Page
Slow Accel
Slow Accel
ComponentTesting > Functional and Regression tests > Signal Builder Baseline examples > Slow Accel
Baseline Test
DESCRIPTION
REQUIREMENTS
SYSTEM UNDER TEST
PARAMETER OVERRIDES
CALLBACKS
INPUTS
OUTPUTS
CONFIGURATION SETTINGS OVERRIDES
BASELINE CRITERIA
SIGNAL NAME
ABS TOL
REL TOL
SlowAccelbaselineCheckpoint1.mat
0
0.00 %
PROPERTY
VALUE
Name
Slow Accel
Type
Baseline Test
Location
C:\Users\moneil\Deskto...
Enabled
Hierarchy
ComponentTesting > Fu...
Model
sf_car
Simulation Mode
[Model Settings]
Harness Name
SigBdriven
Test Manager
TESTS
VISUALIZE
FORMAT
Clear Plot
Data Cursors
Highlight in Model
Send to Figure
EDIT
ZOOM & PAN
MEASURE & TRACE
SHARE
Test Browser
Results and Artifacts
Filter Results
NAME
STATUS
Results : 2015-Jan-12 17:35:31
Signal Builder Baseline examples
Slow Accel
Fast Accel
Baseline Criteria Result
gear
throttle
vehicle speed
Sim Output (sf_car : normal)
Decel
PROPERTY
VALUE
Name
gear
Status
Absolute Tolerance
0
Relative Tolerance
0.00 %
Block Path
SigBdriven/shift_logic
Start Page
Slow Accel
Comparison
Baseline
Compare To
fourth
third
second
first
None
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Tolerance
Difference
1.0
0.8
0.6
0.4
0.2
0

测试覆盖率



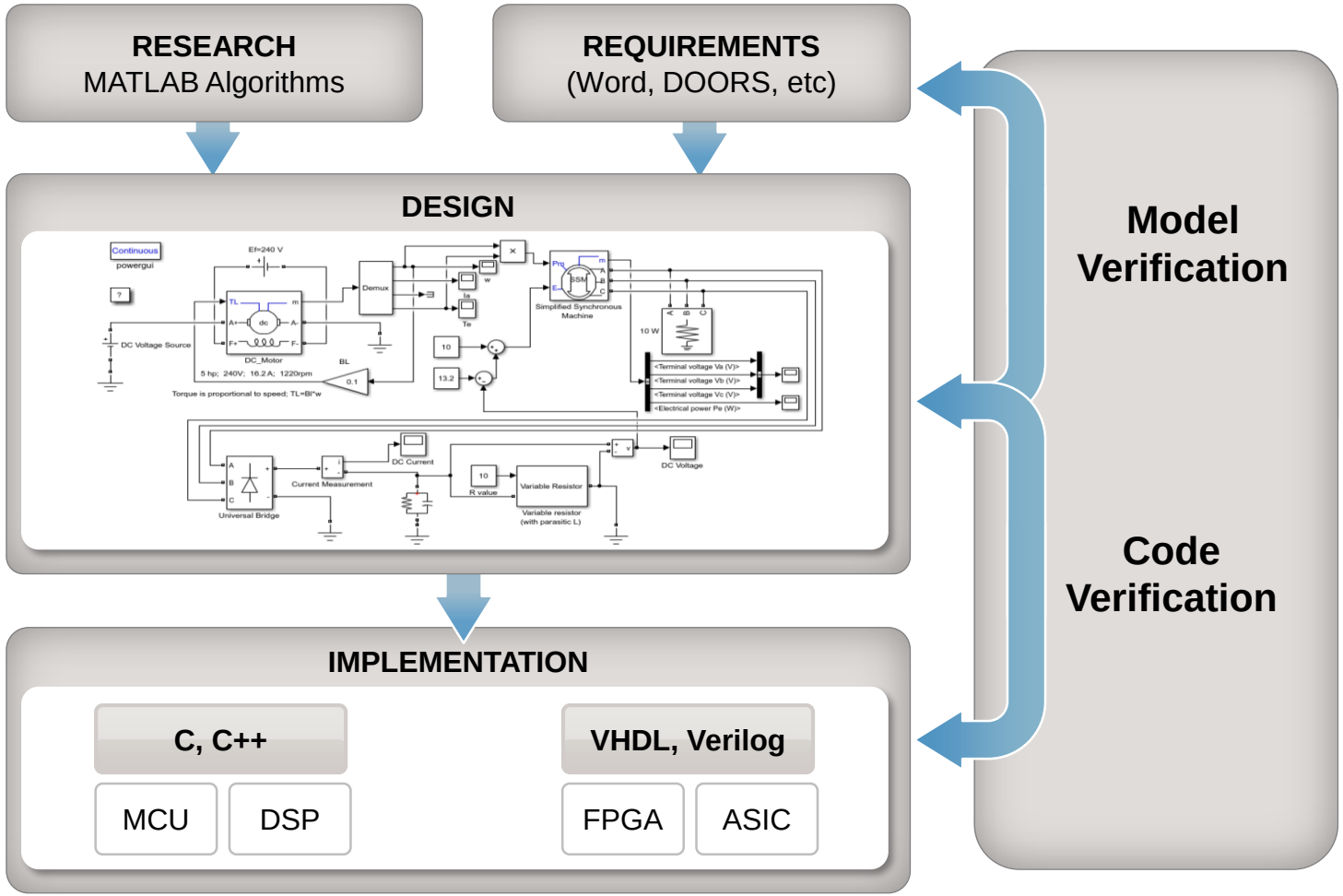
- Identify testing gaps
- Missing requirements
- Unintended Functionality
- Design Errors

功能测试测试用例的产生



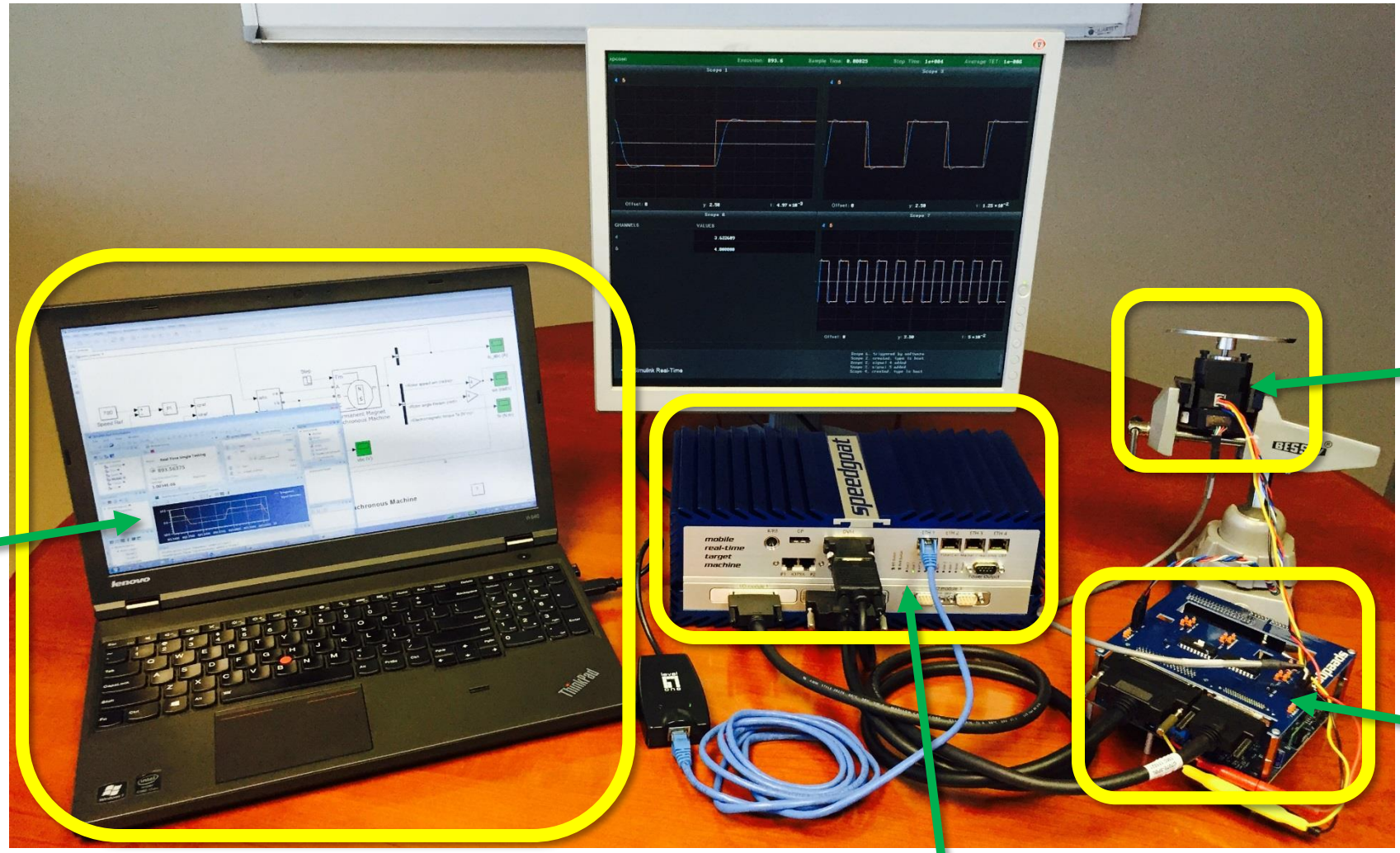
- 指定功能测试目标
  - 定义信号在测试用例中必须满足指定条件
- 指定功能测试条件
  - 定义信号值的约束来约束产生的测试用例

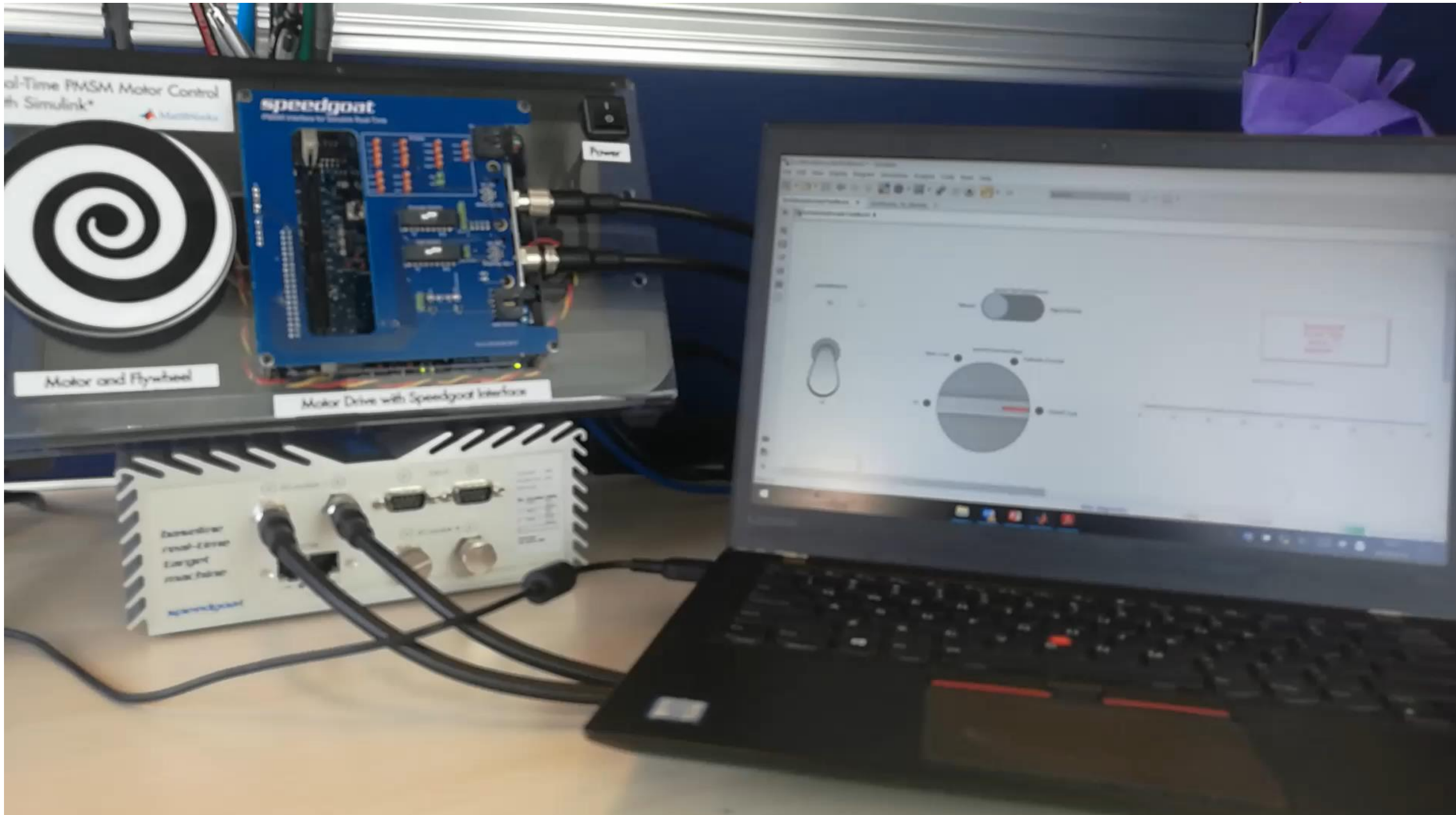
基于模型设计– 实时仿真



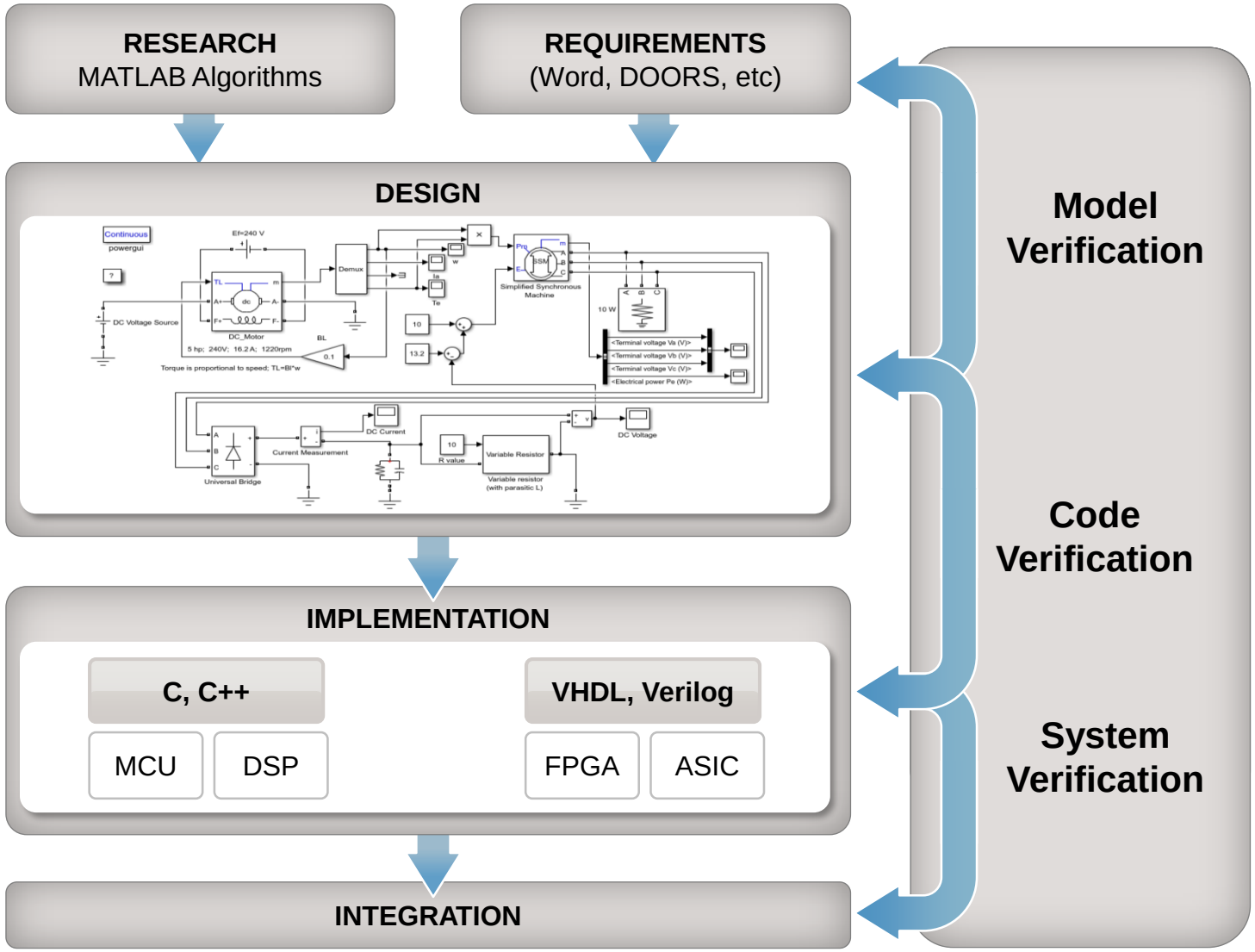
- 生成代码用于执行快速控制原型 (RCP)或硬件在环仿真 (HIL)
- 通过实时仿真对比虚拟系统来验证控制算法和策略

实时仿真


Simulink Host Computer
PMSM Motor
Power Electronics
Real-Time Target Computer


speedgoat
Power
Motor and Flywheel
Motor Drive with Speedgoat Interface

基于模型设计– 产品化代码生成



- 使用验证过的代码执行系统集成测试
- 部署C代码或HDL代码到微控制器、FPGA或SOC上

集成自动生成的代码到软件项目中

Model | **Hand**

Embedded Software Project Pseudo-Code

```
main()
{
    adcInit();
    encoderInit();
    pwmInit();

    controllerInit();

    while(1) {
    }
}
```

```
interruptServiceRountine()
{
    readAdcCountFromDriver();
    readEncoderCountFromDriver();

    controller();

    writePwmCountToDriver();
}
```

欢迎提供反馈意见