MathWorks

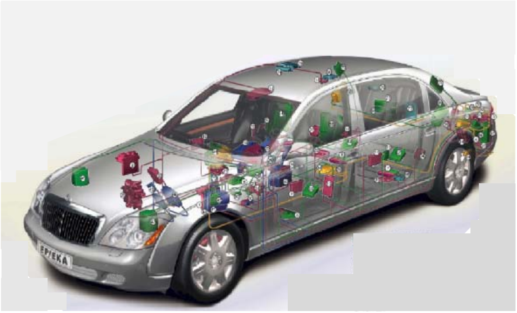
Automatic Code Generation for Embedded Control Systems

Tiffany Liang

Application Engineer

MathWorks

Embedded Control Systems



Automotive

Aero/Def

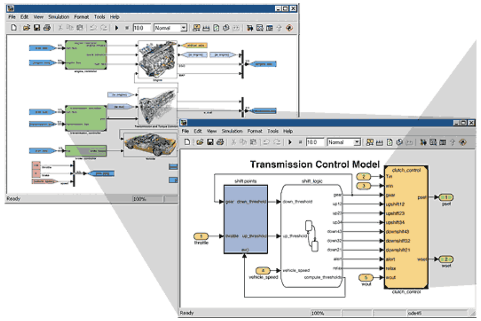
Construction Machine

Power Electronics

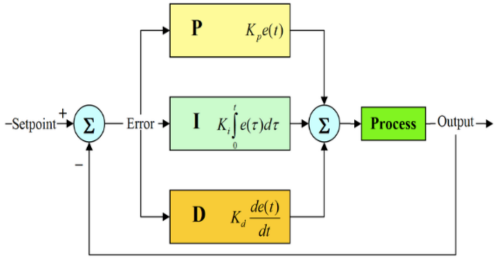
Industrial Equipment

Robot

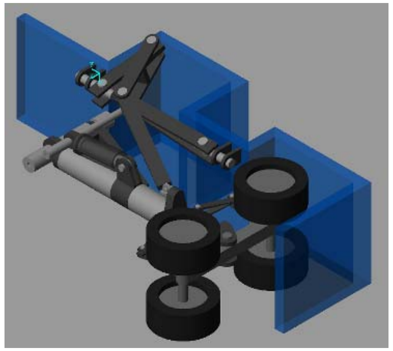
Model-Based Design “From Concept to Code”



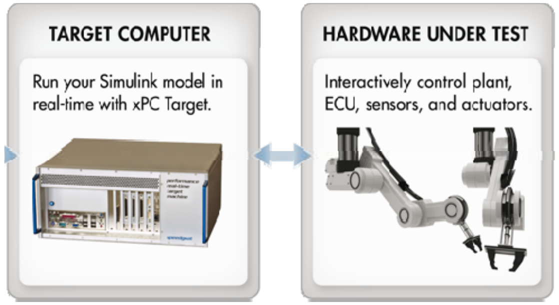
Modeling & Simulation



Control Design



Physical Modeling



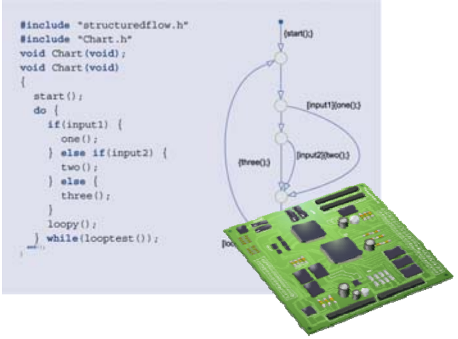
TARGET COMPUTER

Run your Simulink model in real-time with xPC Target.

HARDWARE UNDER TEST

Interactively control plant, ECU, sensors, and actuators.

Real-Time Test

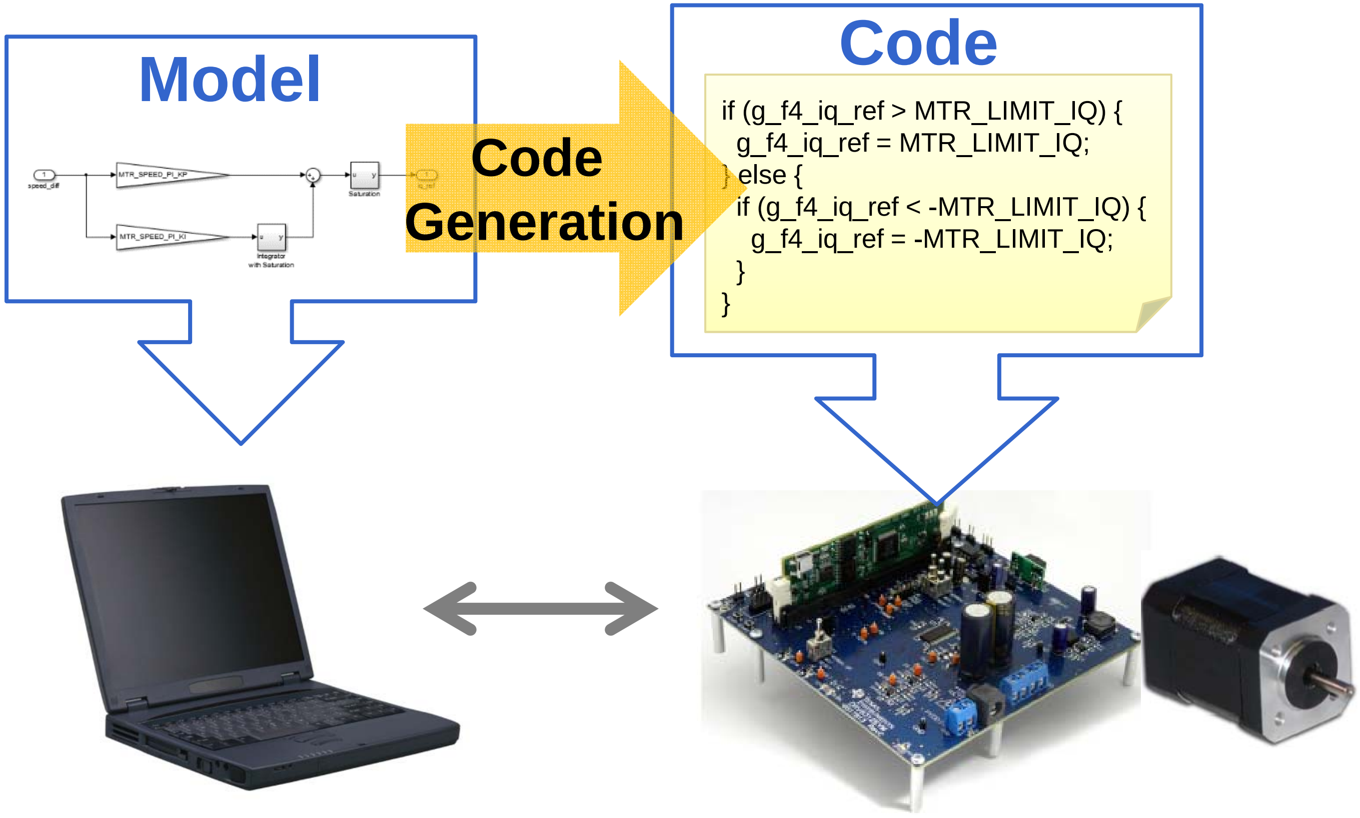


```
#include "structuredflow.h"
#include "Chart.h"
void Chart(void);
void Chart(void)
{
  start();
  do {
    if(input1) {
      one();
    } else if(input2) {
      two();
    } else {
      three();
    }
    loopy();
  } while(looptest());
}
```

Code Generation

Verification & Validation

Quick MBD Overview
Brushless DC Motor Control

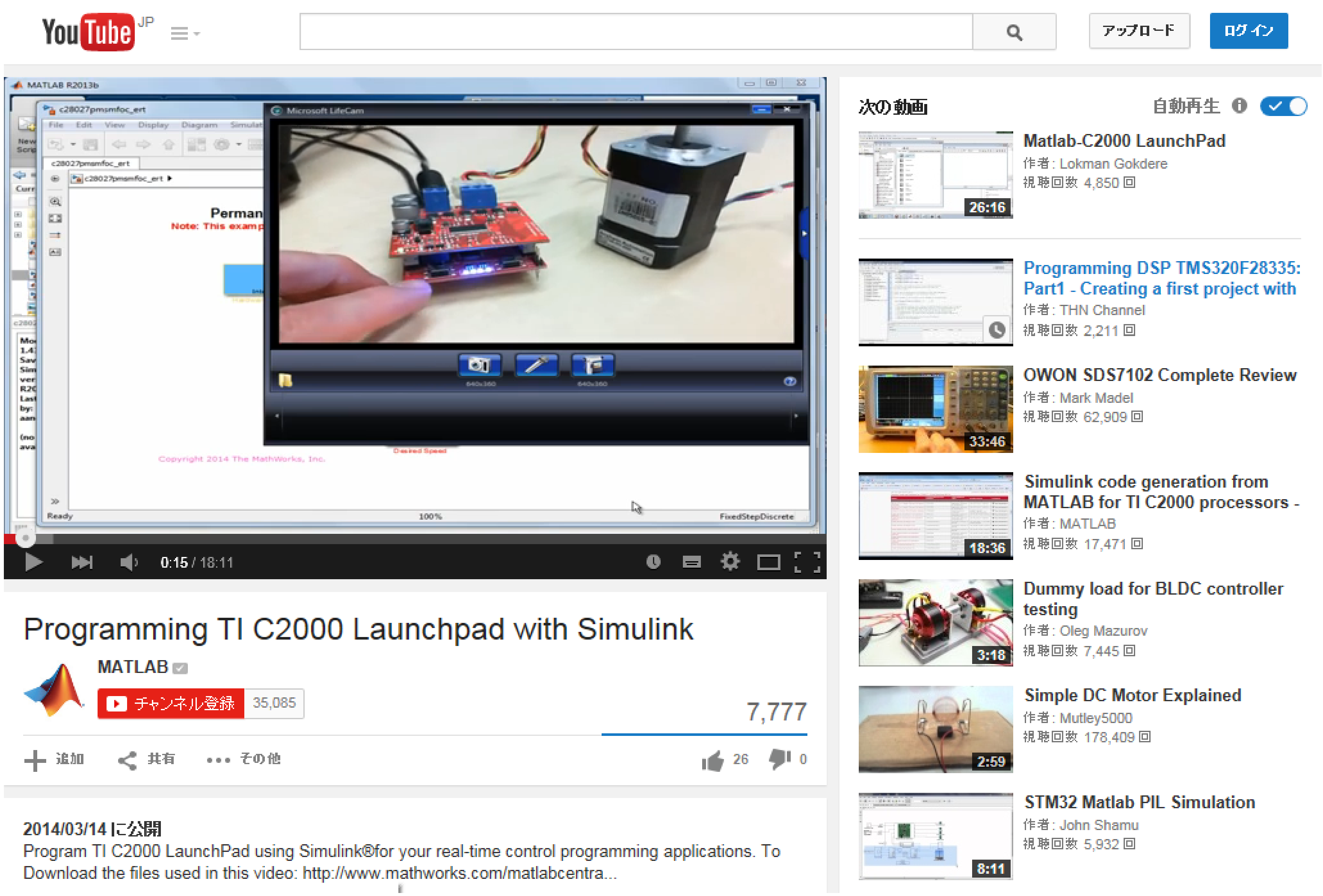


```
if (g_f4_iq_ref > MTR_LIMIT_IQ) {
  g_f4_iq_ref = MTR_LIMIT_IQ;
} else {
  if (g_f4_iq_ref < -MTR_LIMIT_IQ) {
    g_f4_iq_ref = -MTR_LIMIT_IQ;
  }
}
```

TI F28069ISO + DRV8312-C2-KIT used

モーター制御システム外観

Example on YouTube MATLAB Channel



Programming TI C2000 Launchpad with Simulink

MATLAB

2014/03/14 に公開

Program TI C2000 LaunchPad using Simulink®for your real-time control programming applications. To Download the files used in this video: http://www.mathworks.com/matlabcentra...

Matlab-C2000 LaunchPad
作者 : Lokman Gokdere
視聴回数 4,850 回
26:16

Programming DSP TMS320F28335: Part1 - Creating a first project with
作者 : THN Channel
視聴回数 2,211 回

OWON SDS7102 Complete Review
作者 : Mark Madel
視聴回数 62,909 回
33:46

Simulink code generation from MATLAB for TI C2000 processors -
作者 : MATLAB
視聴回数 17,471 回
18:36

Dummy load for BLDC controller testing
作者 : Oleg Mazurov
視聴回数 7,445 回
3:18

Simple DC Motor Explained
作者 : Mutley5000
視聴回数 178,409 回
2:59

STM32 Matlab PIL Simulation
作者 : John Shamu
視聴回数 5,932 回
8:11

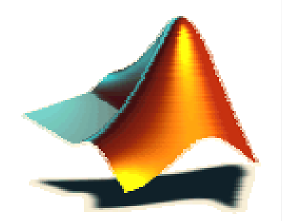
https://www.youtube.com/watch?v=wxYTLbYfBP0

How to Embed Your Model?
Coder Solution!

MATLAB Coder®

MEX

C



MATLAB

Simulink Coder®

C

RCP/HILS

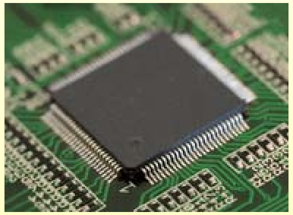
HDL Coder™

HDL

FPGA/ASIC

Embedded Coder®

C/C++



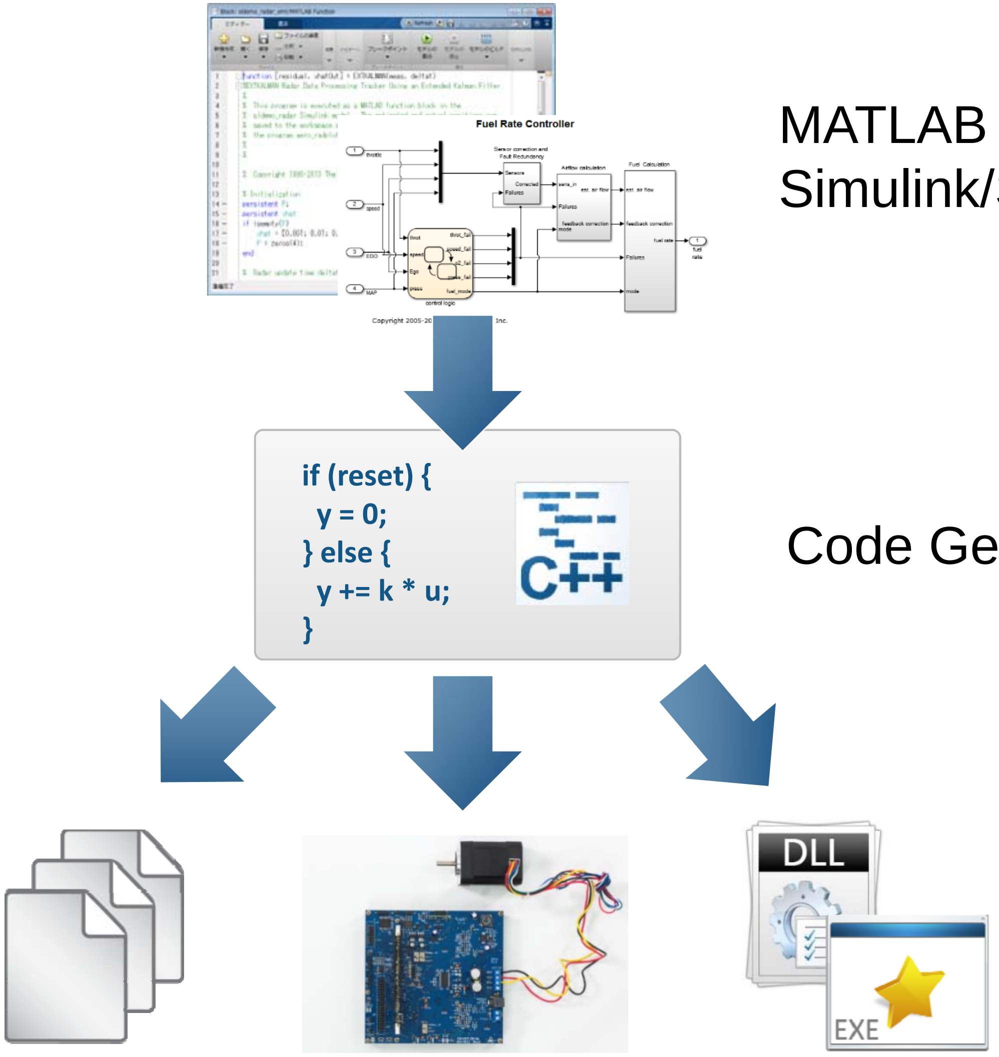
MCU/DSP

Simulink PLC Coder™

ST

PLC

C/C++ Code Development with Embedded Coder



```
if (reset) {
  y = 0;
} else {
  y += k * u;
}
```

MATLAB Program
Simulink/Stateflow Model

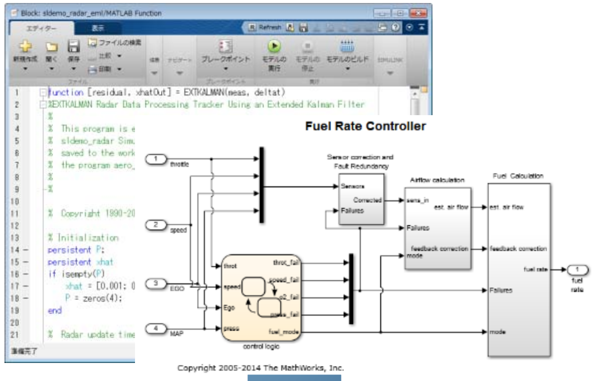
Code Generation

- Used with existing code
- Used for implementation
- Standalone executable/dll

What is Your Merit?

Modeling & Simulation

- Graphical modeling
  - Readable, easy understanding
- Early verification & validation
  - Concept test without hardware



```
function [residual, xhatOut] = EXTKALMAN(meas, deltat)
%EXTKALMAN Radar Data Processing Tracker Using an Extended Kalman Filter
%
%  This program is e
%  sldemo_radar Simu
%  saved to the work
%  the program aero_
%
%


%  Copyright 1990-20

% Initialization
persistent P;
persistent xhat
if isempty(P)
    xhat = [0.001; 0
    P = zeros(4);
end

%  Radar update time
```

Automatic Code Generation

- Coding time reduction
- Error reduction from model to code conversion
- Automatic synchronization between model and code

```
if (reset) {
  y = 0;
} else {
  y += k * u;
}
```

C++

User Story

Model-based design was a key enabler to Volt's rapid development.

Credit: General Motors LLC 2011

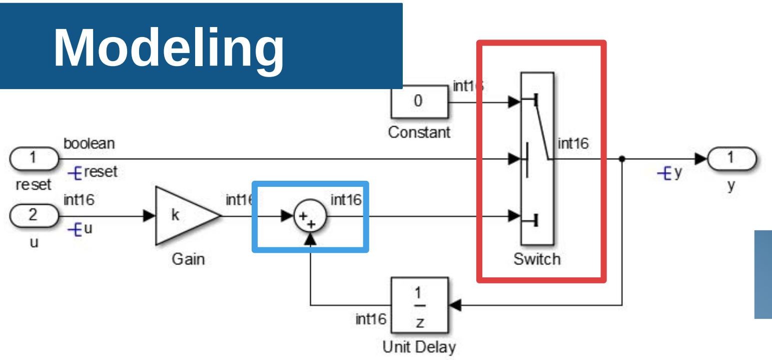
With its more than 100 electronic controllers and about 10 million lines of computer code, the Volt significantly raised the level of controls and systems-integration challenges for GM engineers.

> “We have a single source for how a particular function should behave. Automatic code generation using The MathWorks’ Real-Time Workshop Embedded Coder was vital to meeting Volt’s aggressive program timing.”
>
> Greg Hubbard
> Senior Manager

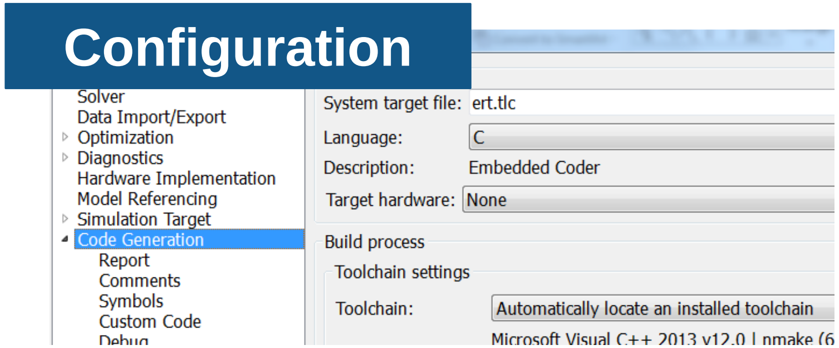
Nearly 100% of the software for many of Volt’s modules was generated automatically.

Embedded Coder Quick Demo

Modeling



Configuration



System target file: ert.tlc

Language: C

Description: Embedded Coder

Target hardware: None

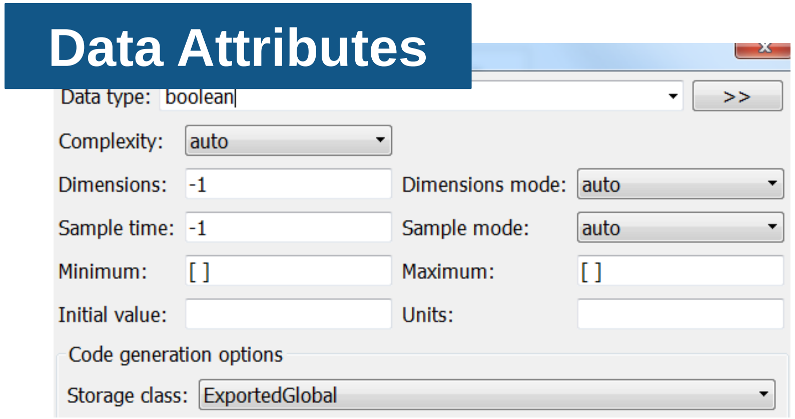
Build process

Toolchain settings

Toolchain: Automatically locate an installed toolchain

Microsoft Visual C++ 2013 v12.0 | nmake (6

Data Attributes



Data type: boolean

Complexity: auto

Dimensions: -1 Dimensions mode: auto

Sample time: -1 Sample mode: auto

Minimum: [ ] Maximum: [ ]

Initial value: Units:

Code generation options

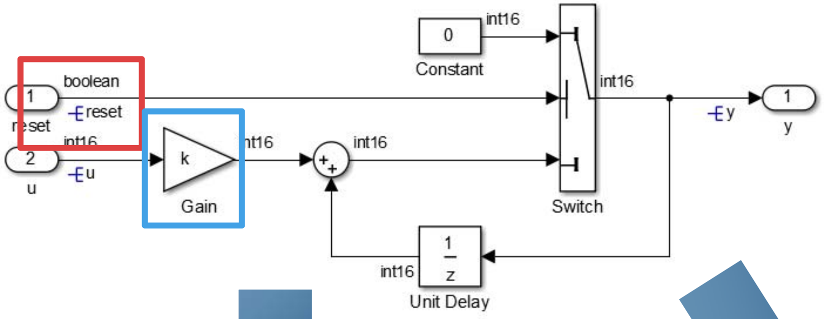
Storage class: ExportedGlobal

```
boolean_T reset;
const volatile int8_T k = 2;

void rst_cntr_step(void)
{
  if (reset) {
    y = 0;
  } else {
    y += (int16_T)(k * u);
  }
}
```

- Equivalent Code as Model
- High Readability & Efficiency

Data Attributes



```
boolean_T reset;
const volatile int8_T k = 2;

void rst_cntr_step(void)
{
  if (reset) {
    y = 0;
  } else {
    y += (int16_T)(k * u);
  }
}
```

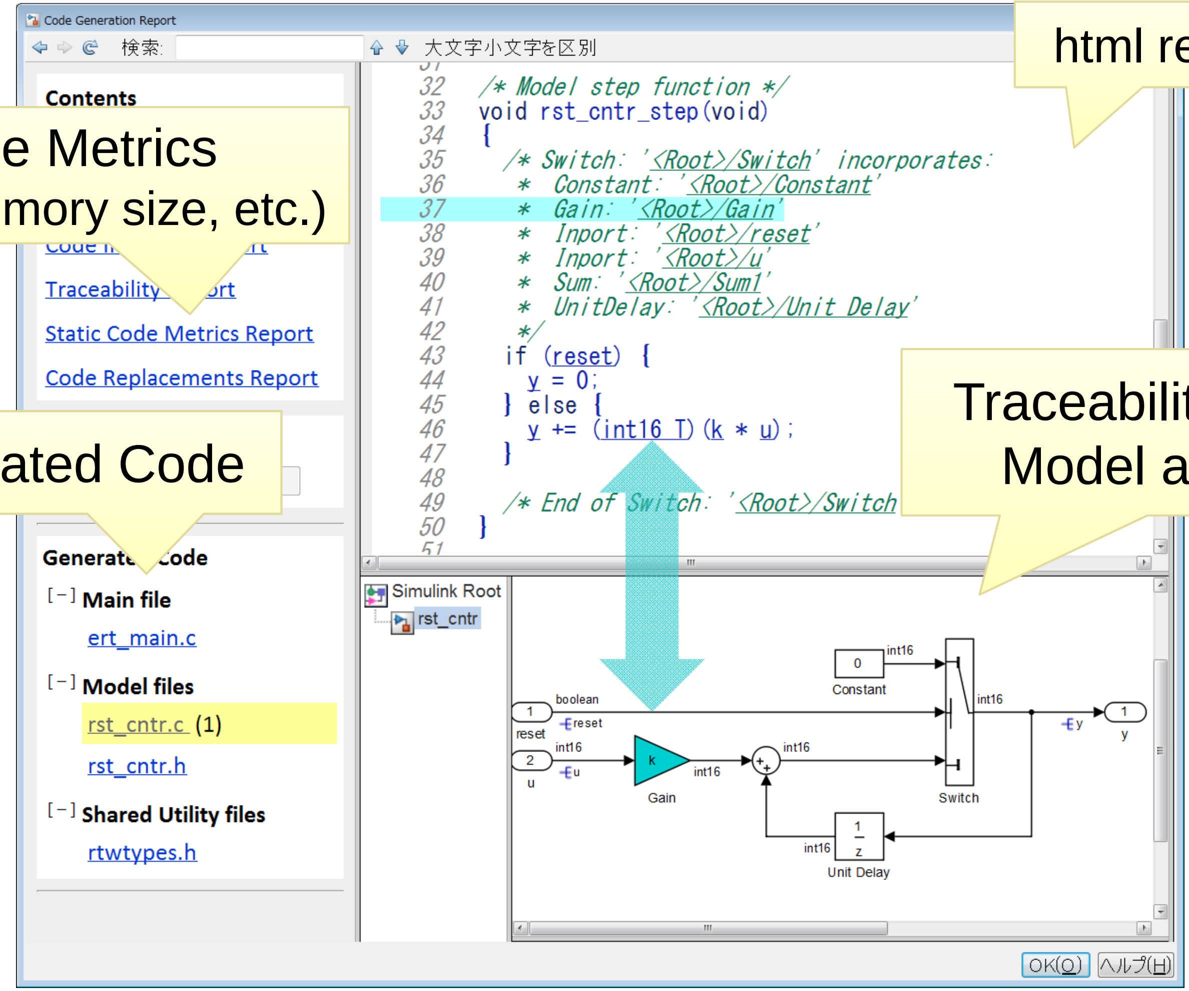
Global Variable

```
void rst_cntr(
  boolean_T reset,
  int16_T u,
  int16_T *y)
```

Function Argument

- You can define data attributes in your model
  - Signal line
  - States (Unit Delay etc.)
  - Block parameter
  - Stateflow data

Code Generation Report



Contents

Code m... ...rt

Traceability ...ort

Static Code Metrics Report

Code Replacements Report

Generate... ...code

[−] **Main file**

ert_main.c

[−] **Model files**

rst_cntr.c (1)

rst_cntr.h

[−] **Shared Utility files**

rtwtypes.h

```
/* Model step function */
void rst_cntr_step(void)
{
  /* Switch: '<Root>/Switch' incorporates:
   *  Constant: '<Root>/Constant'
   *  Gain: '<Root>/Gain'
   *  Inport: '<Root>/reset'
   *  Inport: '<Root>/u'
   *  Sum: '<Root>/Sum1'
   *  UnitDelay: '<Root>/Unit Delay'
   */
  if (reset) {
    y = 0;
  } else {
    y += (int16_T)(k * u);
  }

  /* End of Switch: '<Root>/Switch
}
```

html report

Code Metrics
(lines, memory size, etc.)

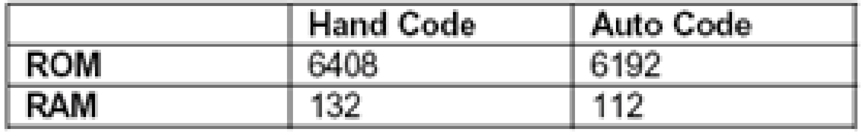
Generated Code

Traceability between
Model and Code

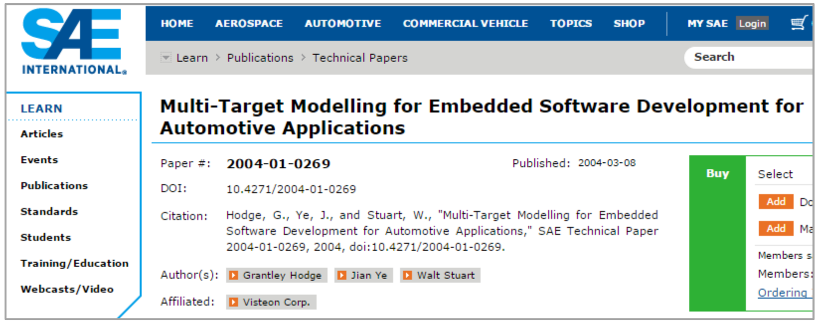
Simulink Report Generator required to generate model view

How about Efficiency of Generated Code?

Table 2 ROM and RAM comparison between a floating-point hand code and auto code.



	Hand Code	Auto Code
ROM	6408	6192
RAM	132	112



Multi-Target Modelling for Embedded Software Development for Automotive Applications

Paper #: **2004-01-0269** Published: 2004-03-08

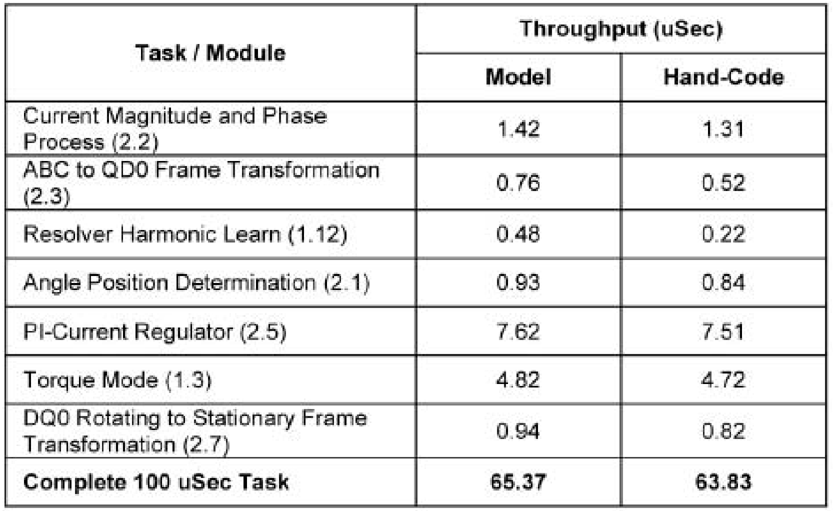
DOI: 10.4271/2004-01-0269

Citation: Hodge, G., Ye, J., and Stuart, W., "Multi-Target Modelling for Embedded Software Development for Automotive Applications," SAE Technical Paper 2004-01-0269, 2004, doi:10.4271/2004-01-0269.

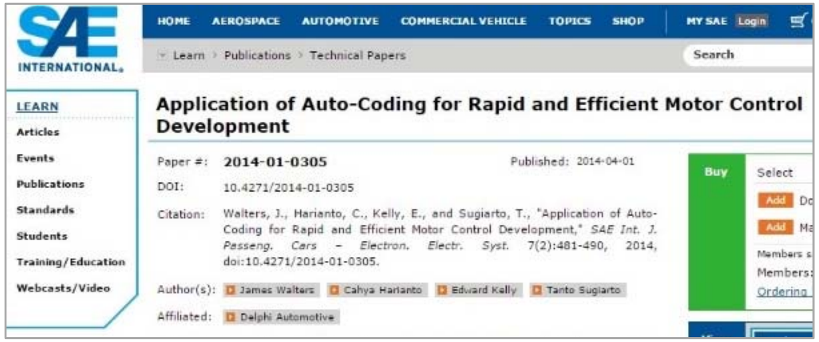
Author(s): Grantley Hodge Jian Ye Walt Stuart

Affiliated: Visteon Corp.

Table 1. Throughput Comparison between Model-Generated Code and Hand-Code



Task / Module	Throughput (uSec)	
	Model	Hand-Code
Current Magnitude and Phase Process (2.2)	1.42	1.31
ABC to QD0 Frame Transformation (2.3)	0.76	0.52
Resolver Harmonic Learn (1.12)	0.48	0.22
Angle Position Determination (2.1)	0.93	0.84
PI-Current Regulator (2.5)	7.62	7.51
Torque Mode (1.3)	4.82	4.72
DQ0 Rotating to Stationary Frame Transformation (2.7)	0.94	0.82
Complete 100 uSec Task	**65.37**	**63.83**



Application of Auto-Coding for Rapid and Efficient Motor Control Development

Paper #: **2014-01-0305** Published: 2014-04-01

DOI: 10.4271/2014-01-0305

Citation: Walters, J., Harianto, C., Kelly, E., and Sugiarto, T., "Application of Auto-Coding for Rapid and Efficient Motor Control Development," *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.* 7(2):481-490, 2014, doi:10.4271/2014-01-0305.

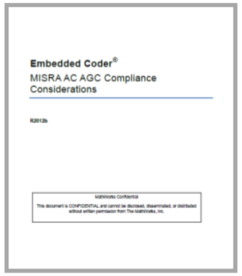
Author(s): James Walters Cahya Harianto Edward Kelly Tanto Sugiarto

Affiliated: Delphi Automotive

How about the Standard Compliance?

MISRA C

- Most rules satisfied
- You can download MISRA compliance document
  http://www.mathworks.com/matlabcentral/answers/102532-misra-c



Embedded Coder®
MISRA AC AGC Compliance Considerations

R2012b

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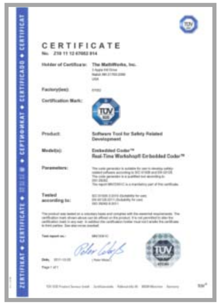
ISO 26262 / IEC 61508

- Tool Qualified by TÜV SÜD
  (ISO26262 ASIL A-D)



CERTIFICATE
No. Z10 11 12 67052 014

Holder of Certificate: The MathWorks, Inc.

Factory(ies):

Certification Mark:

Product: Software Tool for Safety Related Development

Model(s): Embedded Coder™
Real-Time Workshop® Embedded Coder™

Parameters:

Tested according to:

Test report no.:

Date:

Page 1 of 1

ZERTIFIKAT ◆ CERTIFICATE ◆ CERTIFICADO ◆ CERTIFICAT
TÜV

AUTOSAR

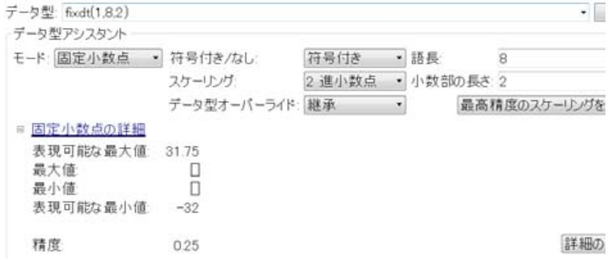
- You can download AUTOSAR Support Package via Simulink menu

Model-Based Design based on AUTOSAR in an Electrical Systems Engineering Environment at Volvo Cars

Dennis Selin, Volvo Cars
Guido Sandmann, MathWorks

How to Design Fixed-Point Controller?
Fixed-Point Designer

Fixed-Point Data Type Settings



データ型: fixdt(1,8,2)

データ型アシスタント

モード: 固定小数点　符号付き/なし: 符号付き　語長: 8

スケーリング: 2 進小数点　小数部の長さ: 2

データ型オーバーライド: 継承

固定小数点の詳細

表現可能な最大値: 31.75

最大値: □

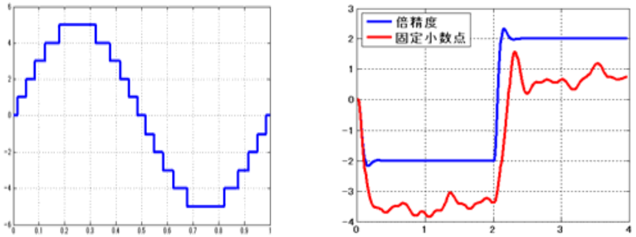
最小値: □

表現可能な最小値: −32

精度: 0.25

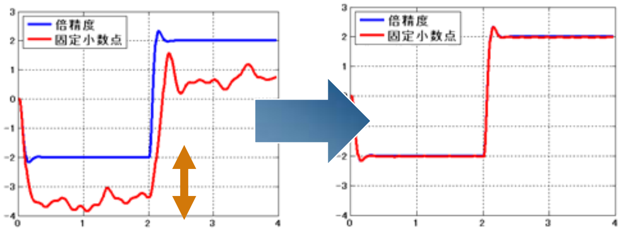
Conversion between Float and Fixed-Point

Useful for Quantization Error Test



Fixed-Point Simulation

Efficient Fixed-Point Scaling



Reduce Quantization Error

Fixed-Point Auto Scaling

Efficient Code Generation

```
int16_T k = 13U;
```

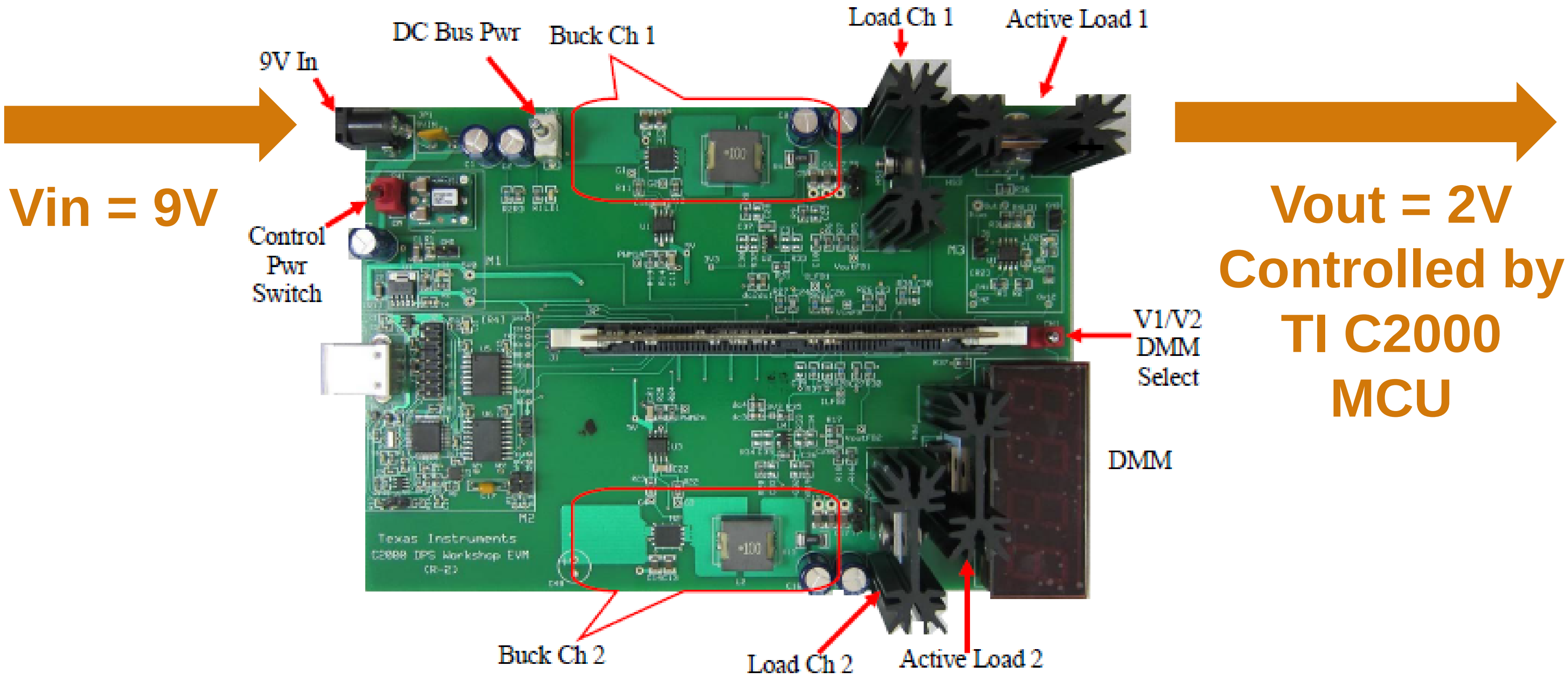
Fixed-Point Value

```
y = y + k * u >> 3;
```

Scaling Adjustment Calculation

Fixed-Point Code Generation

One More Example: Digital DC/DC Converter Control System



Vin = 9V

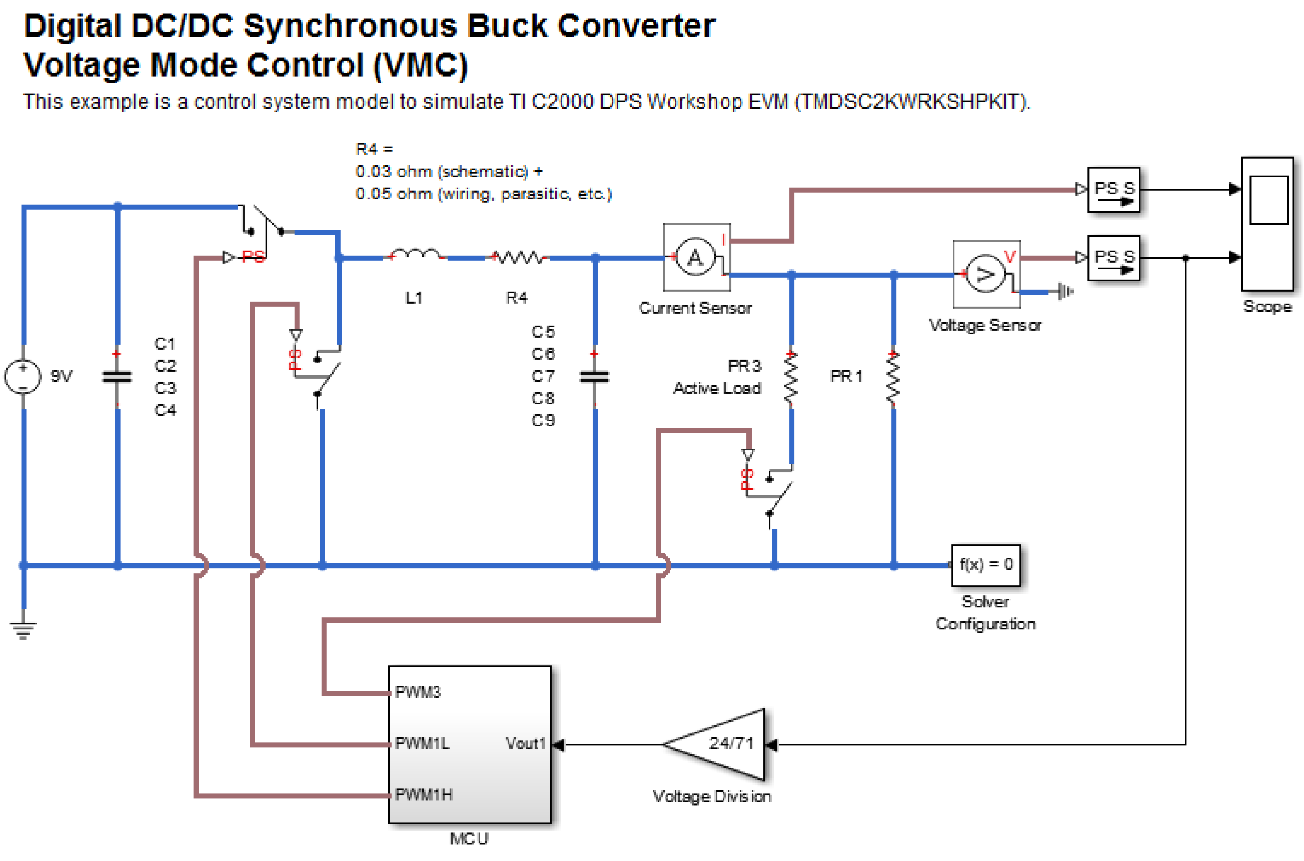
Vout = 2V
Controlled by
TI C2000
MCU

TI C2000 DPS Workshop Kit (CPU: F28035)

Simulation Model

Use for circuit/controller design, parameter tunings

- Making an analog circuit with Simscape components
- Fixed-point PI controller + Rate Limiter (Soft Start)



Digital DC/DC Synchronous Buck Converter
Voltage Mode Control (VMC)

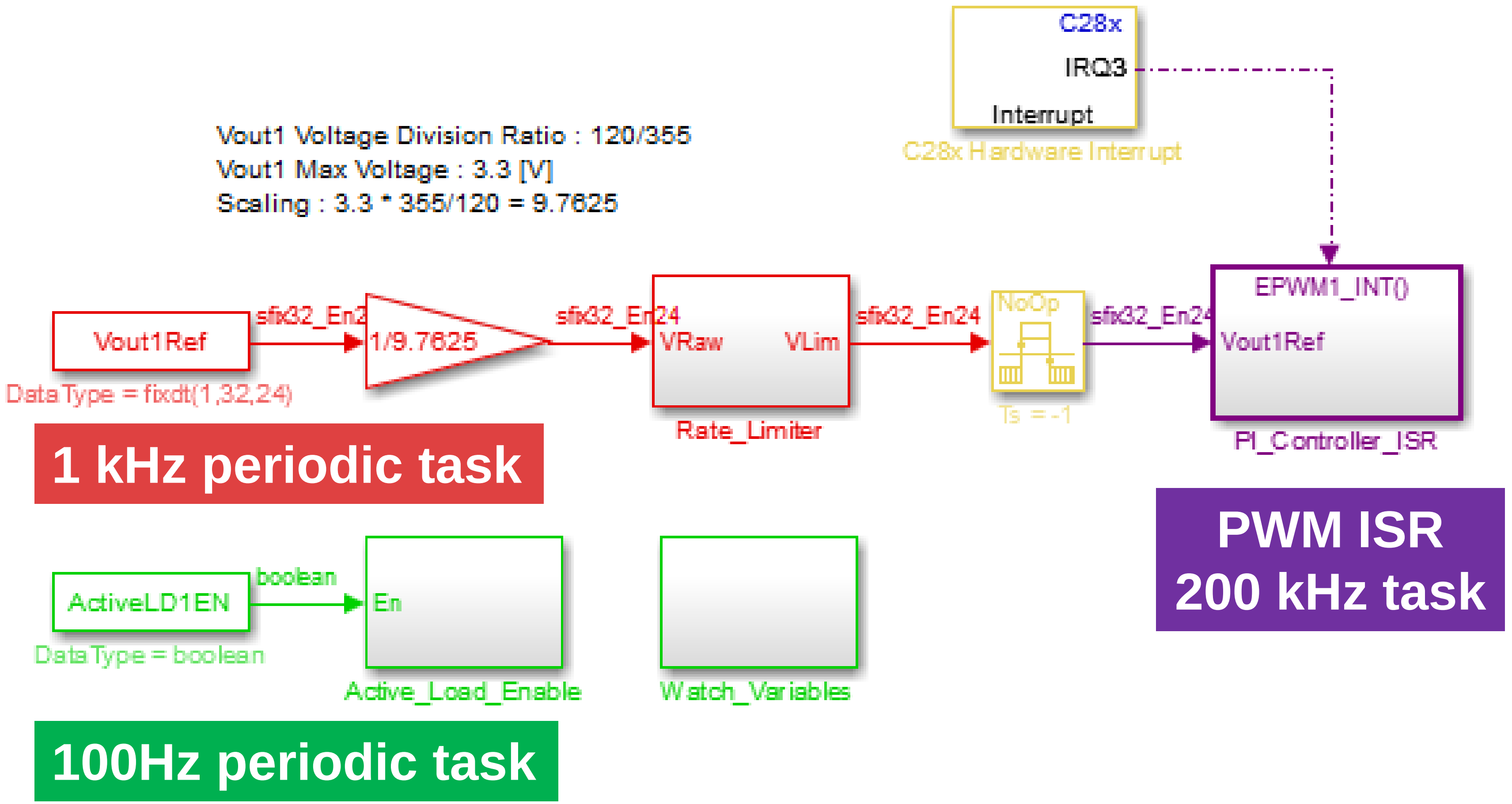
This example is a control system model to simulate TI C2000 DPS Workshop EVM (TMDSC2KWRKSHPKIT).

R4 =
0.03 ohm (schematic) +
0.05 ohm (wiring, parasitic, etc.)

Code Generation Model to F28035

Turnkey to download the controller model into MCU

Using EC TI C2000 support package to implement I/O and ISR



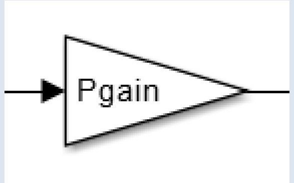
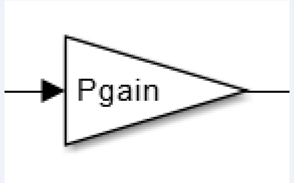
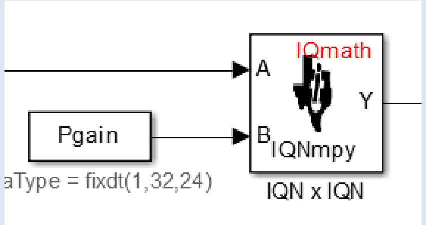
1 kHz periodic task

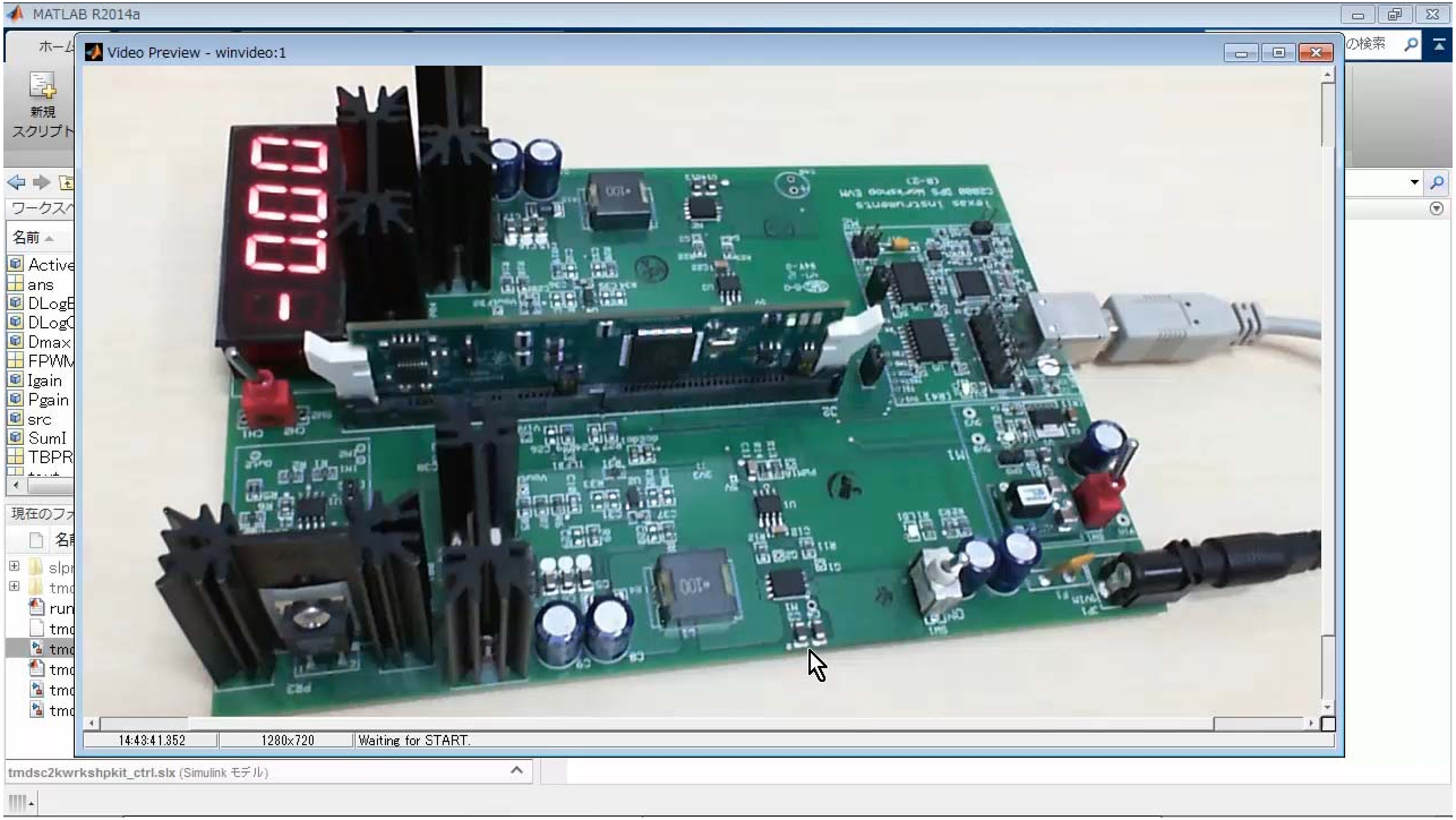
PWM ISR
200 kHz task

100Hz periodic task

CLR/IQmath Blocks and PIL Profiling

C2000 Support Package provides code optimization opportunity and execution time estimation

Model	Generated Code	PIL Execution
ANSI-C (No Optim) 	`rtb_Gain * Pgain`	6.15 us (cannot run at 200 kHz)
TI C28x CLR Only 	`c28x_mul_s32_s32_s32_sr(Pgain, rtb_Gain, 24L)`	3.23 us
TI C28x CLR + IQmath  IQmath A Y B IQNmpy Pgain aType = fixdt(1,32,24) IQN x IQN	`_IQ24mpy(rtb_Gain, Pgain)`	1.8 us

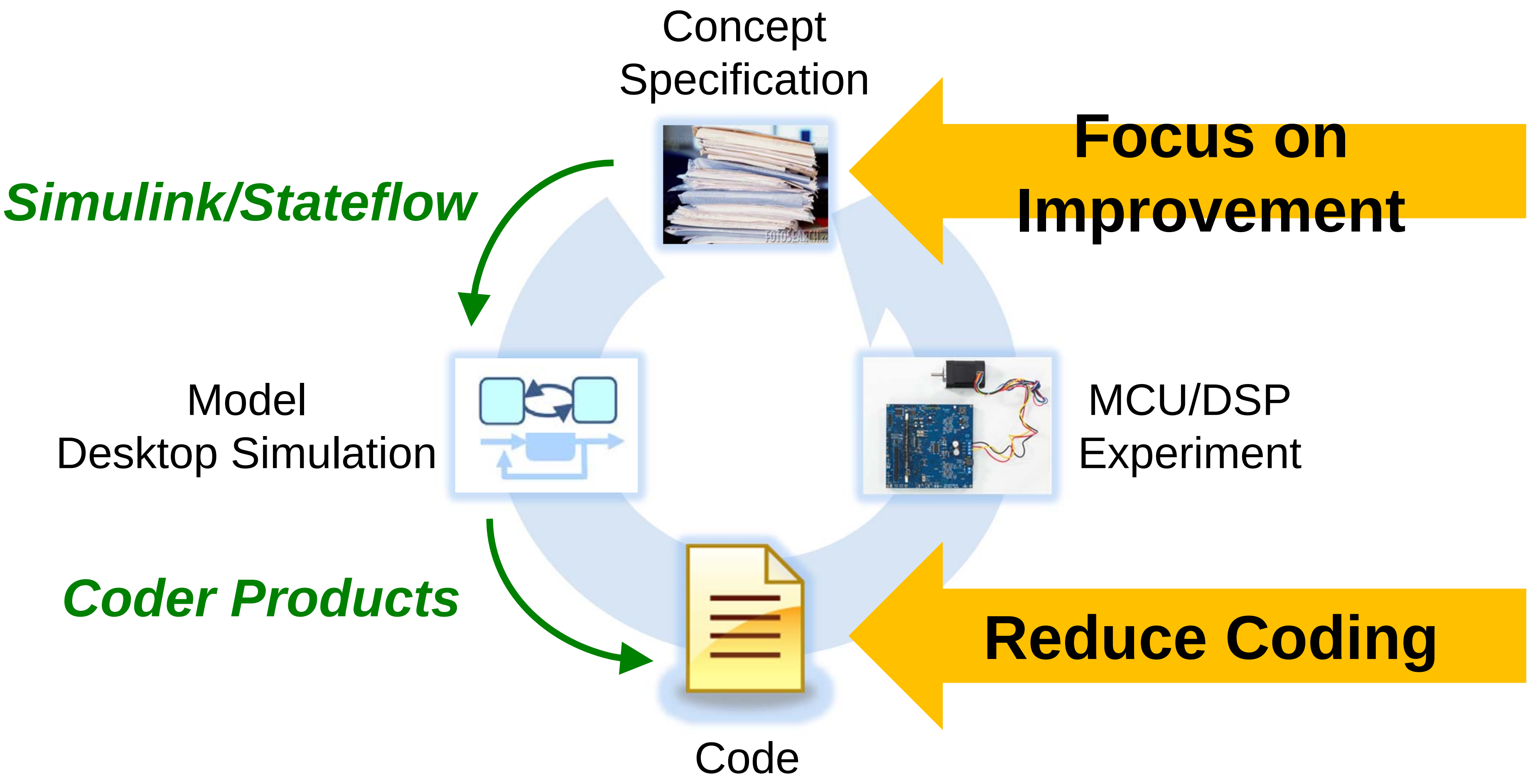


```
14:43:41.352 | 1280x720 | Waiting for START.
```

tmdsc2kwrkshpkit_ctrl.slx (Simulink モデル)

Summary

You can achieve highly efficient development cycle



Concept Specification

Simulink/Stateflow

Focus on Improvement

Model Desktop Simulation

MCU/DSP Experiment

Coder Products

Reduce Coding

Code