APPLICATION OF AUTOMATIC CODE GENERATION FOR RAPID AND EFFICIENT MOTOR CONTROL DEVELOPMENT

Edward Kelly, James Walters, Cahya Harianto, and Tanto Sugiarto

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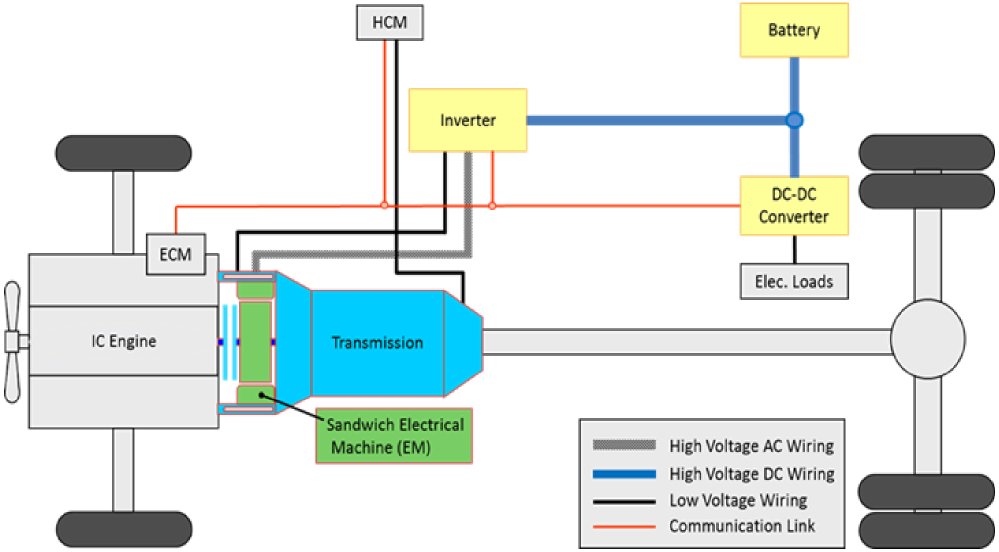
Hybrid Vehicle Motor Controls Overview

Requirements dictate fast algorithm execution

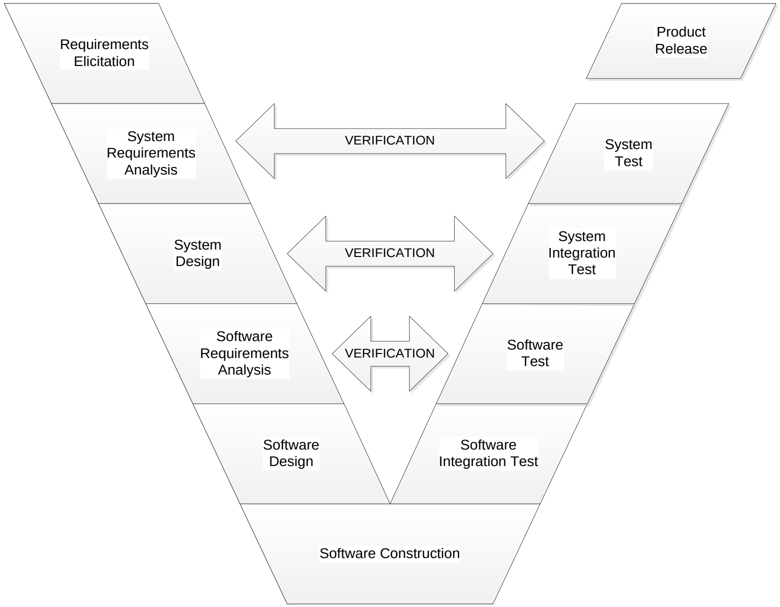
- Torque, speed, voltage and fault reaction modes
  - 1000+ Hz fundamental frequency
  - 500+ Hz current regulator bandwidth
  - 10 kHz PWM rates for DC voltage ripple
- 80 – 100 uSec control loops are common



Software Development Process

General Approach

- Responsibilities
  - Systems: Analyze, derive and specify
  - Software: Implement
  - Software/Systems/Validation: Verify
- Time consuming and error prone
  - Requirements formation, implementation and verification are too dispersed
  - Decoupling of domain knowledge from implementation



Automatic Code Generation

Benefits

- Linking of simulation, code development and testing
  - Common in 5 – 10 mSec task rates
  - Improves testability.
- Implementation responsibility transitions to domain experts
- Potential for time savings
  - Faster verification of implementation
  - Production hardware can be used for design and detailed problem solving

Challenges

- Creating and maintaining easily understood environment and models
- Identifying preferred implementations

Goal

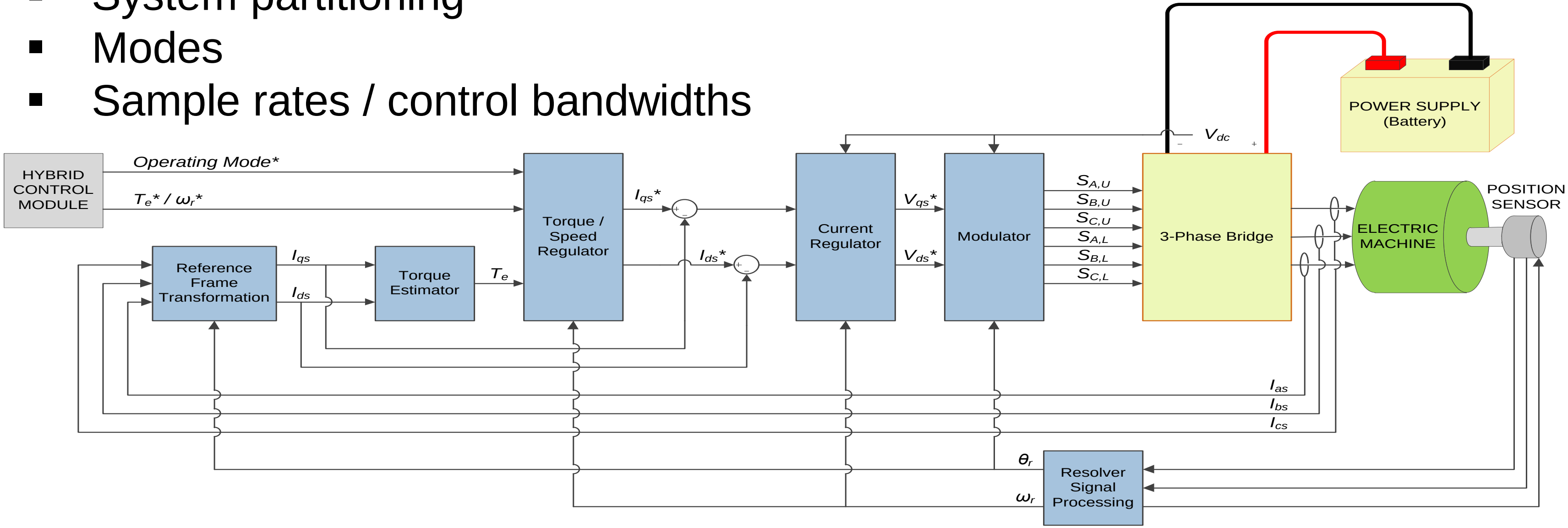
Develop automatic code generation process for time critical tasks

- Requirements focused
  - To support Automotive SPICE
- Directly apply system expertise to implementation
  - Create path for high level simulation models to software
- Shorten time between design, implementation and verification steps
  - Reduce development time
- Create easy to understand implementations that can be shared among teams
- Closely match hand-code throughput efficiency

Process: Requirements Derivation / Partitioning Phase

High level design

- Verify overall requirements are met
- Establish derived requirements
  - Architecture
  - System partitioning
  - Modes
  - Sample rates / control bandwidths



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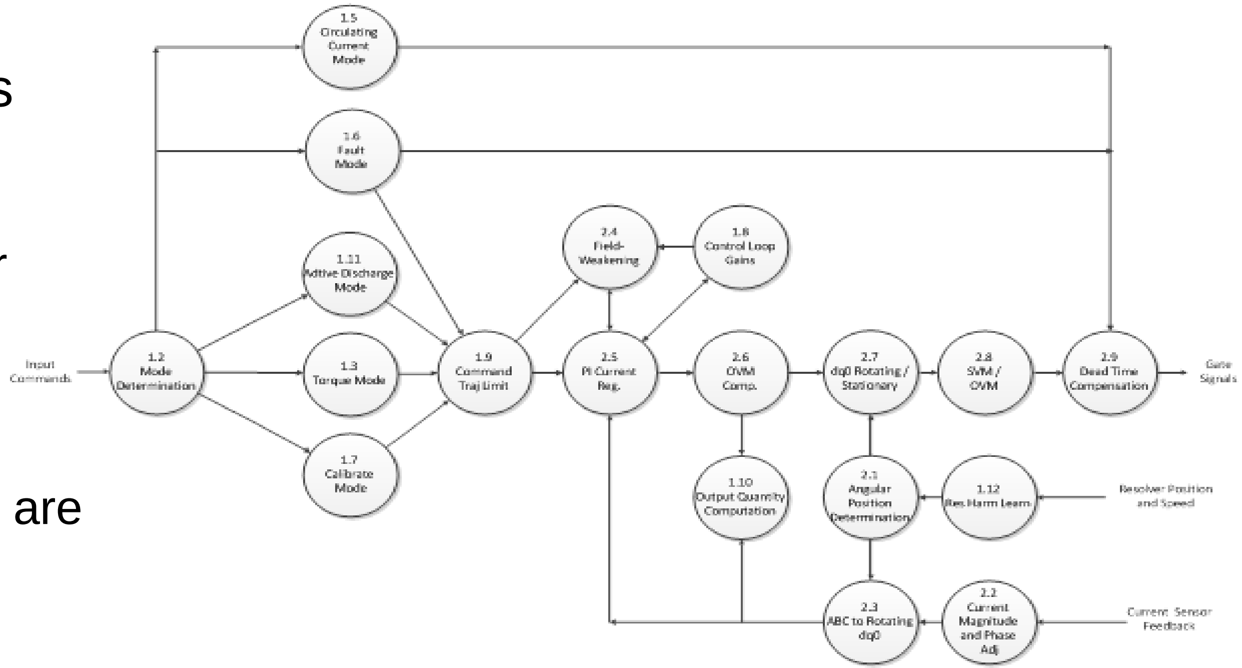
Process: Implementation Phase

Functional Modules

- Testable requirements
  - Inputs / outputs
  - Functionality
  - Execution rate / order
- Model development
  - Best practices
- Documentation
  - Model / requirements are not sufficient
- Test vectors
  - Simulation
  - Requirements verification



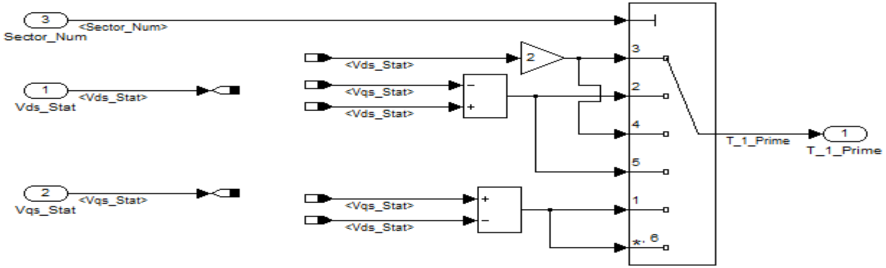
Process: Implementation Phase (Modelling)

Simulation tools offer numerous options for implementation

- Not all approaches will code with equal efficiency
  - Tools have optimization settings
- Consistency of implementation among modules is important for ‘read-ability’
  - Key for sharing among teams
- Peer review process is important to ensure efficient code
  - Systems: Implementation meets requirements
  - Software: Optimization and problem resolution
    - Detailed review of code
    - Identification of best practices

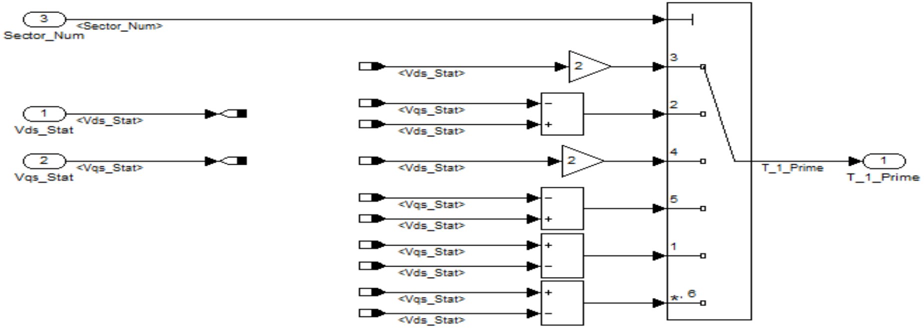
Process: Implementation Phase (Example 1)

Inefficient Model / Code:




```
real32_T rtb_Gain3;
real32_T rtb_Add2;
rtb_Add2 = Vds_Stat - Vqs_Stat;
T_1_Prime = Vqs_Stat - Vds_Stat;
rtb_Gain3 = 2.0F * Vds_Stat;
switch (Sector_Num) {
 case 3:
  T_1_Prime = rtb_Gain3;
  break;

 case 2:
  T_1_Prime = rtb_Add2;
  break;

 case 4:
  T_1_Prime = rtb_Gain3;
  break;

 case 5:
  T_1_Prime = rtb_Add2;
  break;

 case 1:
  break;
}
```

Efficient Model / Code:




```
switch (Sector_Num) {
 case 3:
  T_1_Prime = 2.0F * Vds_Stat;
  break;

 case 2:
  T_1_Prime = Vds_Stat - Vqs_Stat;
  break;

 case 4:
  T_1_Prime = 2.0F * Vds_Stat;
  break;

 case 5:
  T_1_Prime = Vds_Stat - Vqs_Stat;
  break;

 case 1:
  T_1_Prime = Vqs_Stat - Vds_Stat;
  break;

 default:
  T_1_Prime = Vqs_Stat - Vds_Stat;
  break;
}
```

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Process: Implementation Phase (Example 2)

Inefficient Embedded MATLAB code:

```
floor_index = uint32(unfloor_index);
```

Generated code:

```
/*  ================================================================== */
/* '<S3>:1:46' */
tmp = unfloor_index;
if ((unfloor_index < 8.388608E+6F) && (unfloor_index > -8.388608E+6F)) {
  tmp = (unfloor_index < 0.0F) ? ceilf(unfloor_index - 0.5F) : floorf
    (unfloor_index + 0.5F);
}

floor_index = (uint32_T)tmp;
```

Process: Implementation Phase (Example 2)

Inefficient Embedded MATLAB code:

```
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Generated code:

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    (unfloor_index + 0.5F);
}

floor_index = (uint32_T)tmp;
```

Process: Implementation Phase (Example 2)

Efficient Embedded MATLAB Code:

```
        floor_index = coder.ceval('SingleToInteger32',unfloor_index);
```

Hand-coded CustomFuntion.h:

```
#ifndef CustomFunction_H
#define CustomFunction_H

#include "rtwtypes.h"

#define SingleToInteger32(u)   ( (int32_T) u )
```

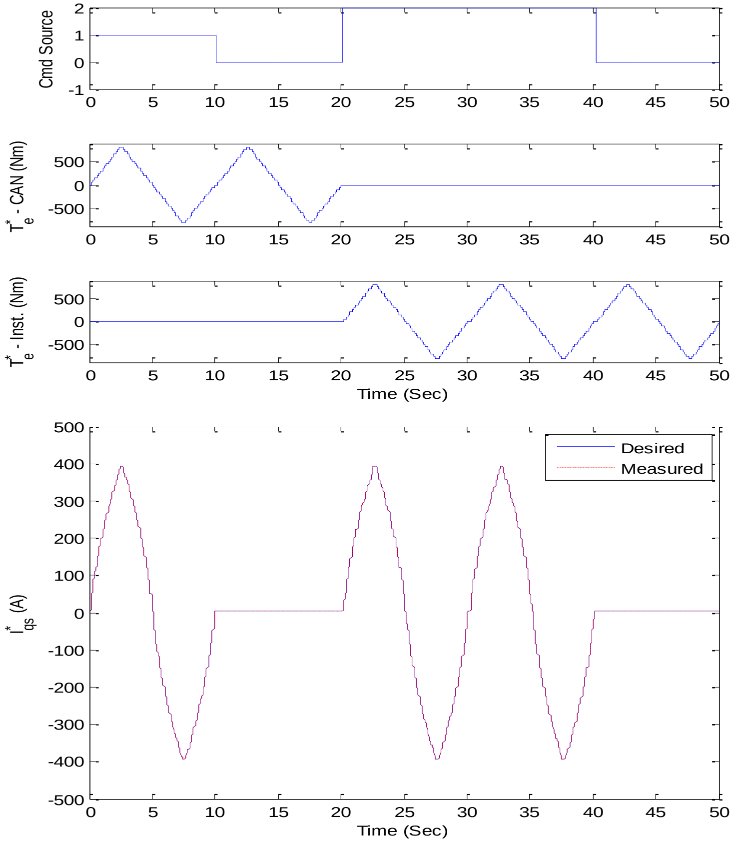
Generated code:

```
/* '<S3>:1:46' */
floor_index = SingleToInteger32(unfloor_index);
```

Process: Verification Phase

Test to verify requirements are met

- Module test vectors
  - Verify functionality
    - Inputs / internal variables / outputs
- Full model test vectors
  - Simulation environment
  - Hardware in the loop
    - Correct compiler
    - Simulate virtual load in processor or test bench



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Evaluation of Process

Verified auto generated software was dynamometer tested to evaluate performance

- Comparison was made to mature hand-code
- Equivalent motor control functionality
- Slight penalty in 100 uSec task throughput
  - 1.54 uSec

Task / Module	Throughput (uSec)	
	Model	Hand-Code
Current Magnitude and Phase Process	1.42	1.31
ABC to dq0 Frame Transformation	0.76	0.52
Resolver Harmonic Learn	0.48	0.22
Angle Position Determination	0.93	0.84
PI-Current Regulator	7.62	7.51
Torque Mode	4.82	4.72
dq0 Rotating to Stationary Frame Transformation	0.94	0.82
Complete 100 uSec Task	**65.37**	**63.83**

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Summary

Structured automatic code generation can be applied to time critical tasks

- A process is required to ensure efficient implementations
- New roles
  - Software: responsible for auto-coding environment, determining best practices, peer reviewing implementations and detailed problem solving
  - System: responsible for forming requirements, creating implementations that demonstrably meet requirements (test vectors) and following identified best practices
- Requirements and models are not sufficient to document implementation
- Automatic code generation should be viewed as a tool to link simulation, implementation and verification testing
  - Concurrent activities speed the software development process

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