

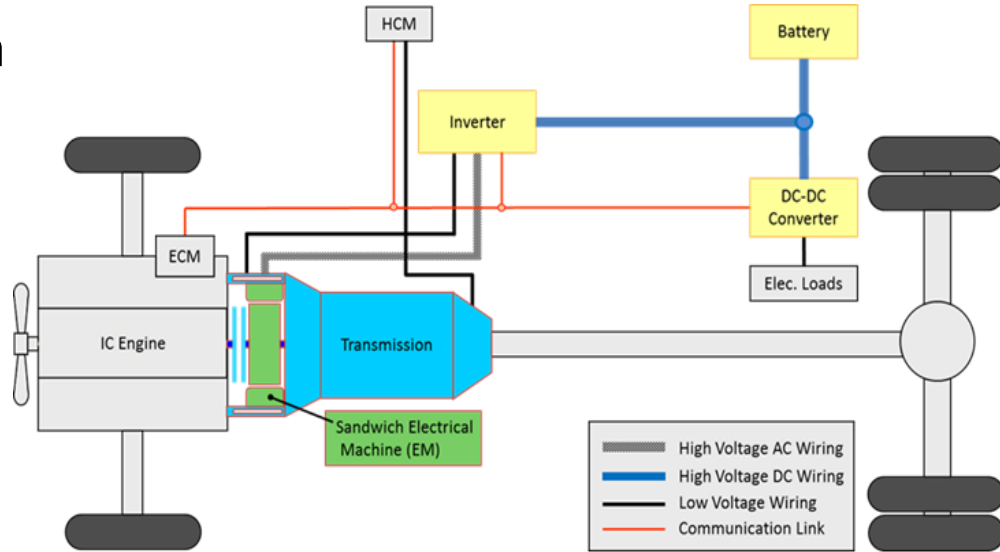
# APPLICATION OF AUTOMATIC CODE GENERATION FOR RAPID AND EFFICIENT MOTOR CONTROL DEVELOPMENT

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# Hybrid Vehicle Motor Controls Overview

Requirements dictate fast algorithm execution

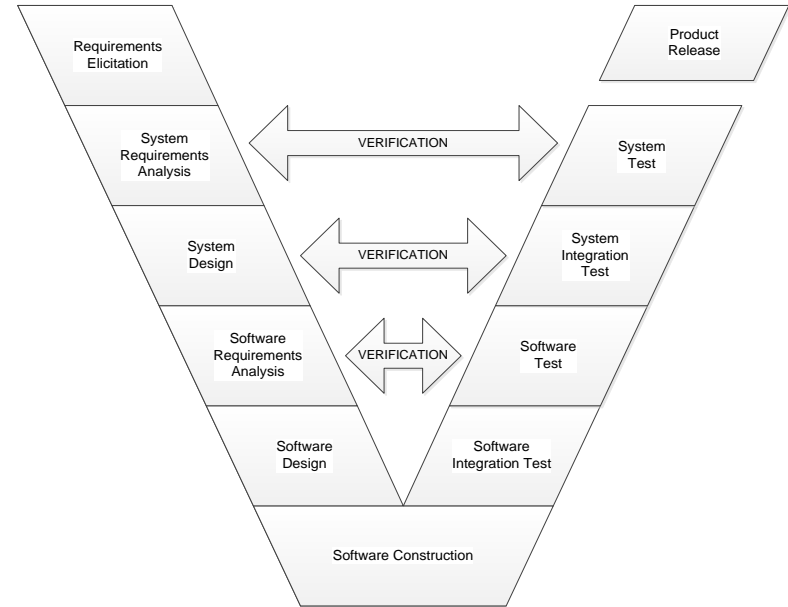
- Torque, speed, voltage and fault reaction modes
  - 1000+ Hz fundamental frequency
  - 500+ Hz current regulator bandwidth
  - 10 kHz PWM rates for DC voltage ripple
- 80 – 100 uSec control loops are common



# 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

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## 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

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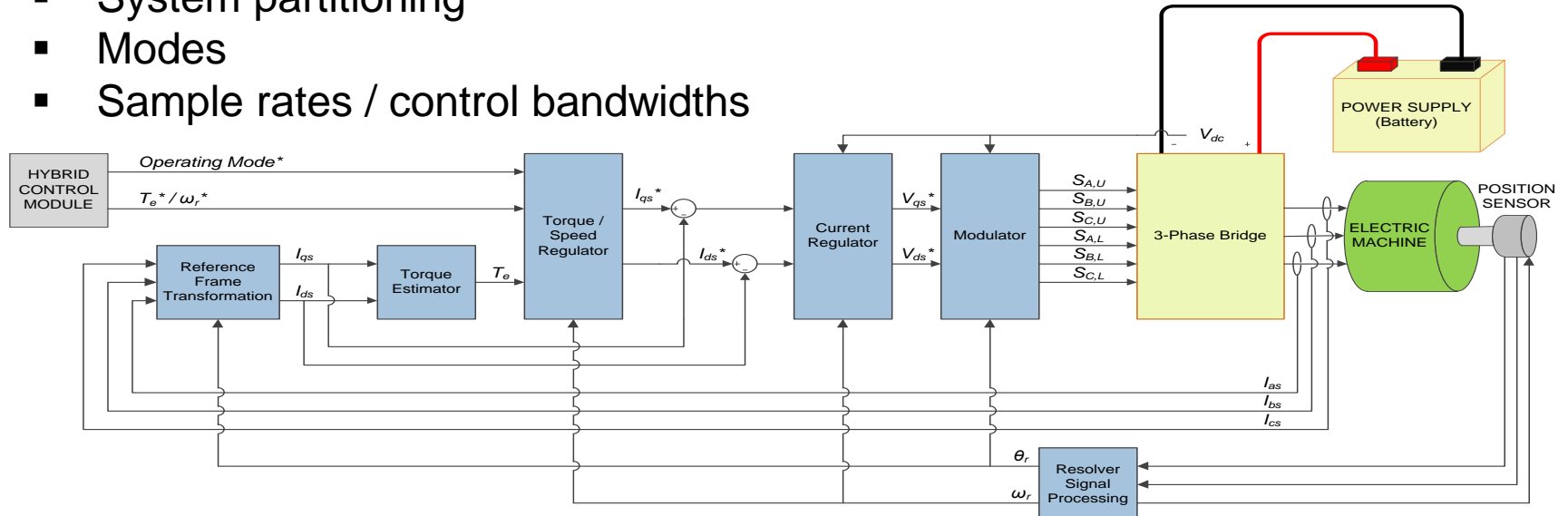
## Develop automatic code generation process for time critical tasks

- 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

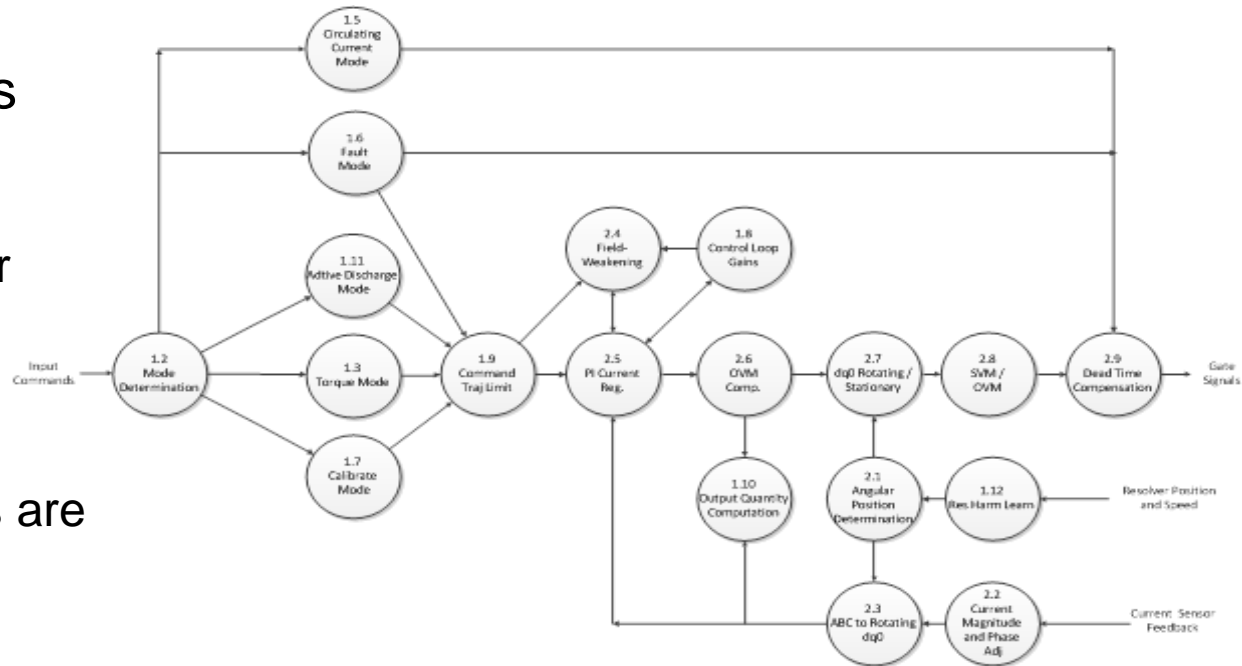
- Verify overall requirements are met
- Establish derived requirements
  - Architecture
  - System partitioning
  - Modes
  - Sample rates / control bandwidths



# 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)

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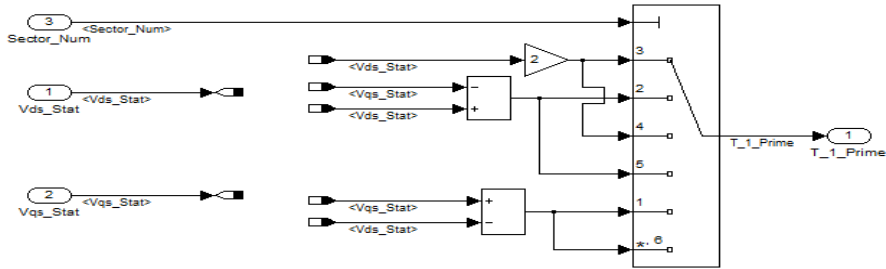
## Simulation tools offer numerous options for implementation

- Not all approaches will code with equal efficiency
  - Tools have optimization settings
- Consistency of implementation among modules is important for 'readability'
  - 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



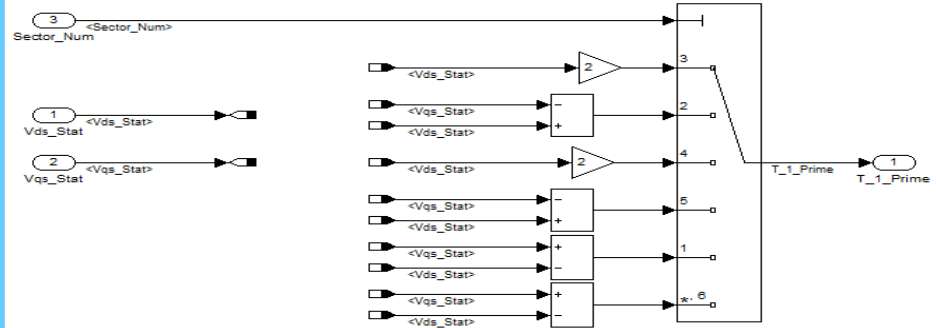
# Process: Implementation Phase (Example 1)

## 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;  
}
```

# Process: Implementation Phase (Example 2)

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## Inefficient Embedded MATLAB code:

```
45  
46 -     floor_index = uint32(unfloor_index);  
47
```

## 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)

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## 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)

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## Efficient Embedded MATLAB Code:

```
45  
46 -     floor_index = coder.ceval('SingleToInteger32',unfloor_index);  
47
```

Hand-coded CustomFunction.h:

```
#ifndef CustomFunction_H  
#define CustomFunction_H  
  
#include "rtwtypes.h"  
  
#define SingleToInteger32(u)  ( (int32_T) u )
```

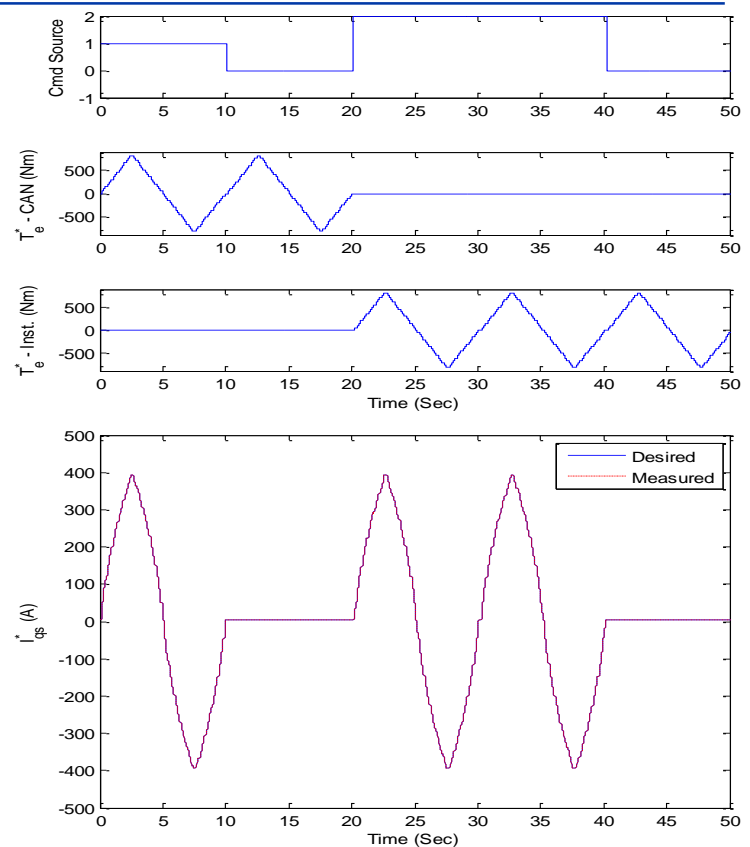
Generated code:

```
/* '<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



# 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         |
| <b>Complete 100 uSec Task</b>                   | <b>65.37</b>      | <b>63.83</b> |

# Summary

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## 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

# Acknowledgement of Support

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