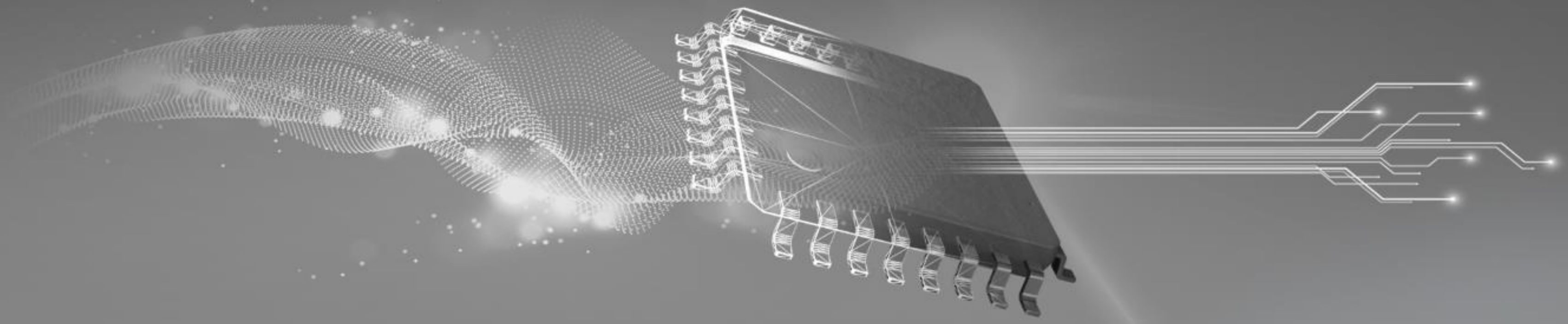
TI TECH DAYS



Integrating high RPM traction inverter, software resolver interface and DC/DC converter with ASIL D concept assessed C2000™ reference design

Ashish Vanjari, Han Zhang, Krishna Allam
C2000 real-time control MCUs

Outline

- C2000 enabling emerging integration trends in EV
- TI reference design
- Functional safety concept
- Highlights of reference design
- Q and A

C2000 ENABLING EMERGING INTEGRATION TRENDS IN EV

Embedded innovation in automotive design

Advanced driver assistance systems (ADAS)

- **Jacinto™ ADAS processors** for camera-based front (mono/stereo), rear, surround view and night vision systems
- Heterogeneous architecture for performance and efficiency

Infotainment & Cluster

- **Jacinto™ automotive digital cockpit processors** provide infotainment, instrument cluster and telematics features
- Scale from entry to premium vehicles

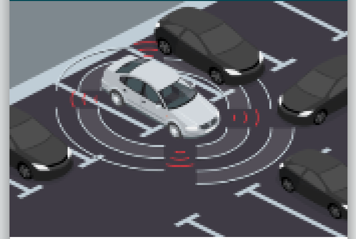
Hybrid/electric and power train systems

- **C2000™ MCUs** optimized for EV onboard charging, DC/DC converters, and traction control
- Advanced power control technology to extend range and reduce charge times

Body Electronics & Lighting

- **SimpleLink™ Bluetooth® low energy wireless MCUs** for vehicle access with relay attack prevention
- Angle of arrival with increased receiver sensitivity to improve accuracy

mmWave Radar



- **Single-chip mmWave sensors** for ADAS, body & chassis and in-cabin applications
- Processor integration with RFCMOS plus a scalable family of devices, enables the smallest form factor sensors

Made for automotive

Scalable hardware & software platforms

Continuous innovation

Quality, reliability & longevity

C2000™ controllers overview

Scalable, **ultra-low latency**, **real-time controller** platform designed for efficiency in power electronics, such as high power density, high switching frequencies, GaN and SiC technologies

C2000™ Real-Time Control Microcontrollers
Texas Instruments

C2000 controllers

Sense

Highly accurate sensing
- 12-/16-bit ADCs, up to 24 channels
- ADC post processing, and externally accessible DACs

Process

High performance processing
Floating-point DSP C28x™ core + parallel multi-core architecture + instructions set optimized for control math, up to 925 MIPS

Control

Highly flexible, High-resolution PWMs:
- Up to 32 outputs
- Integrated comparators, eCAP, eQEP,
- Position Manager, Sigma-Delta Filter Module, trip zones

Interface

CAN, CAN-FD, LIN, UART, SPI, I2C, PMBus, USB, 10/100 Ethernet MAC, EtherCAT®, XEMIF

25 years expertise in real-time control systems

Expertise and support:
Software libraries, reference designs, and functional safety-compliant devices.

Leading innovation:
Configurable Logic Block for peripheral customization, Fast Serial Interface for high-speed communication, ERAD for enhanced diagnostics and profiling

1.2-V core, 3.3-V I/O design	Up to 1.5 MB Flash, 256 kB RAM (ECC protected)	QFN, QFP, BGA packages	-40 to 125C temperature range	Q100 automotive qualified options

Broad range of industrial and automotive applications with compatible software

C2000™ MCU | portfolio for EV performance + integration

F2838xD
200+125 MHz/925 MIPS
1.5MB FLASH

F2837xS & D
200 MHz/800 MIPS
1MB FLASH

F2807x
120 MHz/240 MIPS
512kB FLASH

F28004x
100 MHz/200 MIPS
256kB FLASH

F2803x
60 MHz/120 MIPS
128kB FLASH

F28002x
100 MHz/100 MIPS
128kB FLASH

F2802x
60 MHz/60 MIPS
64kB FLASH

Expanding : Low/Mid/High end

Modular → Integrated

Full Integration : OBC PFC+OBC DC/DC+HV DC/DC+Traction

OBC PFC + OBC DC/DC + HV DC/DC	>1 High Speed Traction Motor with s/w resolver decoding + HV DC/DC	
	>1 High Speed Traction Motor with s/w resolver decoding	
OBC PFC + OBC DC/DC	OBC DC/DC + HV DC/DC	1 Traction Motor with s/w resolver decoding
OBC PFC	OBC DC/DC	HV DC/DC	1 Traction Motor

Q100 Production | Sampling | Development

IP Technology Roadmap

64-bit Floating Point Unit
Improved floating point precision for higher performing applications

Configurable Logic Block (CLB)
Augment existing peripherals and implement custom logic. Integrate critical functions into a single C2000 MCU and reduce in size or completely eliminate your FPGA, CPLD, or external logic components.

Fast Serial Interface
High data-rate (up to 200 MBPs), low pin-count serial communications interface with error detection technology.

CAN-FD Connectivity
Extending our existing CAN support to the latest "flexible data rate" standard

Processing
- CLA Real-time co-processor
- Trigonometric Math Unit
- VCU

Actuation
- High Resolution PWMs

Sensing
- 16-bit ADC
- Programmable Gain Amplifiers
- Sigma Delta Filters

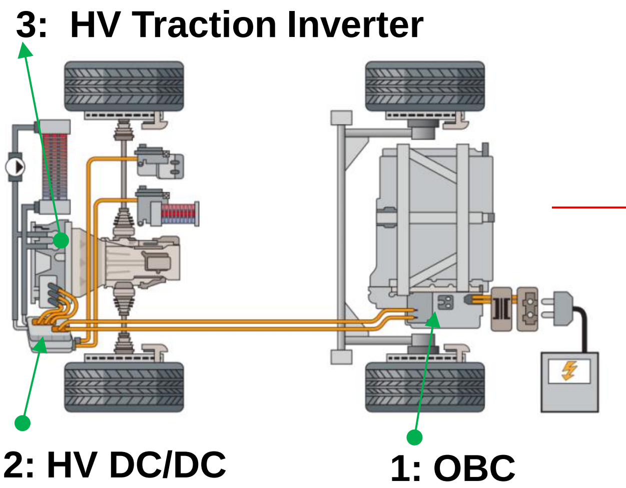
Connectivity
- LIN
- Ethernet Connectivity

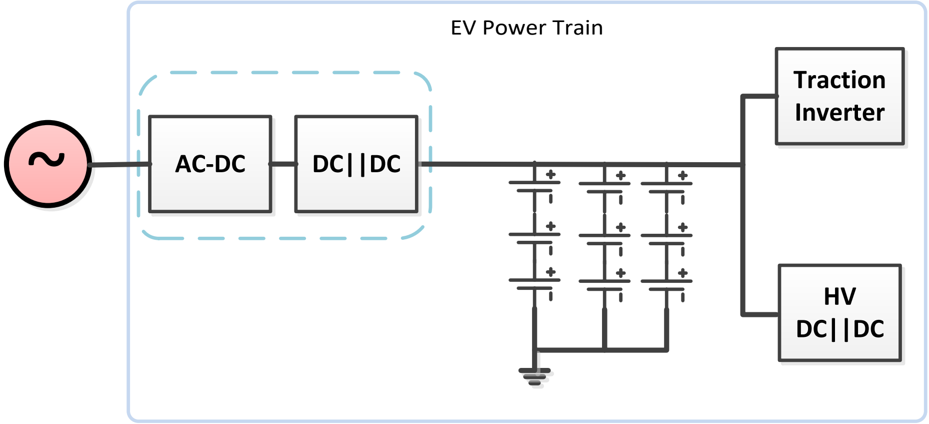
Technology
- InstaSPIN Motor Technology

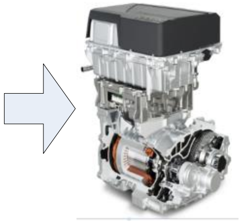
Safety : ASIL-B/ASIL-D Device and/or System Level

Texas Instruments

TI C2000™ real-time controllers for electric vehicles







About C2000 Real-time Controllers in Automotive

- C2000 architecture designed for power electronics, **+25 years**
- **Scalable portfolio** from **50** to **925 MIPS**; with advanced integrated analog
- Enabling **Digital Power + Motor Control** on a single C2000 device
- **TI Reference Designs** showcase the capability of C2000 and unlock the efficiency of SiC/GaN
- C2000 on the road for **>15 years** across many automotive applications

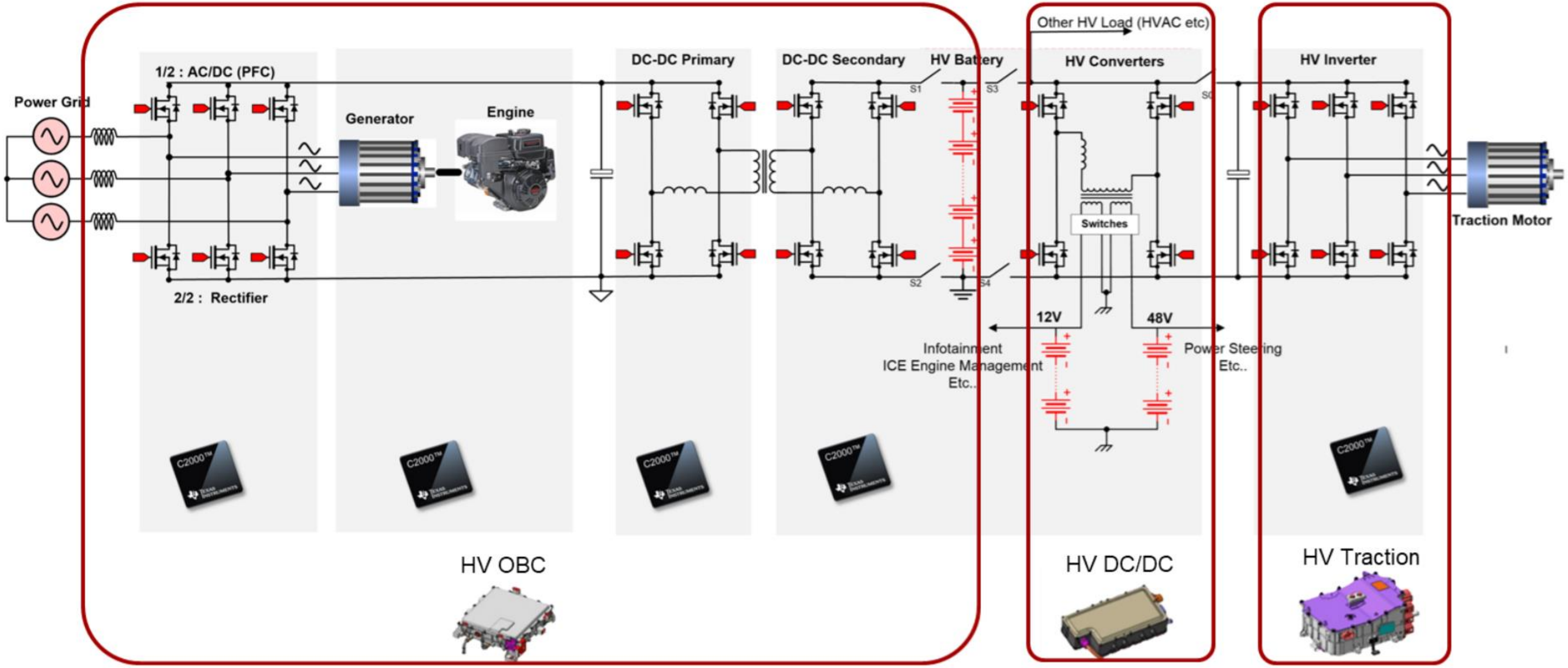
EV Market Trends

- Size reduction
- Mechanical cost reduction
- Greater efficiency, Increased driving range, reduced motor size
- + Safety

EV sub-systems

Real-time

sub-system



Power-Train

sub-system

Safety MCU

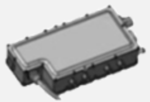
Safety MCU (ASIL D)

C2000 EV: Driving integration + performance

C2000™ Real-Time Control Microcontrollers
Texas Instruments

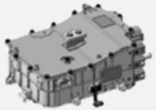
BEFORE

Multiple mechanical enclosures:



DC/DC Conversion

On-Board Charging



Traction Inverter

Limited speed range and torque output and larger/heavier motors

Higher silicon content
- 1 MCU per function (up to 4 functions)
- Up to 24 FETs

AFTER

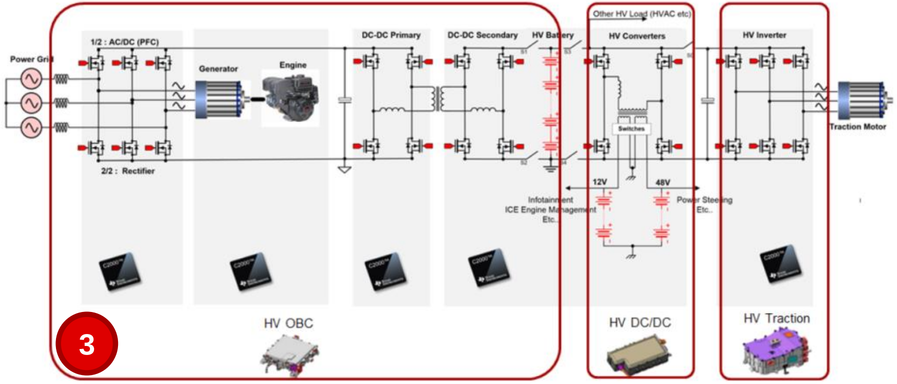
One mechanical enclosure:

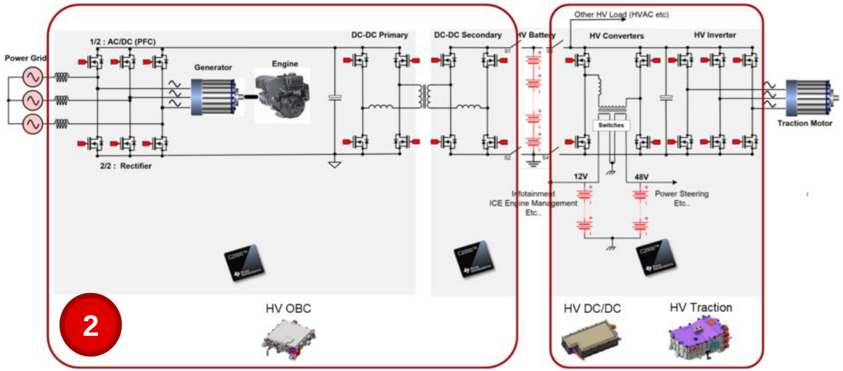
>50% reduction in size/weight
- longer range per charge (up to 15%)

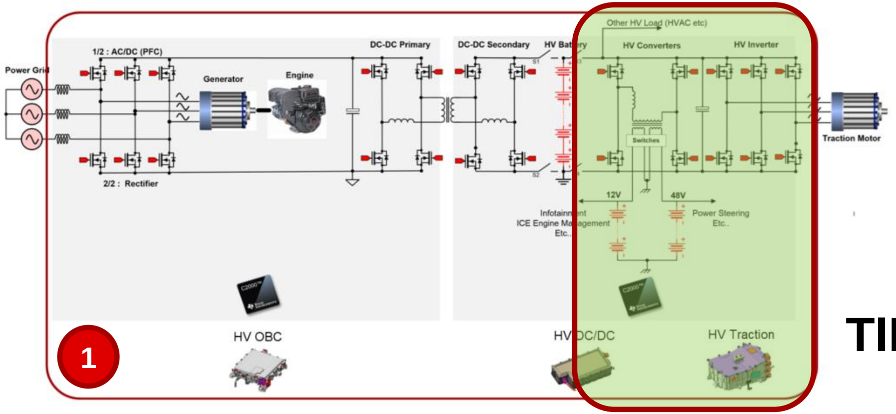
Increase motor speed
- Higher torque
- Reduced motor size (up to 36%)

Reduce cost by eliminating redundant electronics
- Up to 4 functions on 1 MCU
- As few as 14 FETs

C2000 enables real-time integration: 3 boxes into 1







TID

EV TRACTION TI REFERENCE DESIGN

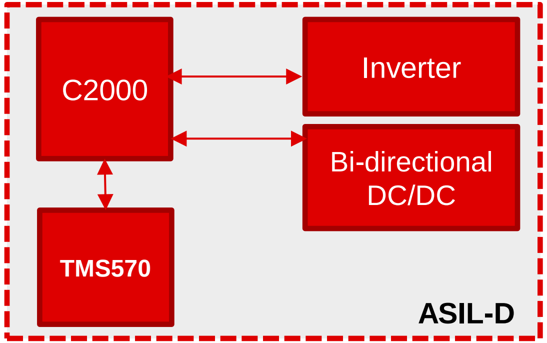
EV traction reference design : Is / is not

C2000 EVT/DCDC TI-RD Is	C2000 EVT/DCDC TI-RD Is Not
A fully *functional* platform able to demonstrate the integration of both EVT and DCDC sub-systems on a single C2000 MCU	Designed to meet form or fit requirements of a production system. (consists of 14 inter-connected hardware boards with no active cooling, interface board etc.)
A scaled down (10kW) EVT sub-system design capable of demonstrating feasibility of >20K rpm EV motor speed	Capable of driving a traction inverter power stage at 150-300 kW (typical requirement for production passenger cars)
Functionally verified limited to TI lab capabilities only	Deployed or tested in a car to validate EMI, EMC compliance etc.

TIDM-02009 : TI Reference Design for ASIL D concept assessed EV traction inverter + DC/DC

Features

- C2000 real time power conversion controller
- **Traction** inverter control (10 KW) delivering TI superior motor control capabilities (RPM > 20K RPM)
- **Integrated bi-directional DC / DC** converter control (400V to 12V)
- **TUV assessed** functional safety concept for **ASIL D** with ASIL decomposition*
- Host ASIL D safety MCU – TMS570LS1227
- Traction inverter using TI's ASIL D gate driver and Wolfspeed SiC MOSFET
- SW based resolver to digital conversion (RDC)
- Use integrated CLB in C2000 (instead of CLPD) for specific functions
- CAN-FD support
- Diagnostic interface / tool support (e.g., **ETAS**)



Benefits

- ✓ High Speed Traction Motor Control and Integration – Reduce EV powertrain size, weight and cost, gain more mileage per charge
- ✓ Integration bi-directional HV-LV DC/DC
- ✓ BOM optimization (no CPLD, no hardware RDC)
- ✓ TUV assessed ASIL D safety concept

BOM optimization with TI automotive portfolio

- Real time control MCU - C2000's TMS320F2838x-Q1
- Host control ASIL D MCU – TMS570LS1227
- 600V / 50A inverter using TI's ASIL D gate drivers UCC5870-Q1
- Resolver interface using C2000 and AFE
- Power monitoring using PMIC part TPS65381A-Q1
- CAN-FD interface

Release Timelines

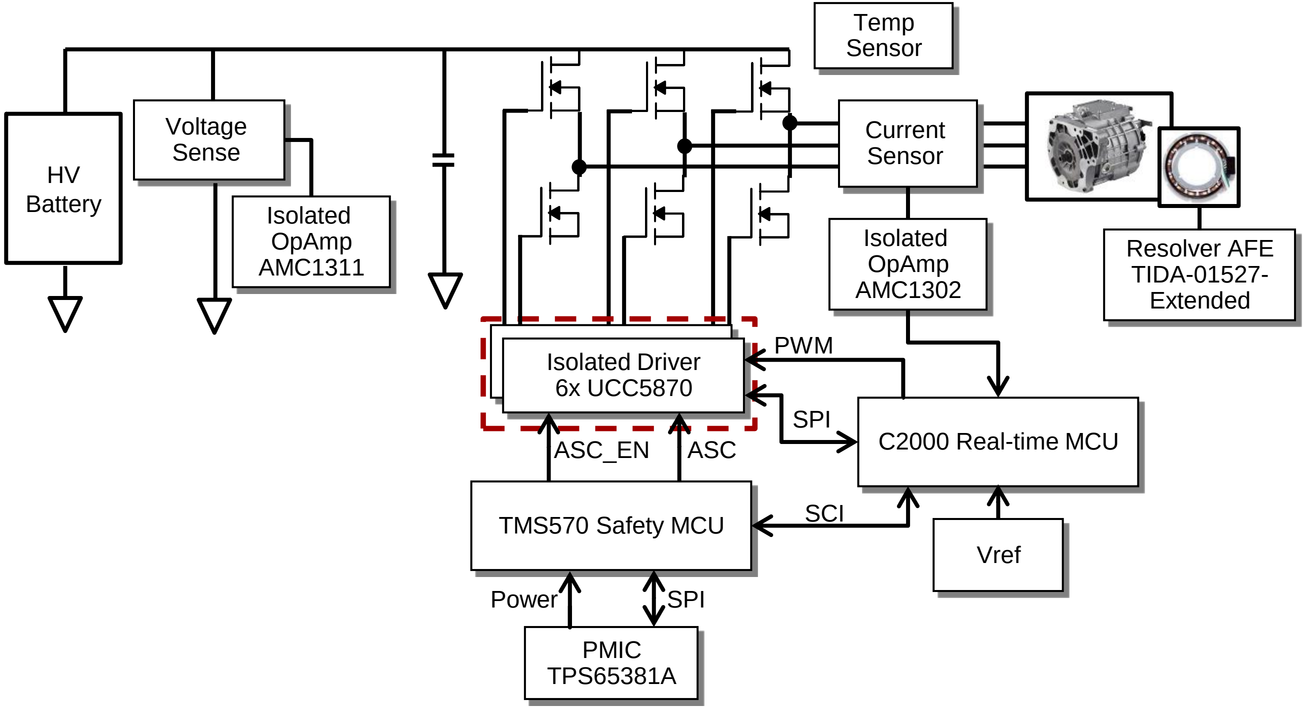
- Alpha version schematic and PCB: Now
- TUV SUD assessed safety concept: Now
- Beta software release + Demo: 4Q 2020
- RTM: 1Q2021

* See http://www.ti.com/lit/wp/sway028/sway028.pdf for an overview of ASIL decomposition

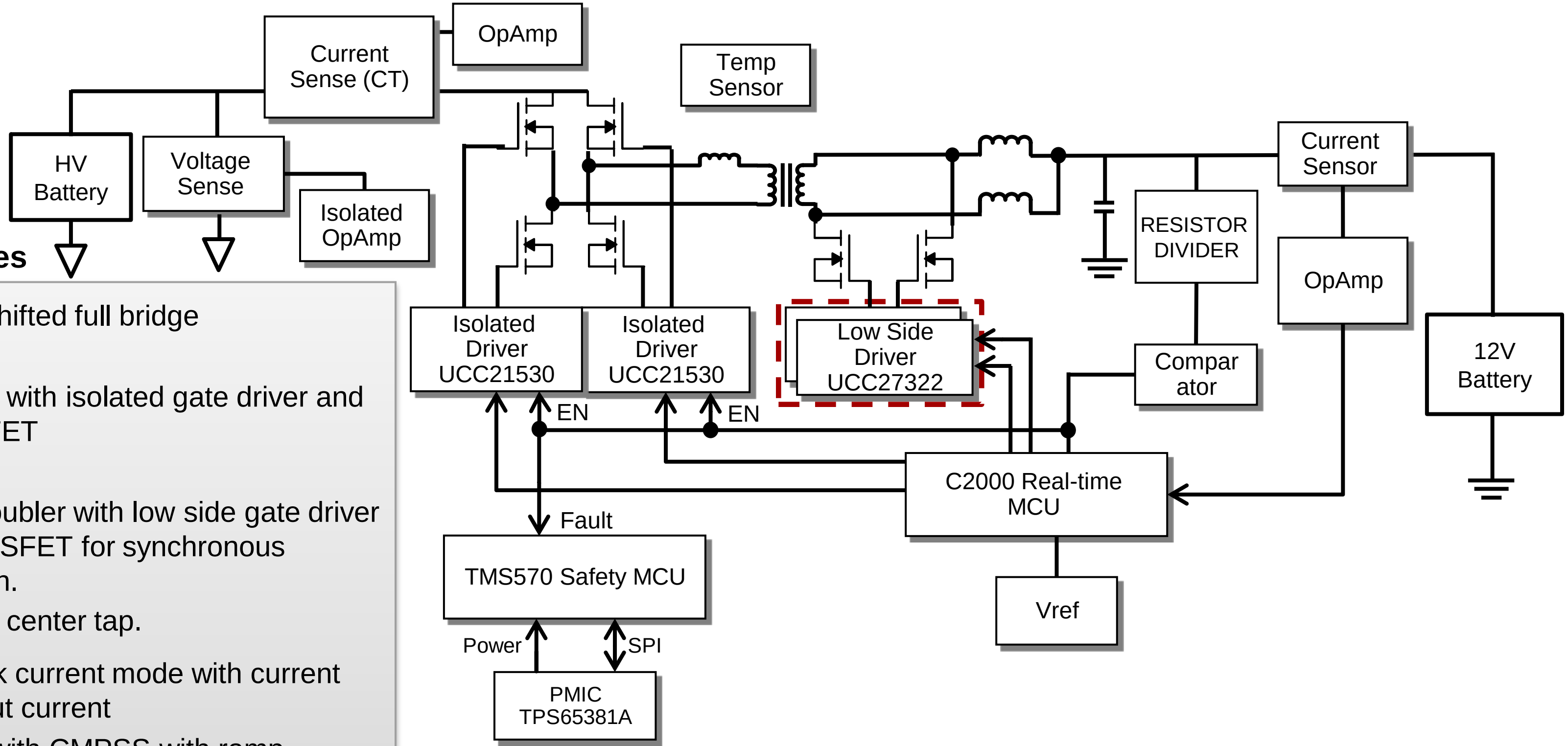
Reference design – traction inverter subsystem

Subsystem Features

- Shunt based phase current sensing with isolated amplifier
- Bus voltage sensing with isolated amplifier
- Software resolver interface
  - TIDA-01527-Extended
  - Refer to “SW Resolver Implementation and Its Safety” section in this slide deck
- Independent programmable safe state activation using C2000 MCU’s Integrated CLB and TMS570 NHET
- TI ASIL D gate driver (UCC5870) with Wolfspeed SiC power module
  - Enable higher switching frequency for high RPM motor
  - Built-in 10-bit ADC for temperature and voltage sensing
  - PWM bypass with ASC and ASC-EN



Reference design – DC-DC subsystem



Subsystem Features

- Topology: Phase-shifted full bridge
  - Primary
    - Full bridge with isolated gate driver and SiC MOSFET
  - Secondary
    - Current-doubler with low side gate driver and Si MOSFET for synchronous rectification.
    - Eliminated center tap.
- Control mode: peak current mode with current transformer on input current
  - Implemented with CMPSS with ramp generator for hardware based slope compensation

ASIL D – technical report

Technical Report

for the testing of the

Safety Concept of Integrated EV Traction Inverter and HV DC-DC with C2000 Real-time Control MCU

Applicant

Texas Instruments Incorporated

13905 University Blvd.,

Sugar Land, TX 77479

USA

Report No.: TS95078T

Version 1.0 of 2020-04-30

Test Body

TÜV SÜD Rail GmbH

Rail Automation
Barthstraße 16
D-80339 München

EV TRACTION TI REFERENCE DESIGN: FUNCTIONAL SAFETY CONCEPT

EV traction reference design : Is / is not

C2000 EVT/DCDC TI-RD Is	C2000 EVT/DCDC TI-RD Is Not
A fully *functional* platform able to demonstrate the integration of both EVT and DCDC sub-systems on a single C2000 MCU	Designed to meet form or fit requirements of a production system. (consists of 14 inter-connected hardware boards with no active cooling, interface board etc.)
A scaled down (10kW) EVT sub-system design capable of demonstrating feasibility of >20K rpm EV motor speed	Capable of driving a traction inverter power stage at 150-300 kW (typical requirement for production passenger cars)
Functionally verified limited to TI lab capabilities only	Deployed or tested in a car to validate EMI, EMC compliance etc.
Developed according to TI (internal) hardware tools development and release spec – QRAS SC00098	Developed to comply with ISO 26262-4:2018 and/or IEC 61508-2:2010
Securing TUV technical report for a functional safety *concept* assessment for enabling an ASIL D customer system • i.e. similar to an SEooC assessment at chip level and • Based on assumptions that provide a starting point for customers	A TUV certified turn-key *system* assessment and solution that customers could immediately start mass-producing • i.e. a requirement for customers to engineer and mass-produce for actual (final) usage
Developing a partial and representative HARA (hazard analysis & risk assessment) for the EVT and DCDC converter sub-systems at the component level	A full HARA at item level.

Assumed safety goals

* Based on partial subset of critical system safety goals

Traction Inverter

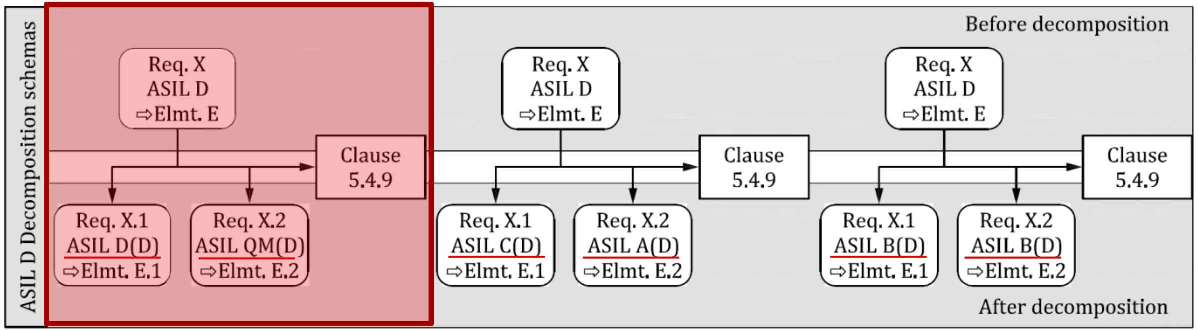
Sl No:	Hazard	Safety Goal	Assumed System Safe State	MCU Safe State	ASIL	FTTI
EVTR_SG1	Motor over-torque	Avoid over-torque	Torque off Driver indication	(i) PWM Tripped (ii) ERROR reported	D	10ms
EVTR_SG2	Too low torque	Avoid unintended low torque	Driver indication	(i) ERROR reported	A	10ms
EVTR_SG3	Motor over speed	Avoid over speed	Apply torque off (over-speed) or apply ASC (over-Voltage & over-speed) Driver indication	(i) PWM Tripped (ii) ERROR reported	D	10ms
EVTR_SG4	Motor or inverter operating beyond permissible temp	Avoid operation of motor and inverter beyond the permissible temperature range	Limit Torque Driver indication	(i) Limit Torque (ii) ERROR reported	B	10ms

DC-DC

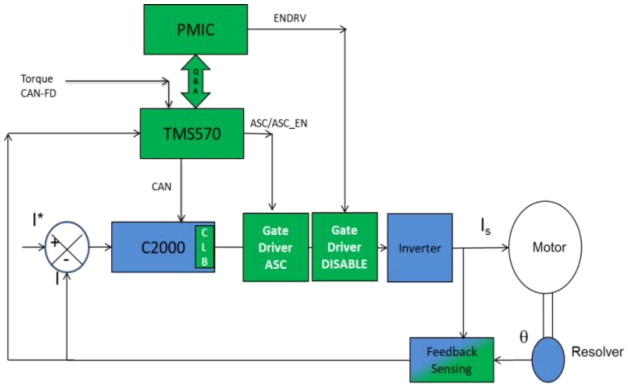
Sl No:	Hazard	Safety Goal	Assumed System Safe State	MCU Safe State	ASIL	FTTI
EVTR_SG5	Overvoltage on DC-DC output	Avoid over 14V on the LV side of DC-DC for more than continuous 10 ms	Turn off DC-DC and Driver indication	(i) Disable primary (HV side) gate driver (ii) ERROR reported	D	100 ms
EVTR_SG6	Overvoltage on DC-DC output	Avoid instantaneous over 16V on the LV side of DC-DC	Turn off DC-DC and Driver indication	(i) Disable primary (HV side) gate driver (ii) ERROR reported	D	100 us

ASIL decomposition – From ISO 26262:2018-9

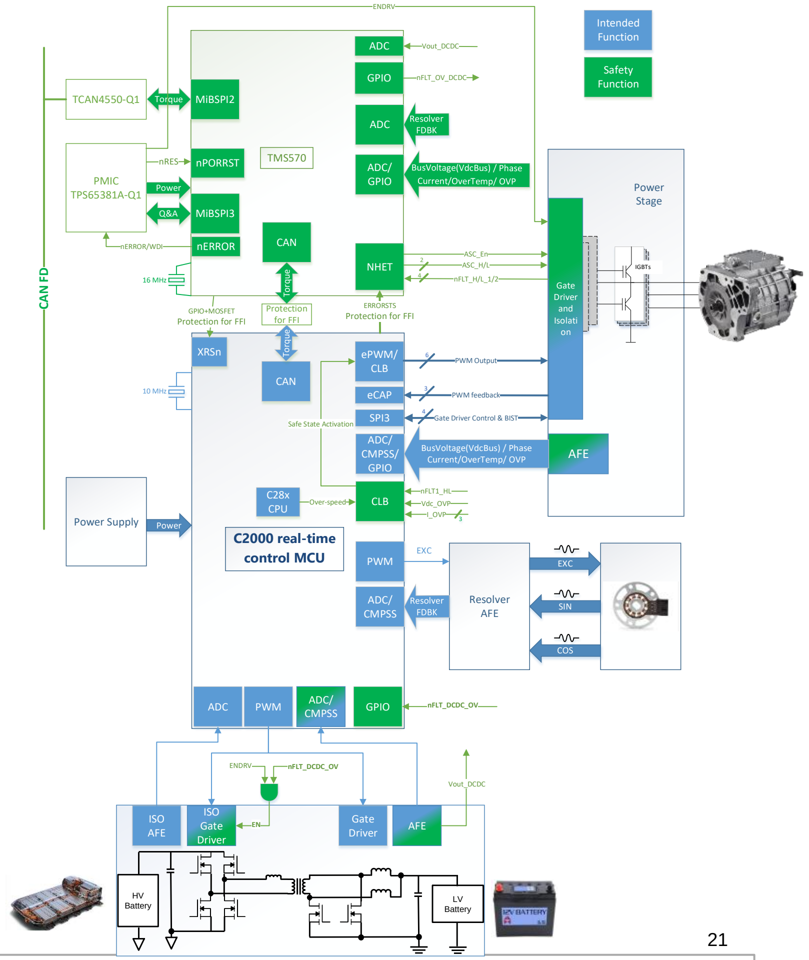
- *ASIL decomposition allows the apportioning of the ASIL of a safety requirement between several elements that ensure compliance with the same safety requirement addressing the same safety goal.*
- **Redundant** and **Independent** architectural elements implement the safety requirement
- *ASIL decomposition between an intended functionality and its corresponding safety mechanism is allowed under certain conditions*
  - *a safety requirement shall be allocated to the intended functionality*
  - *the associated safety mechanism should be assigned the higher decomposed ASIL;*



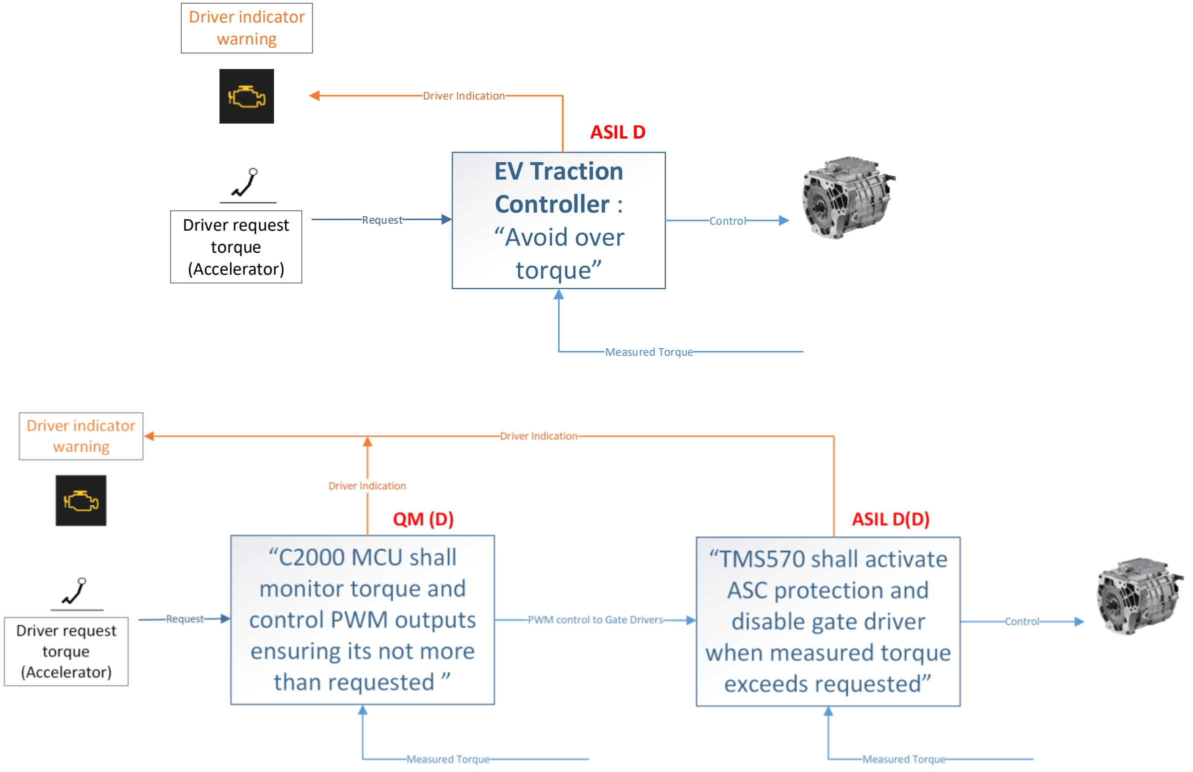
Overall system block diagram

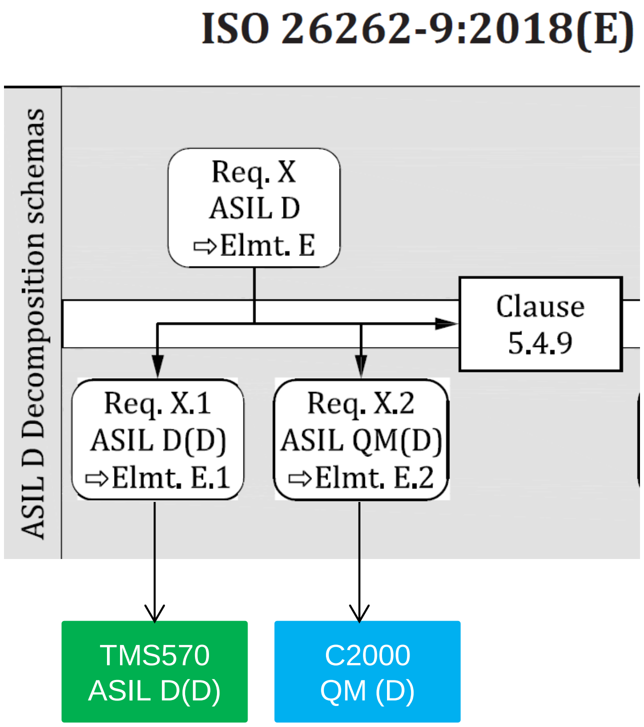


I* → Reference current
I → Measured current
I_s → Motor current

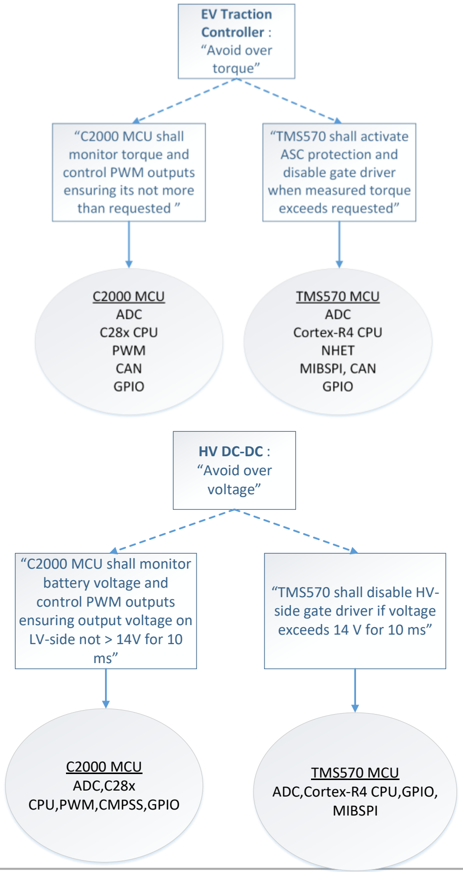


ASIL decomposition





Allocation of safety requirements



Safety Goal ID	Brief Safety Goal	Initial Safety Requirement	ASIL	Redundant Safety Requirements after ASIL decomposition		Allocated ASIL	Components allocated from system
EVTR_SG1	Avoid over-torque	The system shall not deliver more torque than requested by the user	D	SG1-SR1	C2000 MCU shall monitor torque and control PWM outputs ensuring it is not more than requested.	QM (D)	C2000 MCU (ADC,C28x CPU, PWM, CAN, GPIO) UCC5870, Inverter AFE, Resolver AFE
				SG1-SR2	TMS570 shall activate Active Short Circuit (ASC) protection and disable gate driver when measured torque exceeds requested. Report error to VCU.	D (D)	TMS570 MCU (ADC, Cortex-R4 CPU, NHET, MIBSPI, CAN, GPIO), Inverter AFE, Resolver AFE, TCAN4550
EVTR_SG2	Avoid unintended low torque	Report error to VCU in case of too low torque	A	-	TMS570 shall report the error to VCU for driver indication when measured torque is too less than user-requested.	A	TMS570, TCAN4550
EVTR_SG3	Avoid over speed	The system shall not allow motor speed to operate beyond the maximum threshold	D	SG1-SR1	C2000 MCU shall monitor speed and control PWM outputs ensuring operation below the maximum speed	QM (D)	C2000 MCU (ADC,C28x CPU,PWM, CAN, GPIO), UCC5870, Inverter AFE, Resolver AFE
				SG1-SR2	TMS570 shall disable gate driver (torque off) when measured speed exceeds the maximum threshold. TMS570 shall activate ASC protection when overvoltage along with over speed detected. Report error to VCU.	D (D)	TMS570 MCU (ADC, Cortex-R4 CPU, NHET, MIBSPI, CAN, GPIO), Inverter AFE, Resolver AFE, TCAN4550

Concept FMEA

No	The element of the System	Related to Safety Goals	Allocated ASIL	Function	Failure Mode	Impact on Safety Function	Safety Measure to control/detect the fault	DC
1	C2000 - ADC	EVTR_SG1 EVTR_SG2 EVTR_SG3 EVTR_SG4 EVTR_SG5 EVTR_SG6	QM (D)	Measurement of Bus Voltage, Current, Temperature, and resolver feedback	Incorrect conversion of Speed, Voltage, Current, Temperature	Failure in detecting over-torque, over speed, over-voltage, and over-temperature	ADC - Information Redundancy Techniques	-
6	TMS570-ADC	EVTR_SG1 EVTR_SG2 EVTR_SG3 EVTR_SG4 EVTR_SG5 EVTR_SG6	D (D)	Measurement of Bus Voltage, Current, Temperature, and resolver feedback	Incorrect conversion of Speed, Voltage, Current, Temperature.	Failure in detecting over-torque, over speed, over-voltage, and over-temperature	ADC - Hardware Redundancy	99%

* Based on partial subset of critical system safety goals

- Are redundant architectural structures 'Independent?
  - *Common Cause Failure Analysis (CCF/DFA)*
- Is effectiveness of safety implementation 'free from interference from lower ASIL'?
  - *Co-existence analysis*
- The effectiveness to be re-evaluated by the system integrator in context of the specific system design implementation.

Common cause failure & co-existence analysis

1. **Power Supply, Clock, Reset :**
   – Monitoring power supply, Avoiding CCF on Clock/Reset
2. **Communication on CAN-FD**
   – Implement with ASIL D (end-to-end (E2E) safing techniques)
3. **Analog Front End (AFE) circuits**
   – **Inverter AFE:**
   - **Phase Current**: information redundancy in SW (sum of all phase currents = 0)
   - **DC Bus Voltage (Vdc)**: Redundancy in DC bus voltage fault detection
   - **Temperature**: implement function with ASIL D(UCC 5870)

   – **Resolver AFE**: SW and HW techniques to detect failres in resolver AFE
4. **Processing units and Software:** heterogeneous Instruction Set Architecture (ISA) of C2000, and TMS570 minimizes CCF. System integrator to ensure no CCF in implementation of application.

- <u>**Co-existence Analysis**</u>
  – Interference on CAN bus from C2000 to TMS570 will be covered by “E2E” with ASIL D
  – System integrator to provide protection avoid cascading HW failures from C2000 to TMS570

Results and summary from TUV report

Safety Concept of Integrated EV Traction Inverter and HV DC-DC with C2000 Real-time Control MCU
TIDM-02009

Table of Contents

No.	Title	Document number / ID	Rev.	Date
The following documents were issued by the customer:				
/D1/	Safety Concept - EV Traction Reference Design TIDM-02009	EV Traction Reference Design - Safety Concept_ver0.8.docx	0.8	2020-04-28

Table 5: Safety Concept documentation

No.	Reference	Description
/N1/	ISO 26262:2018 (ASIL D)	Road vehicles — Functional safety

Table 3: Functional safety standards

Result:
The safety concept is refined down to requirements for the hardware components. The analyses show that sufficient safety measures are planned. The result of the document review shows that the requirements according to /N1/ can be met. This review result is recorded in [R1]. The effectiveness of the applied measures shall be re-evaluated by the system integrator in context of the specific system design implementation. This includes (but is not limited to) the interference freeness between the CPU subsystems.

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e-mail: Axel.Koehnen@tuev-sued.de

Rail

5 Summary

The Safety Concept of Integrated EV Traction Inverter and HV DC-DC with C2000 Real-time Control MCU and the defined safety measures are suitable for achieving the applicable requirements of /N1/, ASIL D for the two sub-systems.

The effectiveness of the measures defined for the concept shall be re-evaluated by the system integrator in context of the specific system design implementation.

Department Manager Software

Digital unterschrieben von Claudio Gregorio
Datum: 2020.04.30 10:16:04 +02'00'

Claudio Gregorio

Project Manager

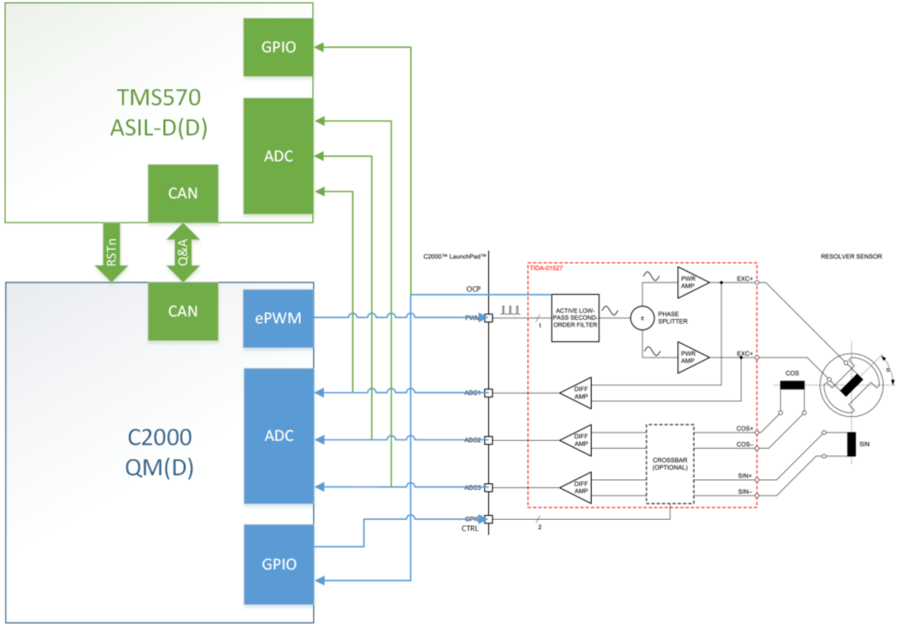
Digital unterschrieben von Axel Köhnen
Datum: 2020.04.30 10:10:17 +02'00'

Axel Köhnen

SOFTWARE RESOLVER IMPLEMENTATION AND ITS SAFETY

This section documents how the SW resolver is implemented in this reference design, along with the safety concept that can enable SW resolver’s ASIL D implementation

SW resolver implementation and its safety (1/2)



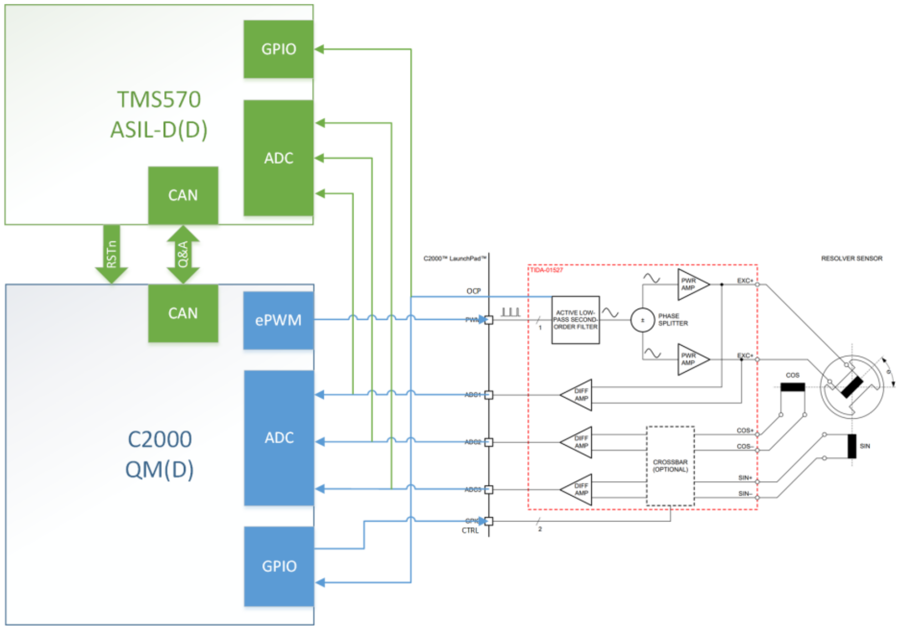
- SW Resolver Implementation

Function	Responsible HW
Excitation signal generation	Generated by C2000 (PWM) (signal filtered and amplified by external analog Filter + power amplifier)
Excitation signal feedback	Processed by both C2000 and safety MCU (signal generated at power amplified output fed back through another op-amp)
SIN COS feedback	Processed by both C2000 and safety MCU (post AFE)
Resolver decoding	Run on both C2000 and safety MCU

- Safety concept for overall resolver implementation realized using a combination of
  - ASIL decomposition between C2000 (QM(D)) and safety MCUs (ASIL D(D))
  - Systematic integrity of software resolver code* (QM on C2000 and ASIL D on safety MCU)
  - In-built over current protection measures in the excitation power amplifier
  - System level safety measures
    - TMS570 health monitoring using PMIC (Power monitor, Q&A watchdog)

* Note that SW resolver code in TID is intended to be only a reference, hence does not adhere to the systematic SW development flow requirement

SW resolver implementation and its safety (2/2)

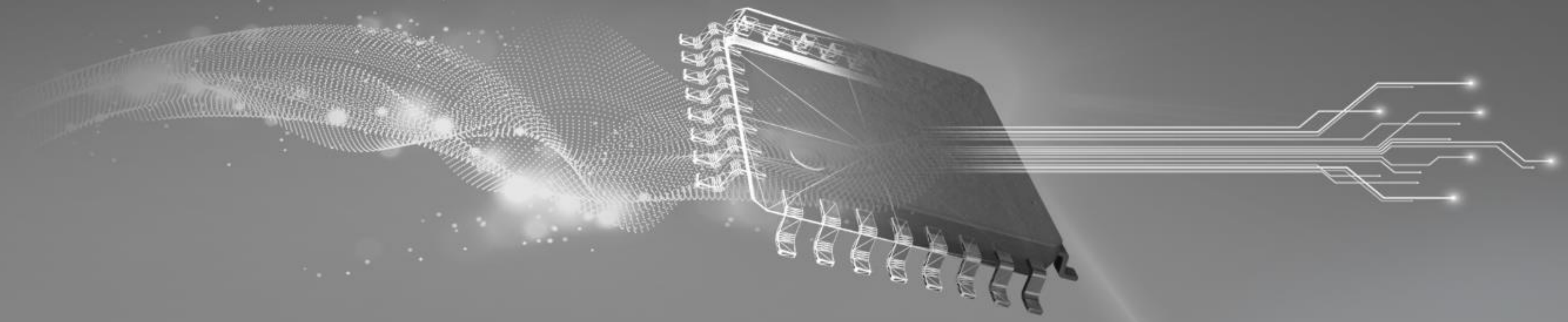


- SW Resolver Implementation Safety

Failure	Safety Mechanism
Excitation line short circuit and signal integrity	• Built-in over current protection feature of excitation power amplifier • Excitation signal loopback to safety MCU for integrity check
SIN COS signal integrity (loss of resolver signals, out-of-range input signals, etc)	• Redundant ADCs used for feedback signal on safety MCU • Signal integrity test by safety MCU
Resolver decoding (wrong calculation result, loss of position tracking)	• Software running on safety MCU developed per ASIL D systematic • Position tracking error monitored by software

- Additional safety measures can be implemented in this architecture. An example below -
  - If the integrity of position information for motor control is a safety goal of the system, cross compare of the result periodically between C2000 and safety MCU can be done.
    - Refer to section on end-to-end communication safety to ensure safe cross-compare

TI TECH DAYS



Questions?

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