FTF FREESCALE TECHNOLOGY FORUM 2014

An Overview of the Resolver Interface for **Motor Control** Applications

FTF-AUT-F0234

Leos CHALUPA | Automotive MCU Product Group

A P R . 2 0 1 4

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External Use

Session Introduction

- This session will explain cost-effective solutions to interface the resolver position sensor directly to Freescale's automotive MCU.
- We will discuss basic operation, benefits of saving an external IC, run time diagnostics and flexible selection of the “limp” mode.

Session Objectives

- By the end of this session you will:
  - Be more familiar with **resolver**-based position sensing
  - Understand the **run-time diagnostic** principles
  - Describe how to use **Freescale microcontrollers** to save an external IC for Resolver interfacing
  - Name the **advantages** of the presented solution
  - Know where to look for **support**, documentation and examples

Agenda

- Resolver basics
  - Brief history
  - Resolver types, constructions and operation principles
- Angle position sensing
  - Principle of resolver position extraction
  - Sources of position sensing errors
- Direct MCU-resolver interface
- Freescale support, examples, documentation and more

Resolver Basics

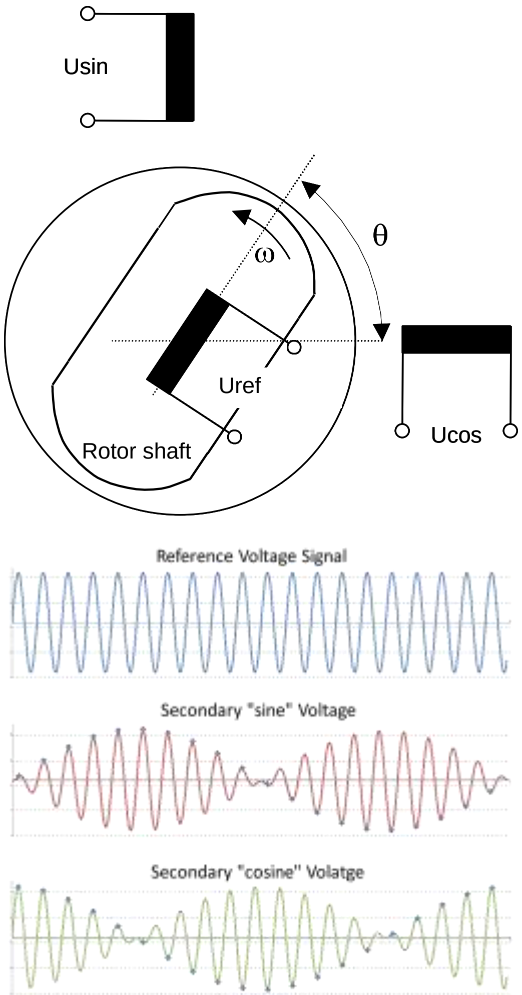
Brief Resolver History

- Developed in 1940s at MIT (Supported by the U.S. military)
- Resolvers have been part of electromechanical servo and shaft angle positioning systems for over 50 years
- Resolver position sensor constructions evolved over time
  - 1970s: Brushless resolver
  - 1980s: Hollow shaft brushless resolver
  - 1990s: Variable reluctance resolver
- Resolver position conversion methods evolved from phase analog techniques to tracking observer-based digital techniques with run-time diagnostic
- Since 2000, the Freescale Motor Control team has investigated different approaches of the resolver-to-digital conversion using available MCUs/DSCs.

  The first application was the SMT pick and place machine where fast dynamics and high precision is a key for overall cost effectiveness.

  Until today, the method was continuously improved and ported to practically all el. motor control MCUs, including special CPU autonomous version based on the eTPU to target ramping EV and HEV markets

Resolvers: Electro-magnetic Induction Angle Sensors



Rotor is put directly on the drive's shaft

Stator is fixed on drive's shield

Simple assembly and maintenance

No bearings – "unlimited" durability

Resist well against distortion, vibration, deviation of operating temperature and dust

Worldwide consumption is millions of pieces at present time

Widely used in precise positioning applications

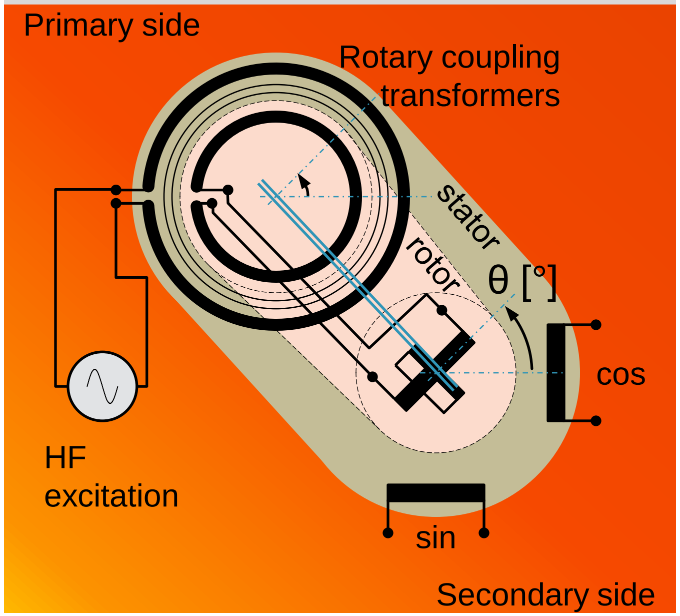
The number of generated sine and cosine cycles per one mechanical revolution depends on the number of resolver pole-pairs (usually 1-3 cycles)

Basic parameters:

- Electrical Error – +/-10', Transformation Ratio – 0.5, Phase Shift – +/-10°
- Input Voltage – 4-30V, Input Current – 20-100 mA, Input Frequency – 400 Hz – 40 kHz

Resolver Types

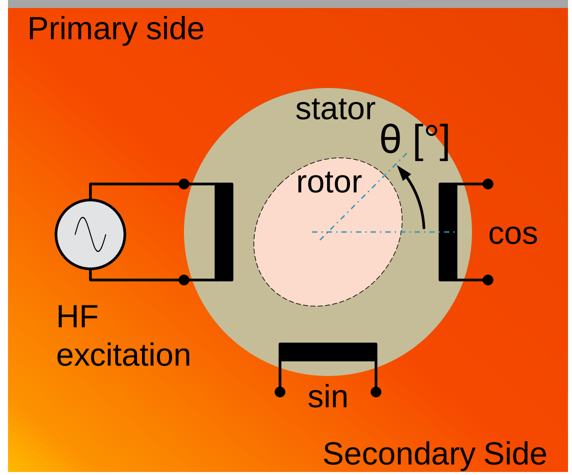
Traditional Brushless



Rotating magnetic coupling transfers HF energy from the stator (primary) to the rotor (secondary), connected directly to the resolver primary. This generates an AC magnetic field with a sinusoidal distribution, hence causing HF voltages in the stator windings (secondary side) with amplitudes dependent (sine/cosine) on the rotational angle of the rotor.

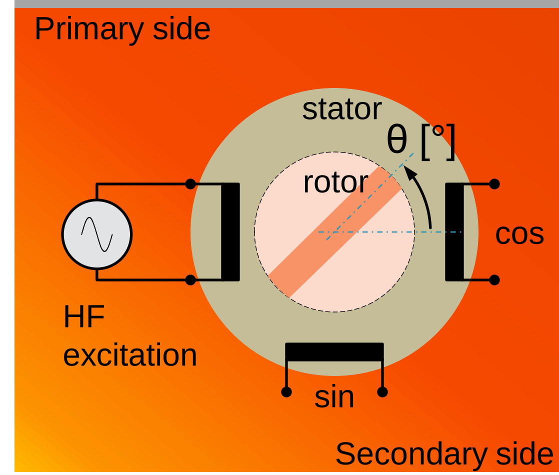
Brushless Variable Reluctance

With variable air-gap



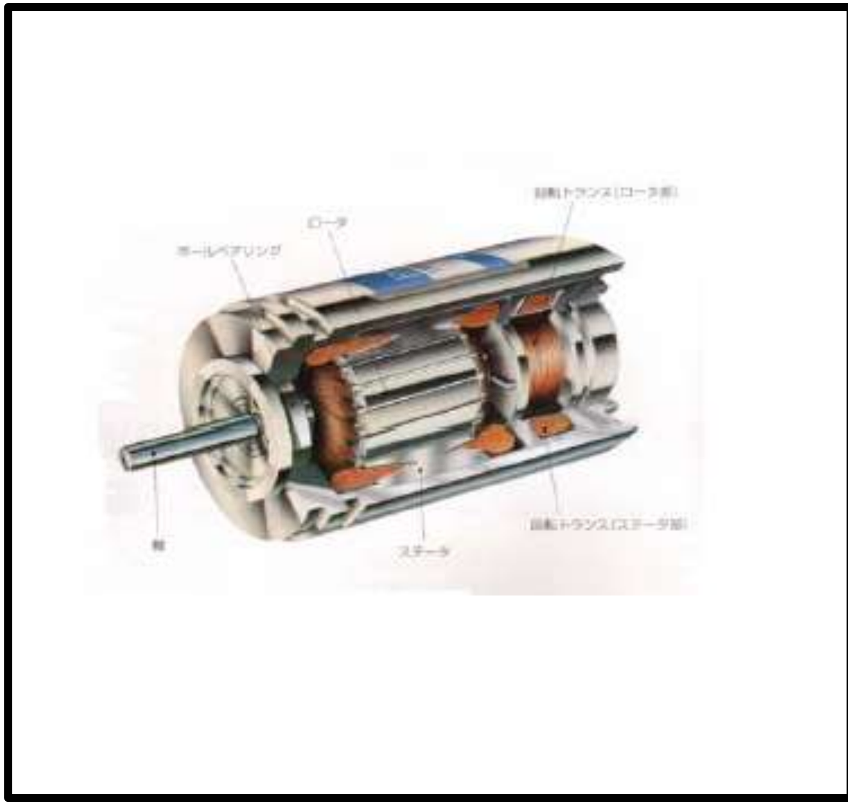
The VR variable air-gap resolver has primary and secondary windings in the stator, therefore it does not need a rotating magnetic coupling. The contour of rotor is made as the permeance of air-gap between the stator and rotor is varied in sinusoid oscillation. Thus, the induced voltage amplitudes correspond to the sine and cosine of the rotor angle.

With solid rotor



The VR solid rotor resolver has primary and secondary windings in the stator, therefore it does not need a rotating magnetic coupling. The rotor contains a diagonal section of highly permeable material that varies the magnetic field across the stator as the rotor turns. Thus, the induced voltage amplitudes correspond to the sine and cosine of the rotor angle.

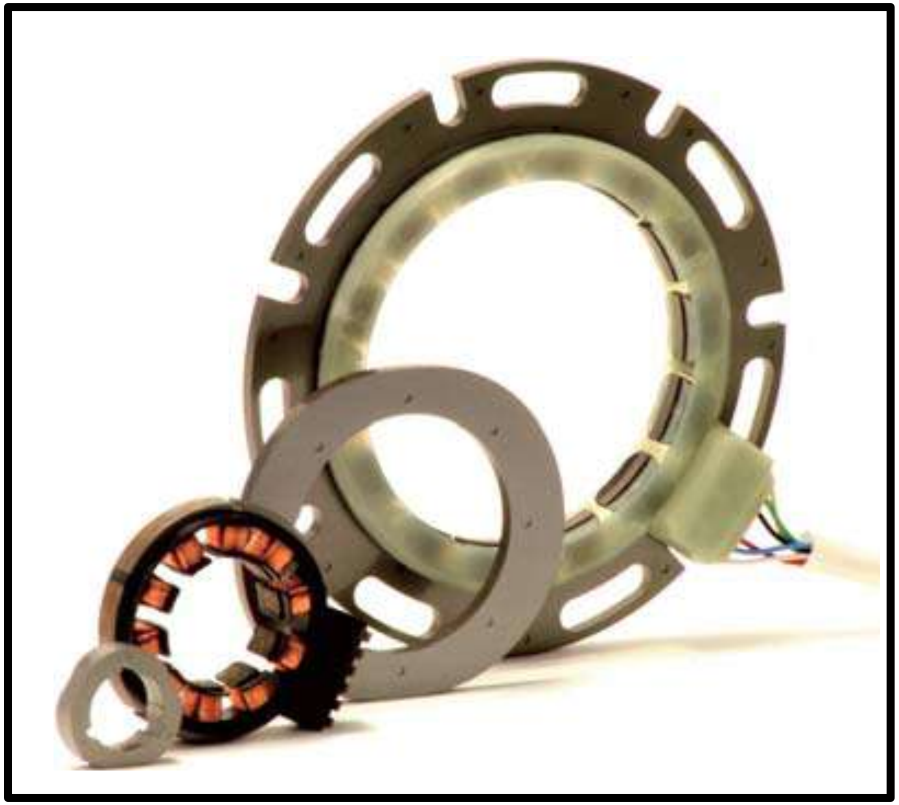
Traditional Brushless Resolver



Source: Tamagawa Seiki co., www.tamagawa-seiki.com

Source: Artus, www.psartus.com

Brushless VR Resolver



Source: Tamagawa Seiki co., www.tamagawa-seiki.com

Source: Admotec Inc., machinedesign.com

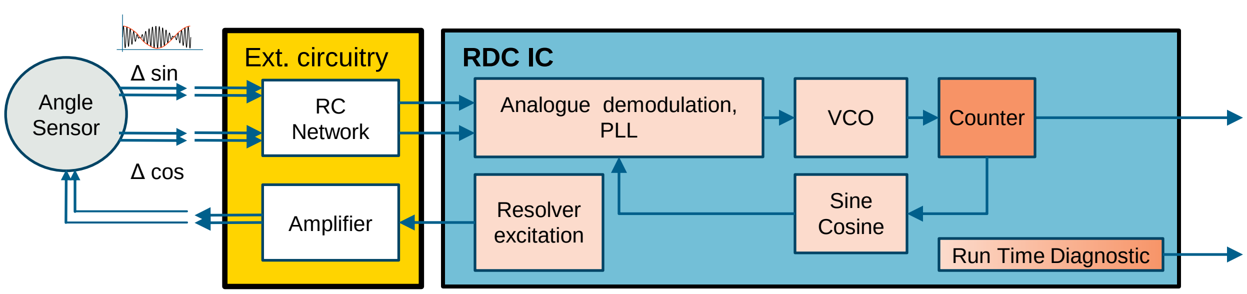
Basic Resolver Terms

- **Excitation** – The winding powered by high frequency (e.g. 10 kHz) sine wave
- **Number of multiples/poles** – The multiplied speed ratio of the output angle signal is indicated. The number of poles is twice that of shaft angle multiplication
- **Transformation ratio** – Ratio of output voltage amplitude to the excitation voltage amplitude
- **Phase shift** – Phase difference between the excitation voltage and output voltage
- **Electrical error** – The difference between electrical angle (presented by the ratio of resolver outputs) and theoretical angle value
- **Input impedance** – The impedance of the excitation side
- **Output impedance** – The impedance of the output windings

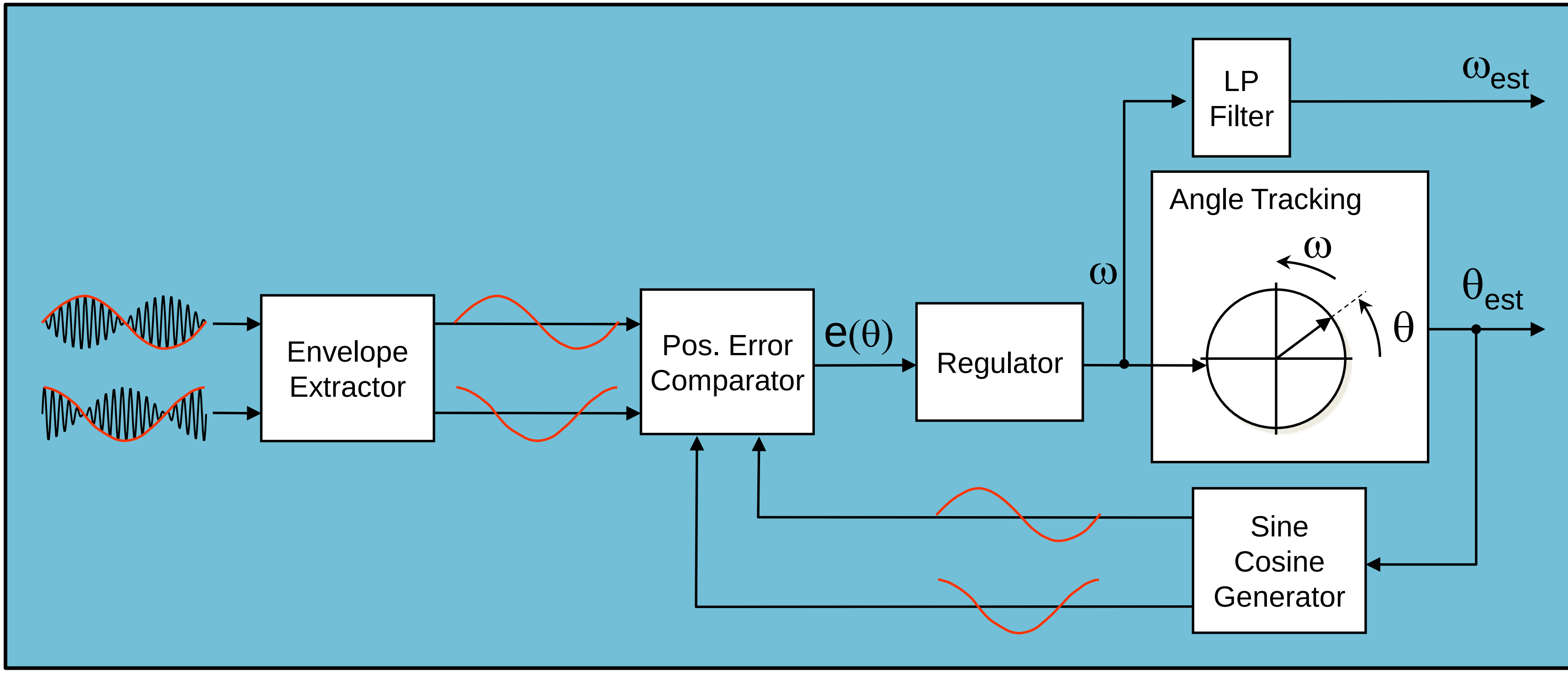
Resolver Angle Position Sensing

Resolver Based Angular Sensing Methods

- **Phase Analog Technique**
  - The two stator windings are excited by signals that are in phase quadrature to each other. This induces a voltage in the rotor winding with an amplitude and frequency that are fixed and a time-phase that varies with shaft angle. This has been the most widely used technique because it can easily be converted to produce a digital signal by measuring the change in phase shift with respect to the reference signal.
- **Angle Tracking Resolver to Digital Conversion (RDC)**
  - A tracking converter contains a phase demodulator. Therefore, frequency variation and incoherent noise do not affect accuracy. Tracking converters can operate with any reference excitation, sine or square wave, with only minor accuracy variations.
  - This technique is implemented by most of the RDC ICs.
  - More will be discussed further in this presentation.

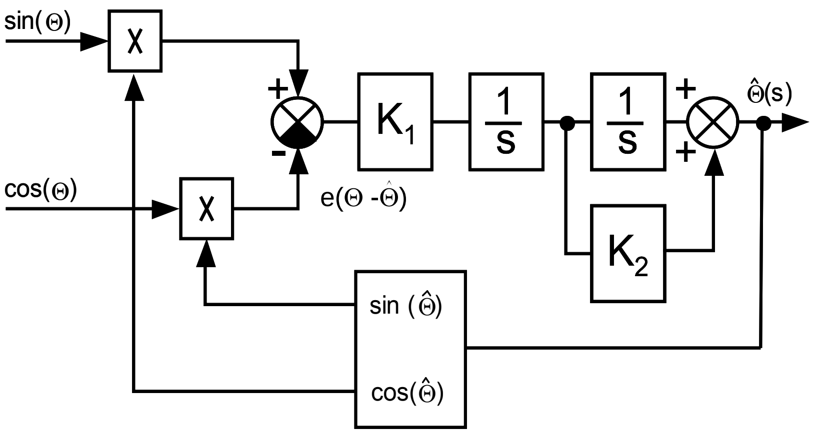


Angle Tracking Observer Principle



Angle Tracking Observer Basics

Implementation Basics:



Angular error evaluation:

$$e(\Theta - \hat{\Theta}) = \sin(\Theta)\cdot\cos(\hat{\Theta}) - \cos(\Theta)\cdot\sin(\hat{\Theta}) = \sin(\Theta - \hat{\Theta})$$

$$e(\Theta - \hat{\Theta}) = \sin(\Theta - \hat{\Theta}) \approx \Theta - \hat{\Theta} \quad \text{for } (\Theta - \hat{\Theta}) \leq 7°$$

Transfer function:

$$F(s) = \frac{\hat{\Theta}(s)}{\Theta(s)} = \frac{K_1(1 + K_2 s)}{s^2 + K_1 K_2 s + K_1}$$

Features:

- Non-sensitivity to disturbance and harmonic distortion of the carrier
- Non-sensitivity to voltage and frequency changes
- High accuracy of the angle extraction

Tuning the Angle Tracking Observer

Transfer function of the General Second Order System:

$$G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

Transient responses:

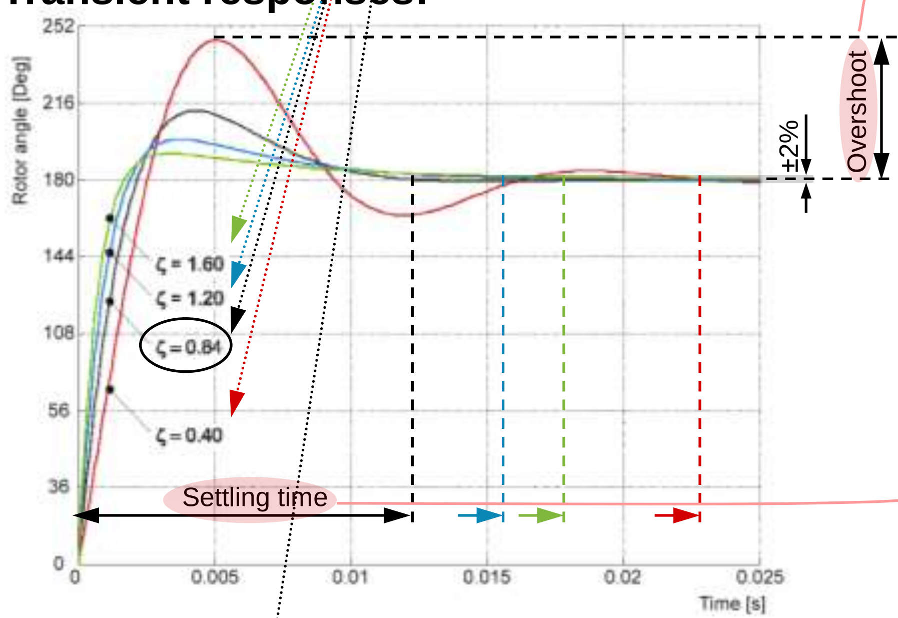
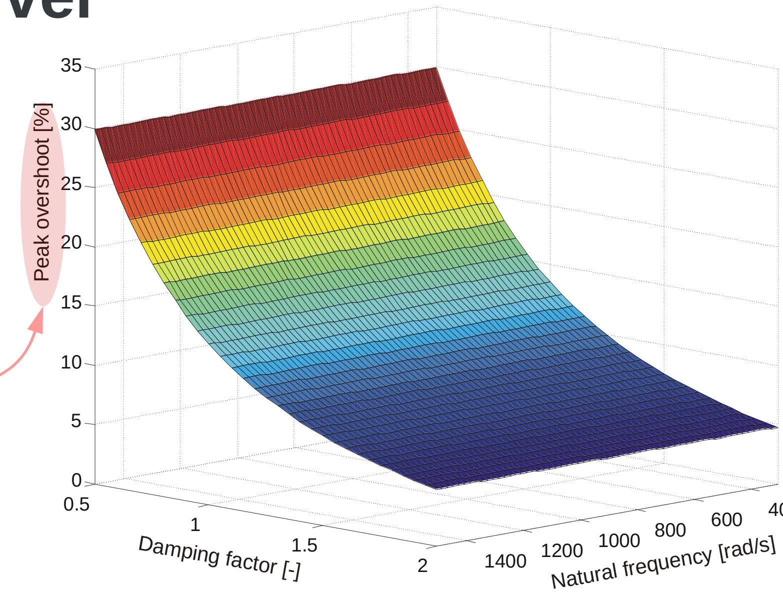
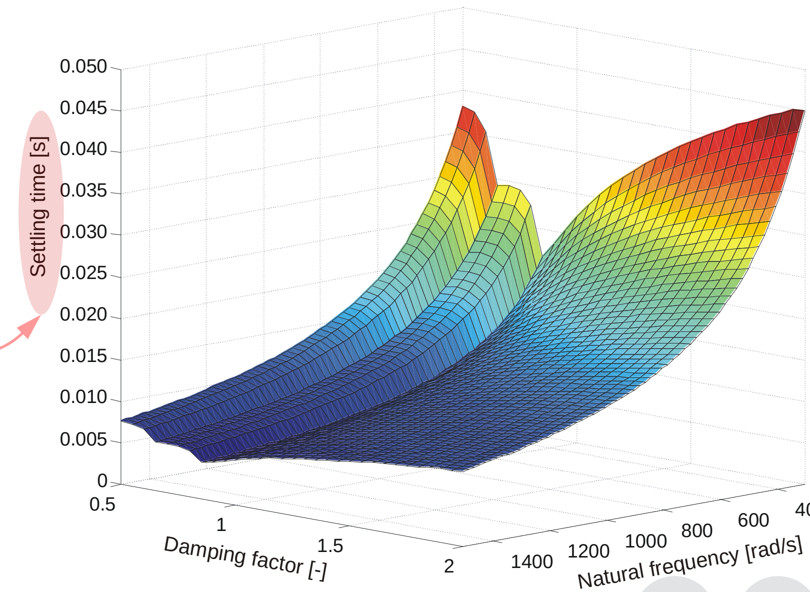


Figure 1-9. Dynamic Responses of the Tracking Observer - $\omega_n = 500\,\mathrm{rad\,s^{-1}}$, $\zeta = 0.4, 0.84, 1.2$ and 1.6



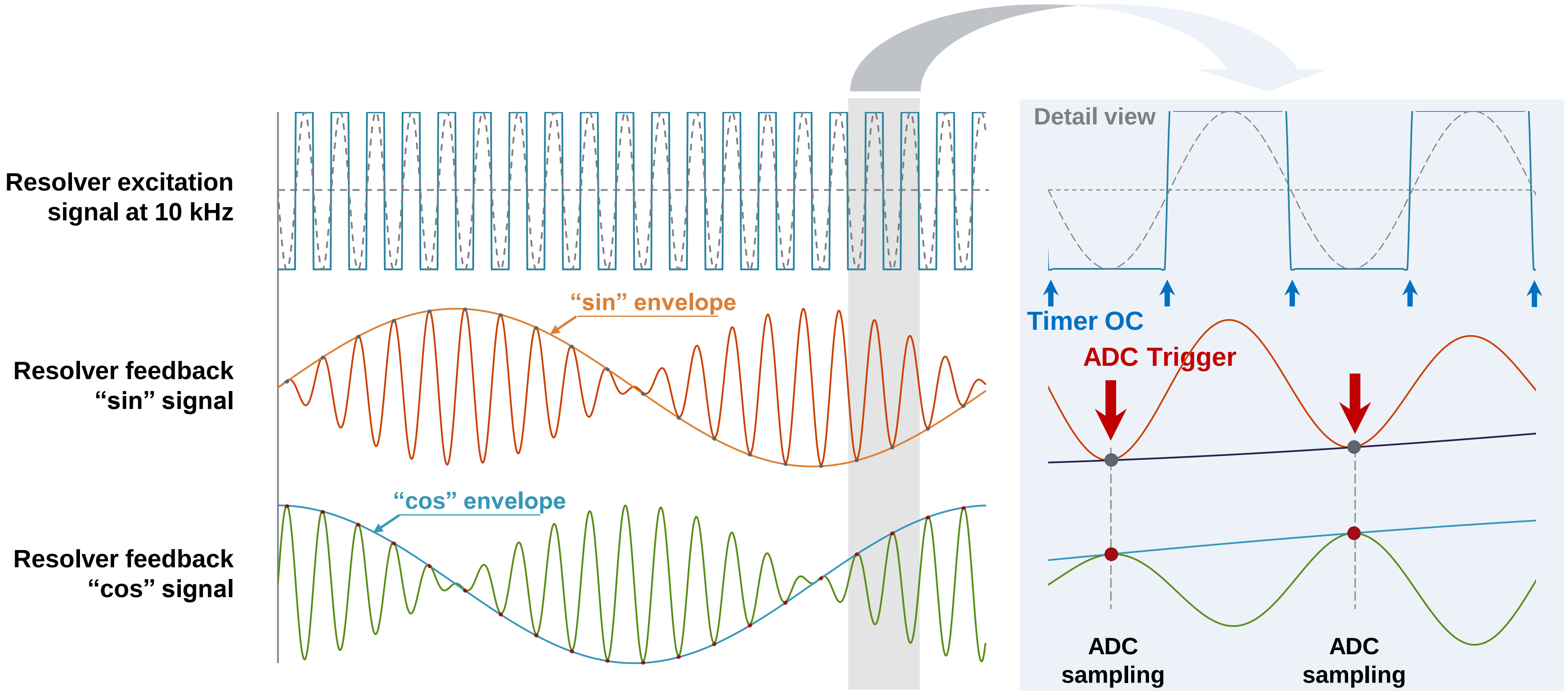


Direct MCU R-D Conversion

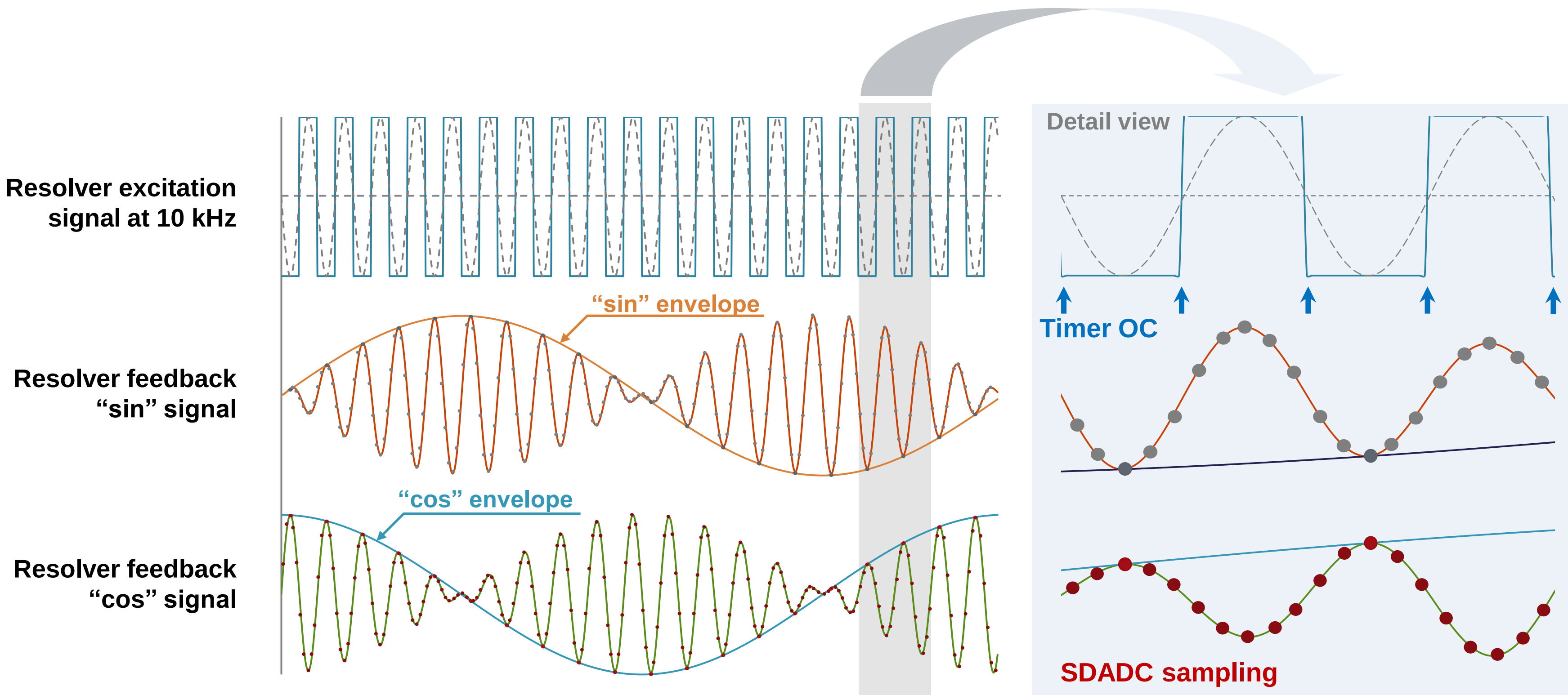
There are two basic approaches to performing resolver-to-digital conversion using on-chip resources

- **Case 1)** – Based on the synchronous “rectification” of the high frequency carrier of the feedback signals:
  - This requires synchronized triggering of the ADC S&H circuit with respect to the resolver excitation signal
  - This is mostly approached by using RSD ADC + triggering timer channels + angle tracking software algorithm
- **Case 2)** – “Demodulation” of the oversampled feedback signals:
  - This does not require synchronized triggering, however it requires fast ADC capable to over-sample two high-frequency feedback signals
  - This is mostly approached by using **Sigma-Delta ADC** + high-frequency digital demodulation + angle tracking software algorithm (with phase-delay compensation)
  - Improves dynamics

Case 1: Sin/Cos Envelope Extractor



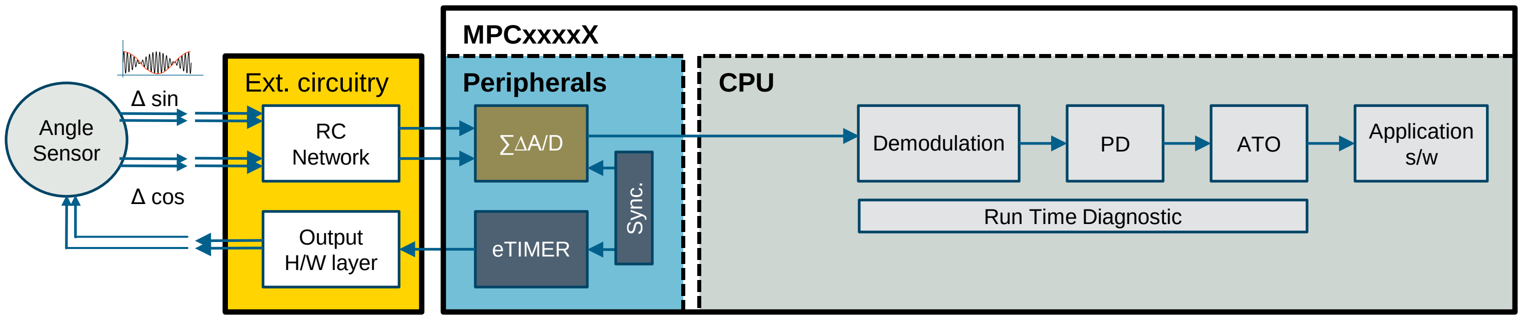
Case 2: Over-sampling of Resolver Signals



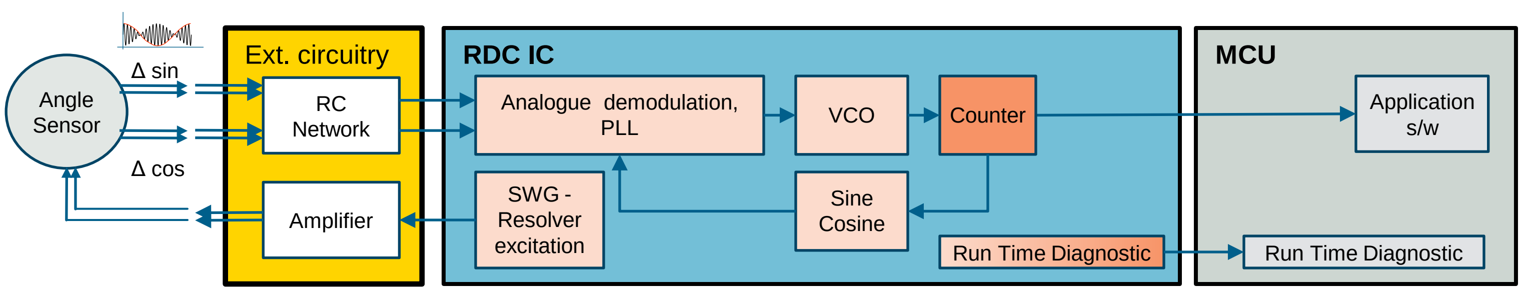
Direct MCU-Resolver Interface

Direct MCU R-D Conversion vs. RDC IC

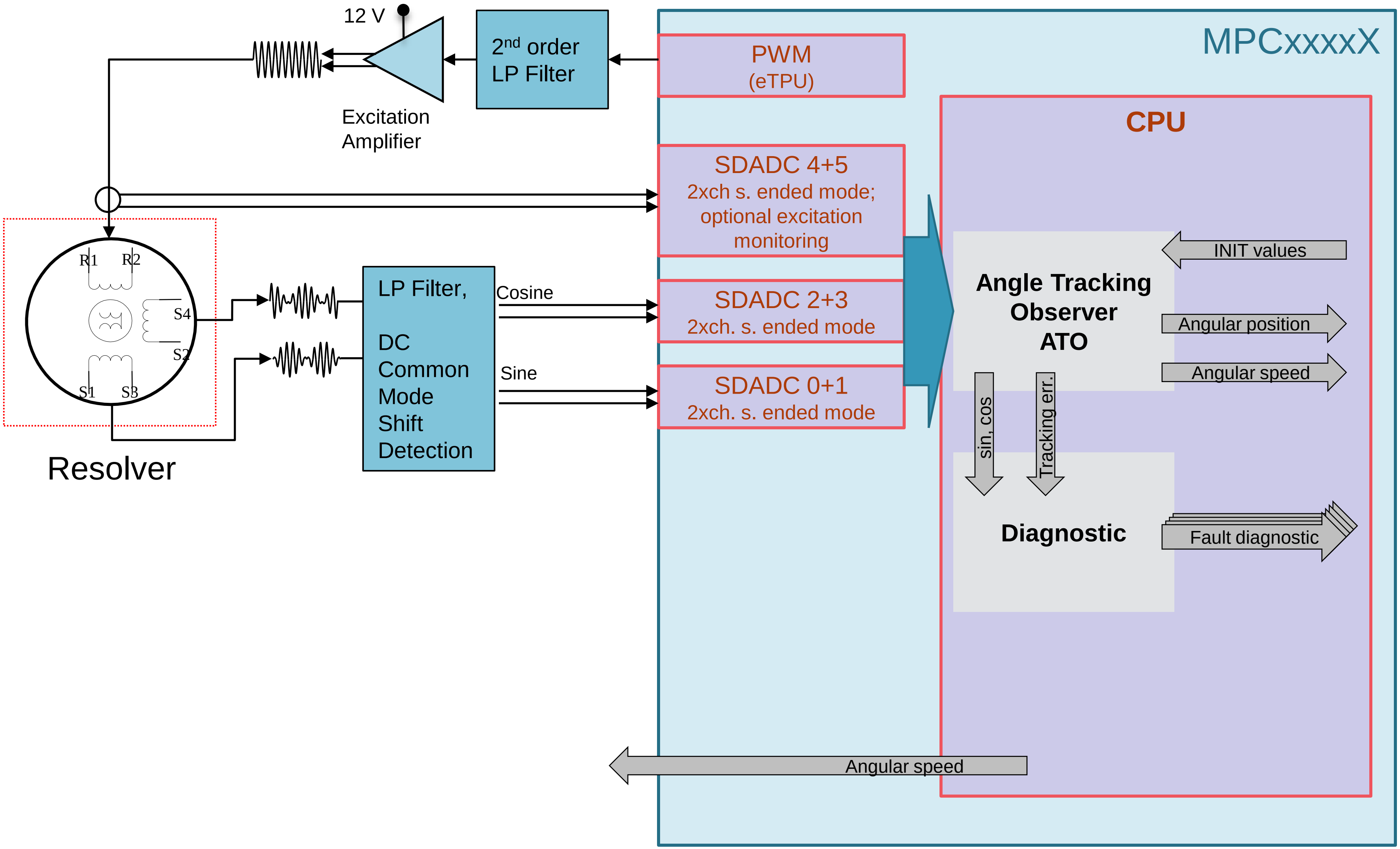
SW RDC



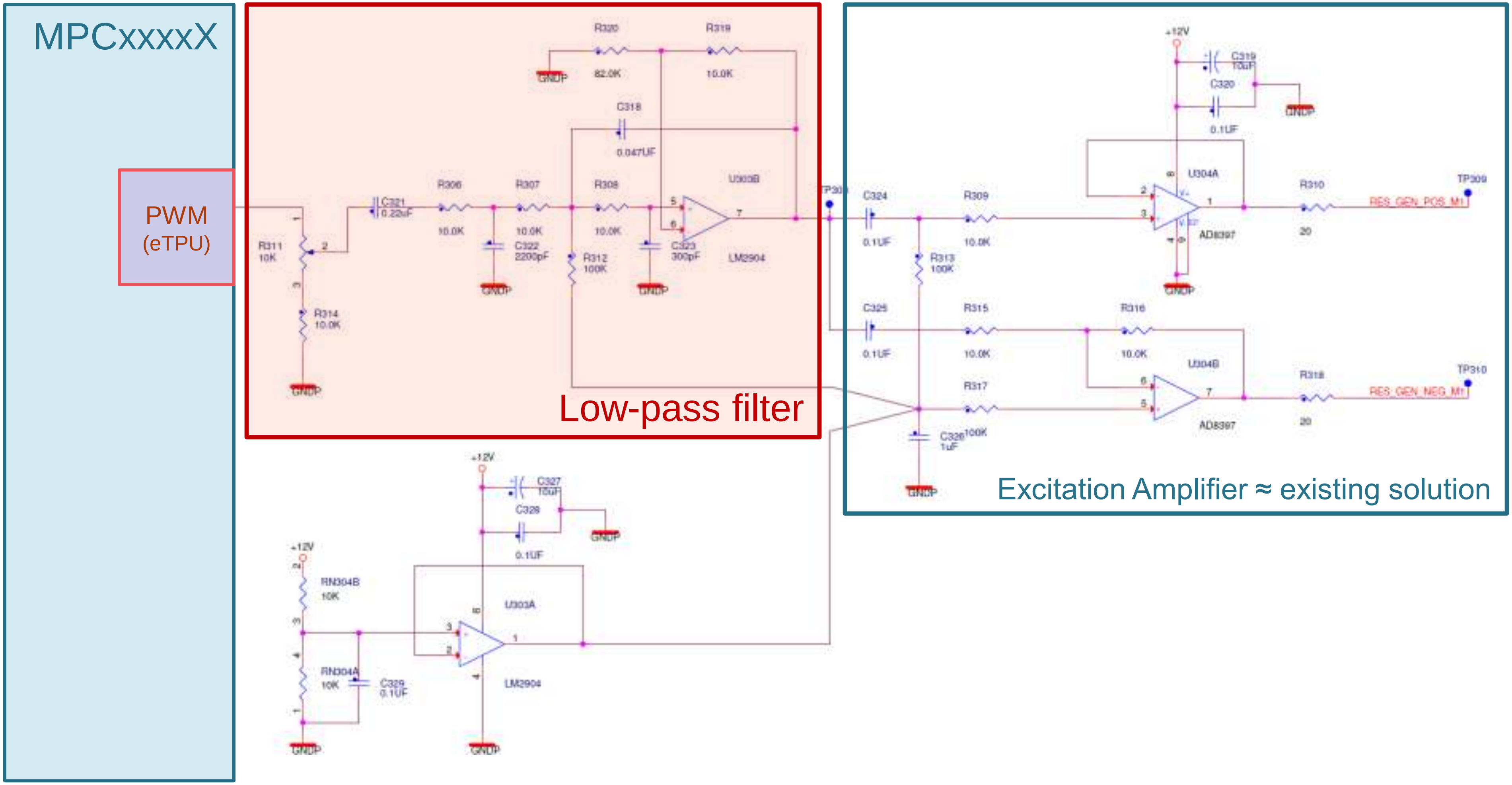
RDC IC



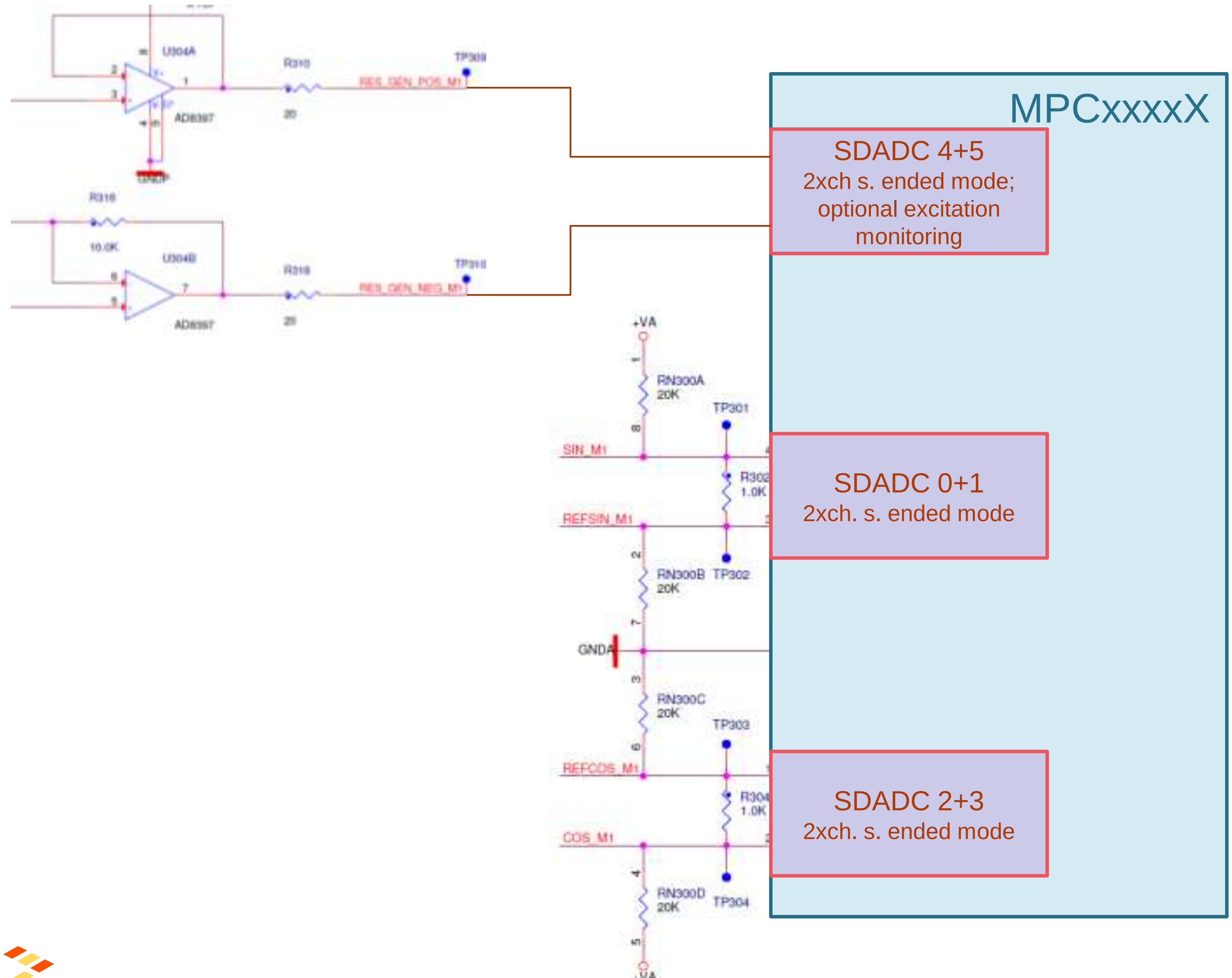
Direct MCU R-D Conversion: Application Example



Resolver Differential Excitation Stage



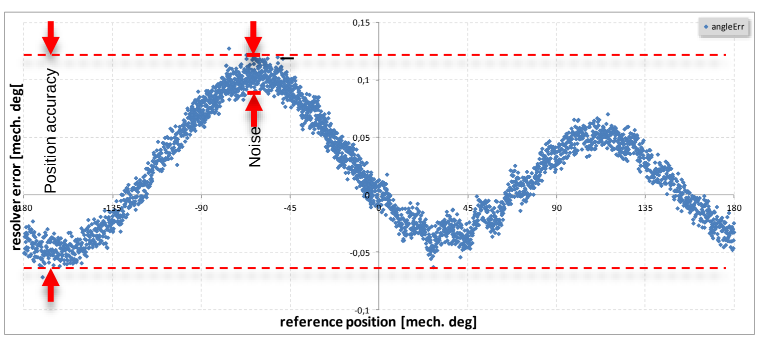
Resolver Input Stage (Phy. Layer)



Evaluation Results

MPC5746M SW RDC

- Position accuracy **±0.09** deg. **12bit ±1LSB**
- External hardware
  - Excitation amplifier
  - Hardware tuned for given resolver
  - Differential measurement
  - Phase difference, offset, gain error <u>uncompensated</u>
  - LP Filter, DC Common Mode Shift Detection
- Noise, repeatability **±0.033** deg.
  - Higher CPU* & ADC load

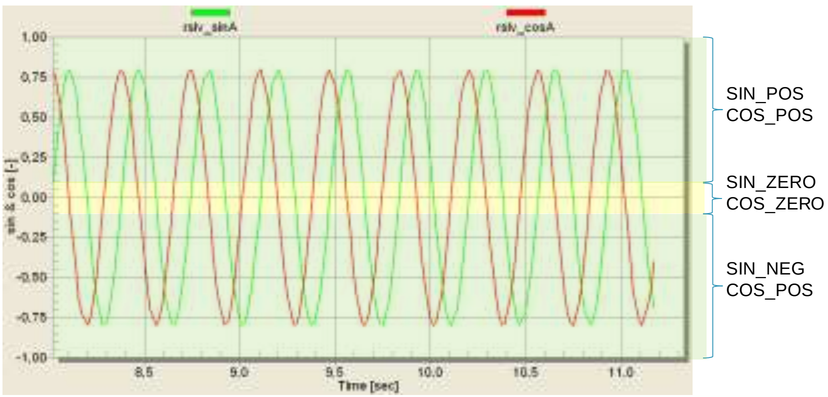


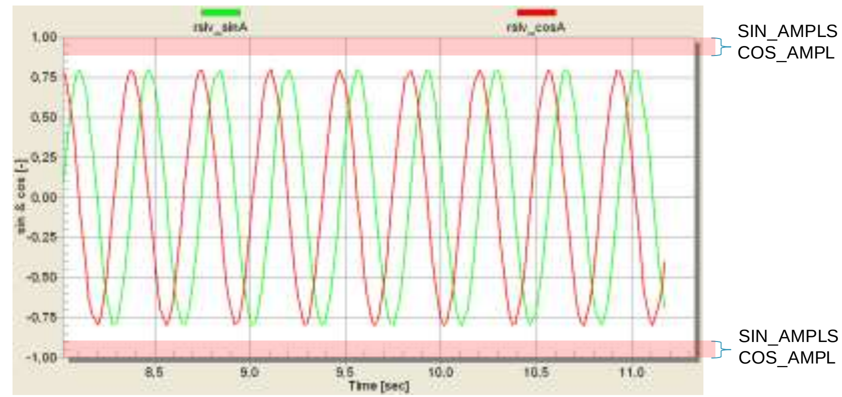
RDC IC

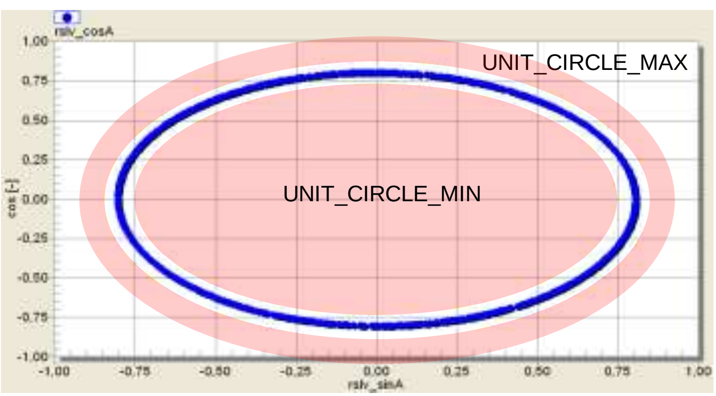
- Position accuracy **±0.13** deg. **12bit ±2LSB**
- External hardware
  - Excitation amplifier
  - LP Filter, DC Common Mode Shift Detection
- True 12-bit resolution without noise
- Repeatability **±0.07** deg.

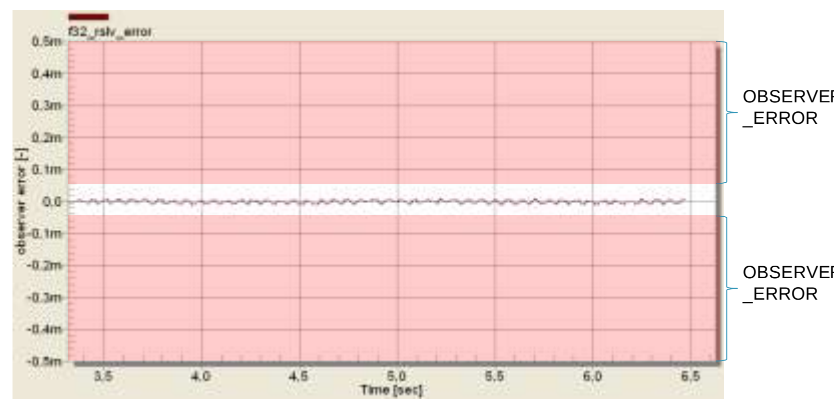
Diagnostics: Calibratable Fault Thresholds

- Fault diagnostic thresholds are implemented in software, therefore can be easily calibrated.

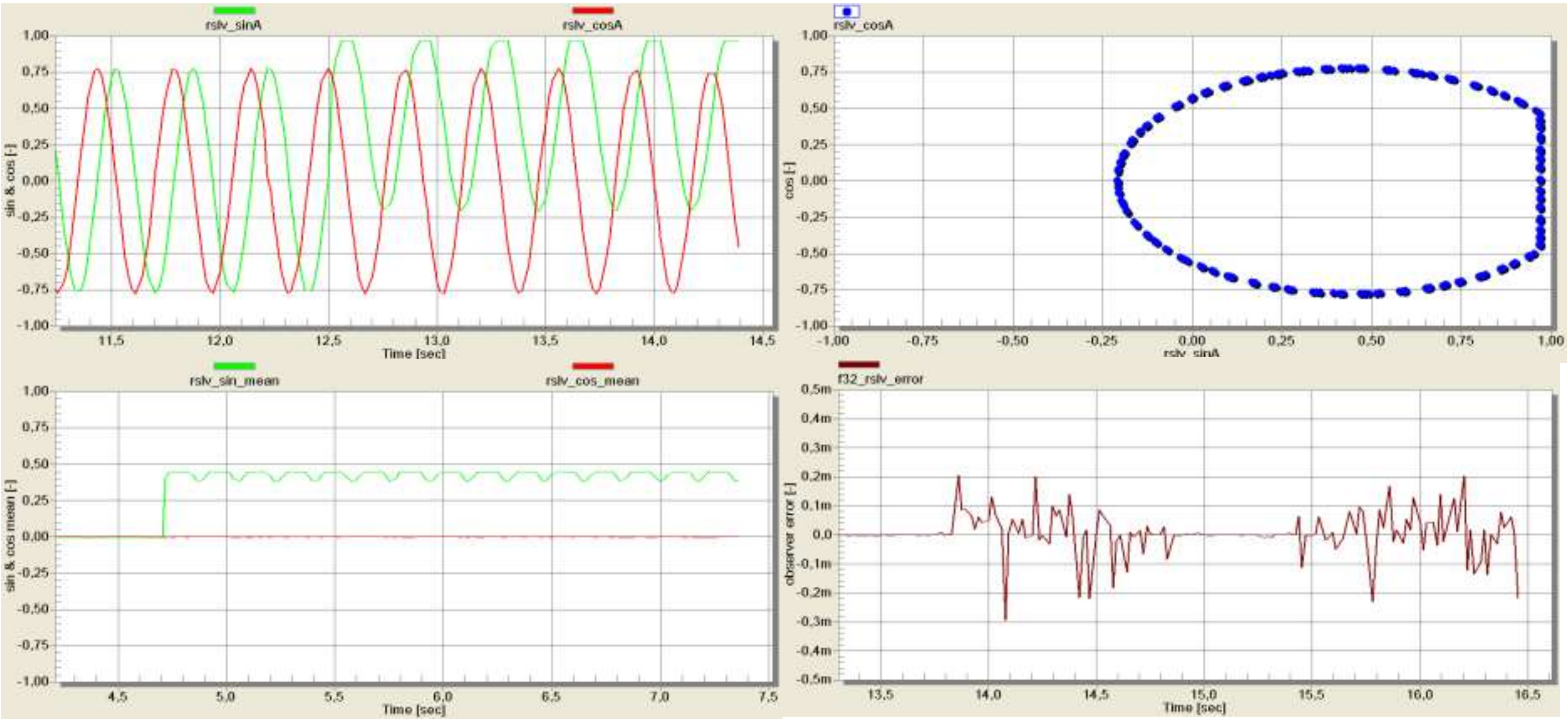






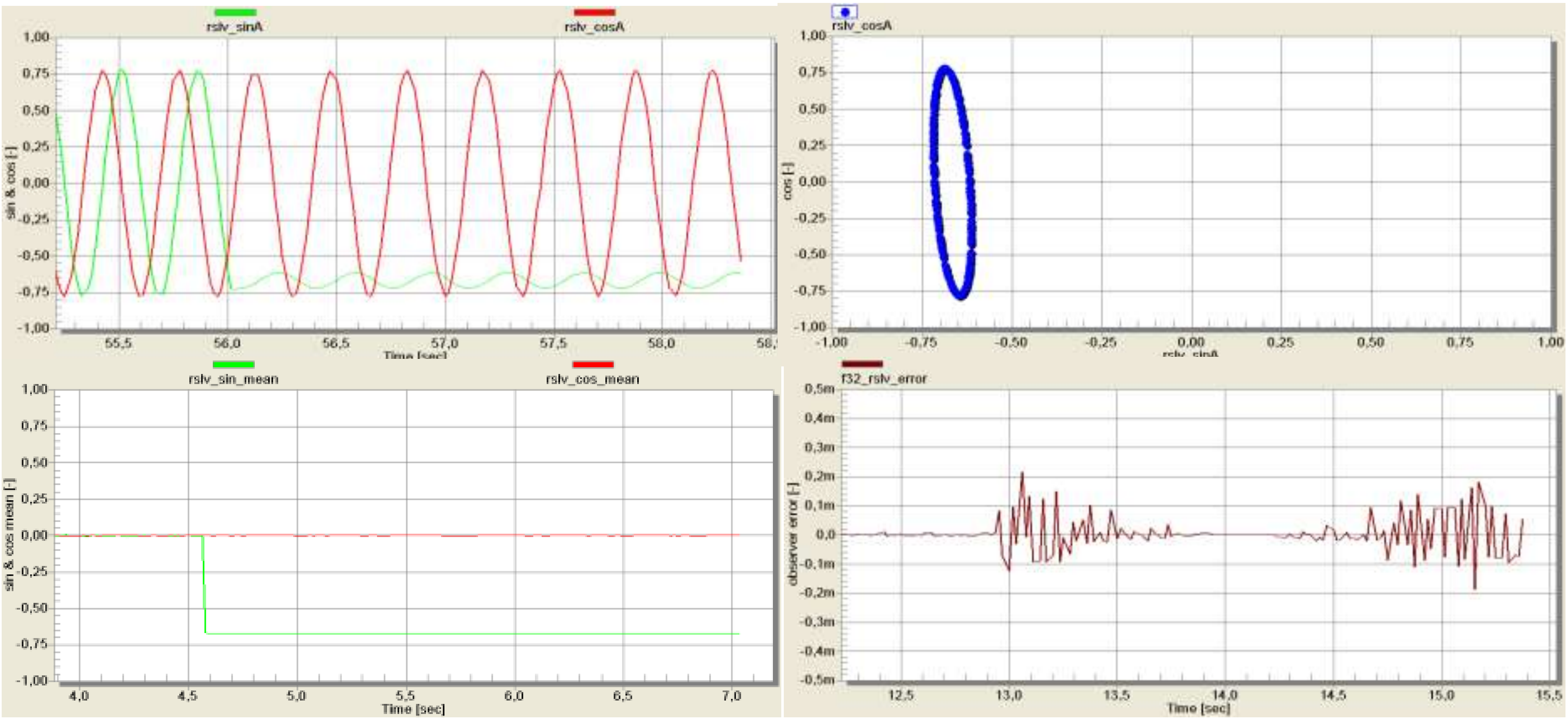


Fault Example: SIN Short to GND



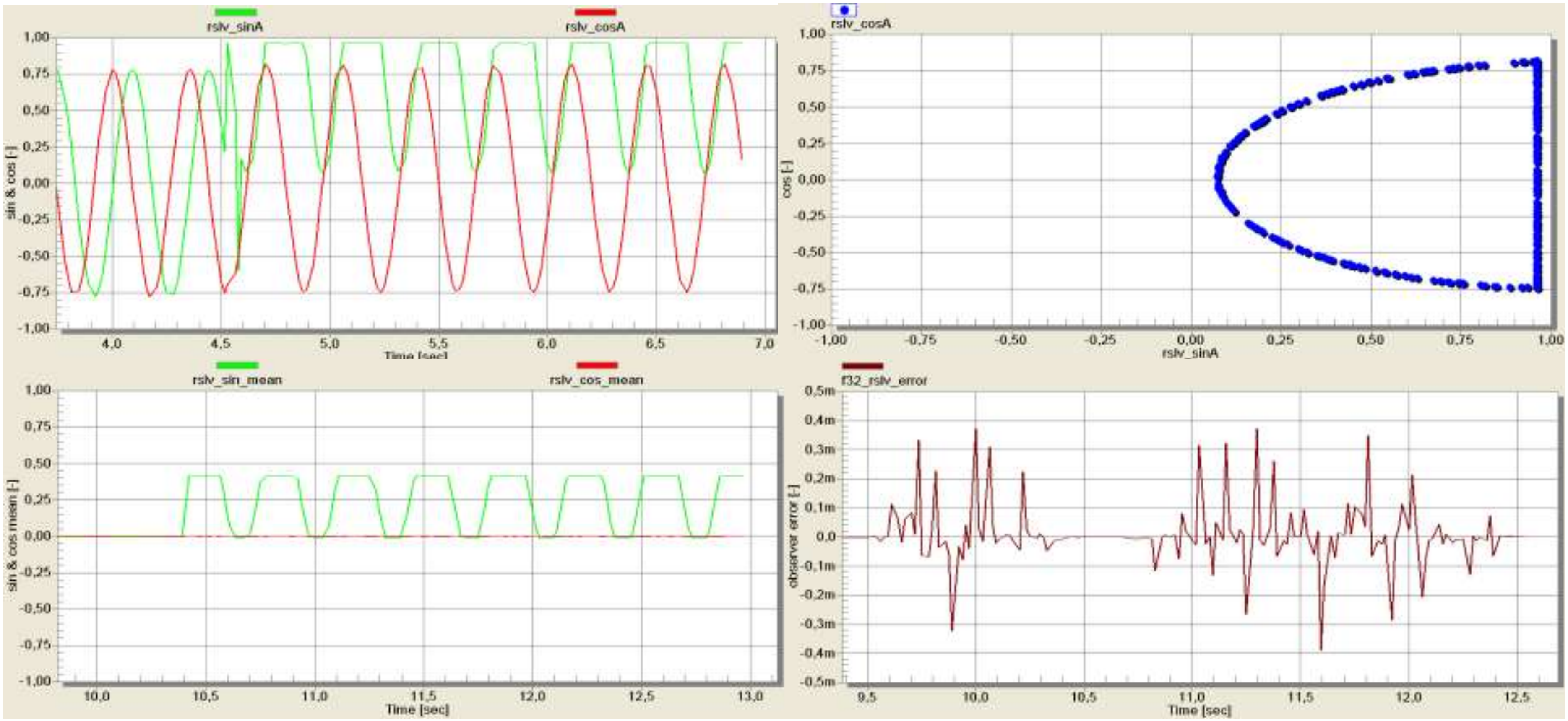
		Sin				Cos				Means				Unit Circle		ATO	
		SIN_ZERO	SIN_POS	SIN_NEG	SIN_AMPL	COS_ZERO	COS_POS	COS_NEG	COS_AMPL	SIN_MEAN_POS	SIN_MEAN_NEG	COS_MEAN_POS	COS_MEAN_NEG	UNIT_CIRCLE_MIN	UNIT_CIRCLE_MAX	OBSERVER_ERROR	Calculated Angle
1.2b	SIN Wire(or pin) short to GND	?	?	?	1	?	?	?	?	1	0	?	?	1	1	?	+/- 35deg

Fault Example: REFSIN Open



		Sin				Cos				Means				Unit Circle		ATO	
		SIN_ZERO	SIN_POS	SIN_NEG	SIN_AMPL	COS_ZERO	COS_POS	COS_NEG	COS_AMPL	SIN_MEAN_POS	SIN_MEAN_NEG	COS_MEAN_POS	COS_MEAN_NEG	UNIT_CIRCLE_MIN	UNIT_CIRCLE_MAX	OBSERVER_ERROR	Calculated Angle
1.3a	REFSIN Wire(or pin) open	?	0	1	0	?	?	?	?	0	1	?	?	1	1	?	wrong

Fault Example: Shortcut REZ_GEN and REFSIN



		Sin				Cos				Means				Unit Circle		ATO	
		SIN_ZERO	SIN_POS	SIN_NEG	SIN_AMPL	COS_ZERO	COS_POS	COS_NEG	COS_AMPL	SIN_MEAN_POS	SIN_MEAN_NEG	COS_MEAN_POS	COS_MEAN_NEG	UNIT_CIRCLE_MIN	UNIT_CIRCLE_MAX	OBSERVER_ERROR	Calculated Angle
2.2	Short between REZ_GEN and REFSIN	?	1	0	1	?	?	?	?	1	0	?	?	1	1	?	wrong

Resolver + R/D IC Comments

- Advantages
  - Position information during MCU initialization stage
  - High resolution: 12-bit
  - Simple SPI interface between MCU and RDC IC

- Disadvantages
  - Only simple diagnostic possible (raw signal data not accessible)
  - No limp operation modes
  - RDC IC may require up to 30 pins
  - Larger board area
  - Higher system cost

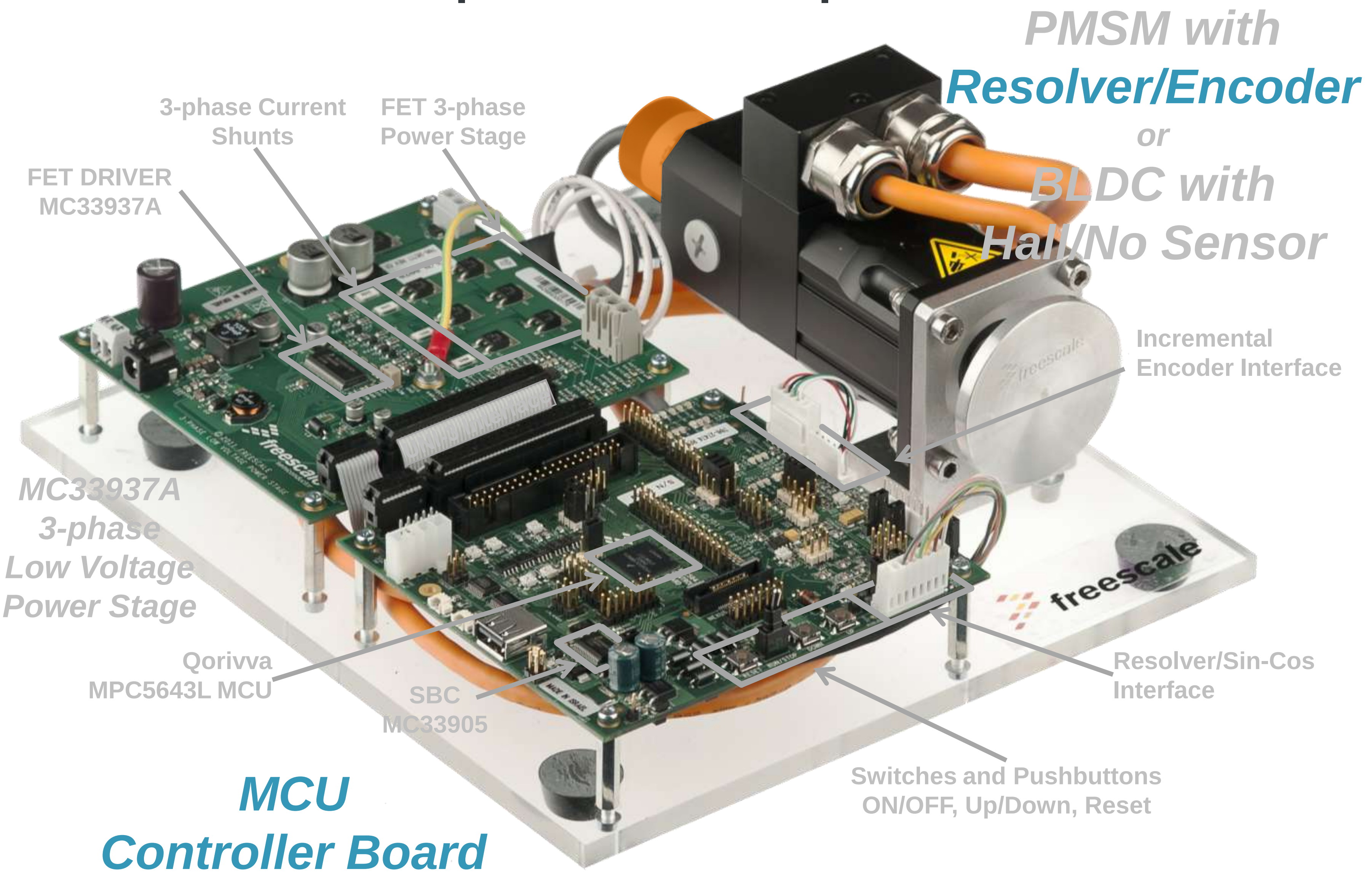
Resolver + SW Observer Comments

- Advantages
  - High resolution: 10-12 bit (dependent on the resolution of A/D converter)
  - Simple hardware
  - Lower cost than resolver + ASIC
  - Intelligent diagnostics possible with complex conditioning for fault source detection
  - Limp mode operation modes possible

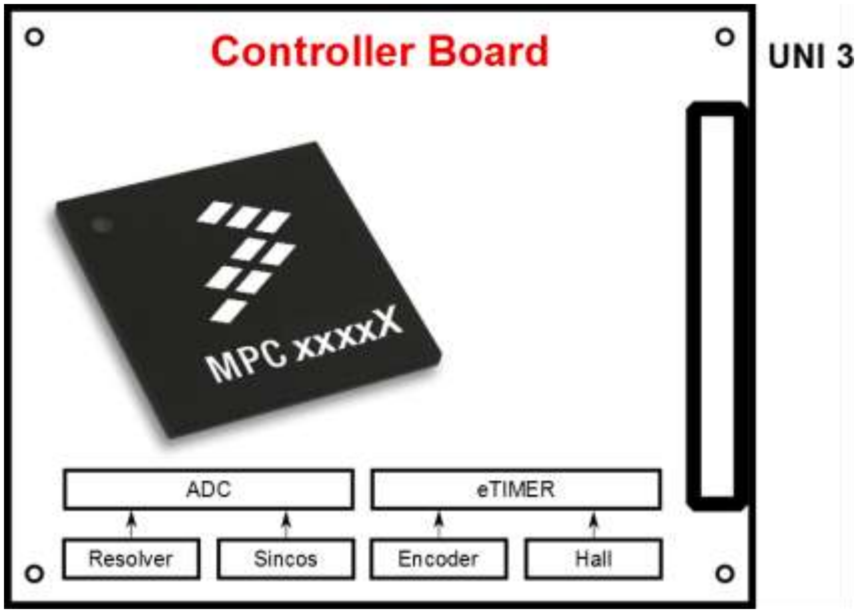
- Disadvantages
  - Intensive calculation needs, higher CPU load easily managed by Freescale 32-bit Qorivva microcontrollers

Freescale Support, Examples, Documentation

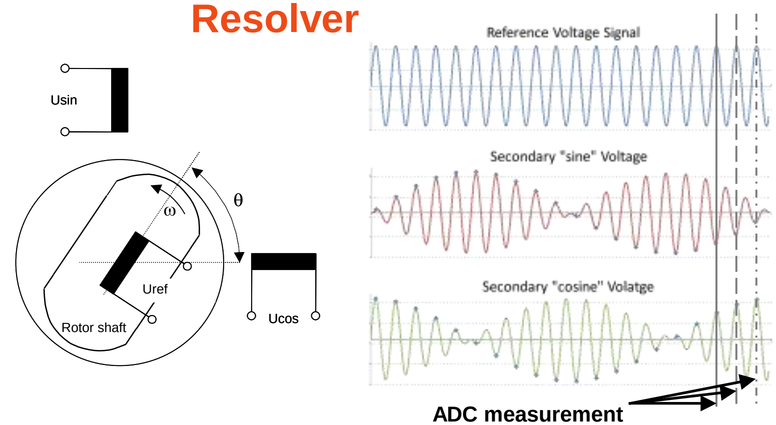
Motor Control Development Kit: Composition



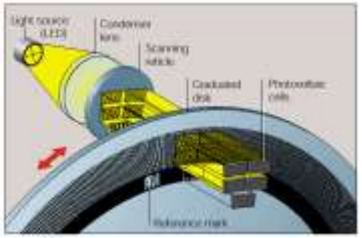
Sensor: Position and Speed Measurement



Resolver



Encoder



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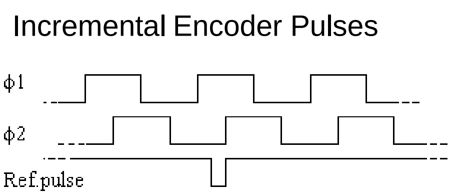


Functional properties:

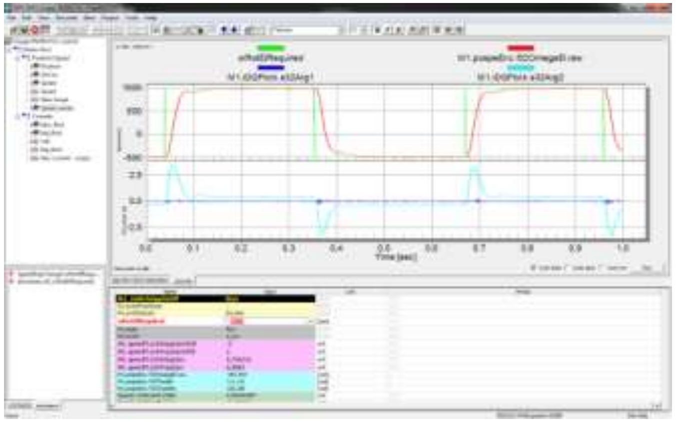
- Sine-wave excitation signal generation
- Position measurement
- Speed measurement
- Revolution measurement

Key features:

- Adjustable magnitude of excitation signal
- Adjustable frequency of excitation signal
- Sensor fault state detection

Motor Control Development Kit Series: Content

- Out-of-the-box experience offers:
  - Complete schematics of the development kit hardware
  - Complete source code of the development kit software application
  - Math and Motor Control libraries (MCLib) in object code
  - FreeMASTER & MCAT interface to easy application visualization / control
  - Extensive documentation including User Guide, Quick Start Guide and Fact Sheet



FreeMASTER Scope

FreeMASTER HTML-based Control Page

www.freescale.com/AutoMCDevKits

Auto Math and Motor Control Library Set

Target Platform	GreenHills Multi	WindRiver Diab	Cosmic
Qorivva MCU	RTM Rev 1.0	RTM Rev 1.0	
S12ZVM			RTM Rev 1.0

MLIB

- **Absolute Value, Negative Value**
  - MLIB_Abs, MLIB_AbsSat
  - MLIB_Neg, MLIB_NegSat
- **Add/Subtract Functions**
  - MLIB_Add, MLIB_AddSat
  - MLIB_Sub, MLIB_SubSat
- **Multiply/Divide/Add-multiply Functions**
  - MLIB_Mul, MLIB_MulSat
  - MLIB_Div, MLIB_DivSat
  - MLIB_Mac, MLIB_MacSat
  - MLIB_VMac
- **Shifting**
  - MLIB_ShL, MLIB_ShLSat
  - MLIB_ShR
  - MLIB_ShBi, MLIB_ShBiSat
- **Normalisation, Round Functions**
  - MLIB_Norm, MLIB_Round
- **Conversion Functions**
  - MLIB_ConvertPU, MLIB_Convert

GFLIB

- **Trigonometric Functions**
  - GFLIB_Sin, GFLIB_Cos, GFLIB_Tan
  - GFLIB_Asin, GFLIB_Acos, GFLIB_Atan, GFLIB_AtanYX
- **Limitation Functions**
  - GFLIB_Limit, GFLIB_VectorLimit
  - GFLIB_LowerLimit, GFLIB_UpperLimit
- **PI Controller Functions**
  - GFLIB_ControllerPIr, GFLIB_ControllerPIrAW
  - GFLIB_ControllerPIp, GFLIB_ControllerPIpAW
- **Interpolation**
  - GFLIB_Lut1D, GFLIB_Lut2D
- **Hysteresis Function**
  - GFLIB_Hyst
- **Signal Integration Function**
  - GFLIB_IntegratorTR
- **Sign Function**
  - GFLIB_Sign
- **Signal Ramp Function**
  - GFLIB_Ramp
- **Square Root Function**
  - GFLIB_Sqrt

GDFLIB

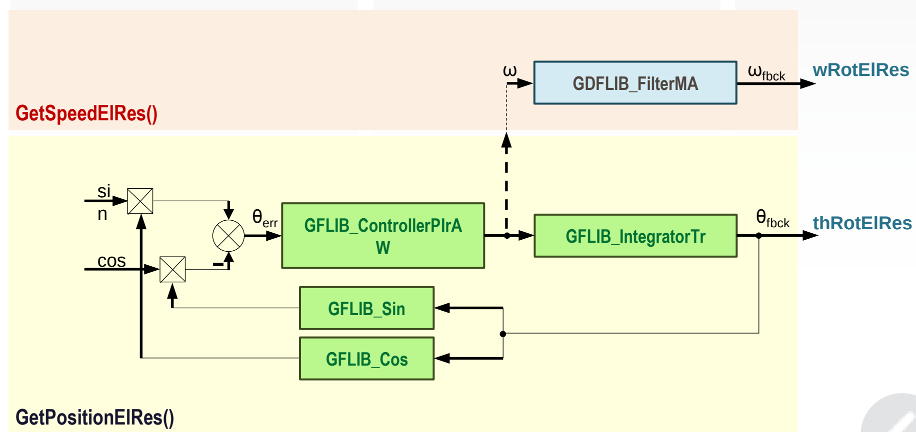
- **Finite Impulse Filter**
  - GDFLIB_FilterFIR
- **Moving Average Filter**
  - GDFLIB_FilterMA
- **1st Order Infinite Impulse Filter**
  - GDFLIB_FilterIIR1init
  - GDFLIB_FilterIIR1
- **2nd Order Infinite Impulse Filter**
  - GDFLIB_FilterIIR2init
  - GDFLIB_FilterIIR2

GMCLIB

- **Clark Transformation**
  - GMCLIB_Clark
  - GMCLIB_ClarkInv
- **Park Transformation**
  - GMCLIB_Park
  - GMCLIB_ParkInv
- **Duty Cycle Calculation**
  - GMCLIB_SvmStd
- **Elimination of DC Ripples**
  - GMCLIB_ElimDcBusRip
- **Decoupling of PMSM Motors**
  - GMCLIB_DecouplingPMSM

ACLIB/AMCLIB

- **Angle Tracking Observer**
- **Tracking Observer**
- **PMSM BEMF Observer in Alpha/Beta**
- **PMSM BEMF Observer in D/Q**
- **Content To Be Defined**



MC Development Kits: Web Page Summary

Motor Control Development Kits

www.freescale.com/AutoMCDevKits

See short promotional video on Freescale's YouTube channel

Math & Motor Control Library Set

www.freescale.com/automclib

Motor Control Application Tuning Tool (MCAT)

www.freescale.com/MCAT

See short promotional video on Freescale's YouTube channel

FreeMASTER

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