STM32 for Motor Control Applications

MCU Division Applications

Features and benefits

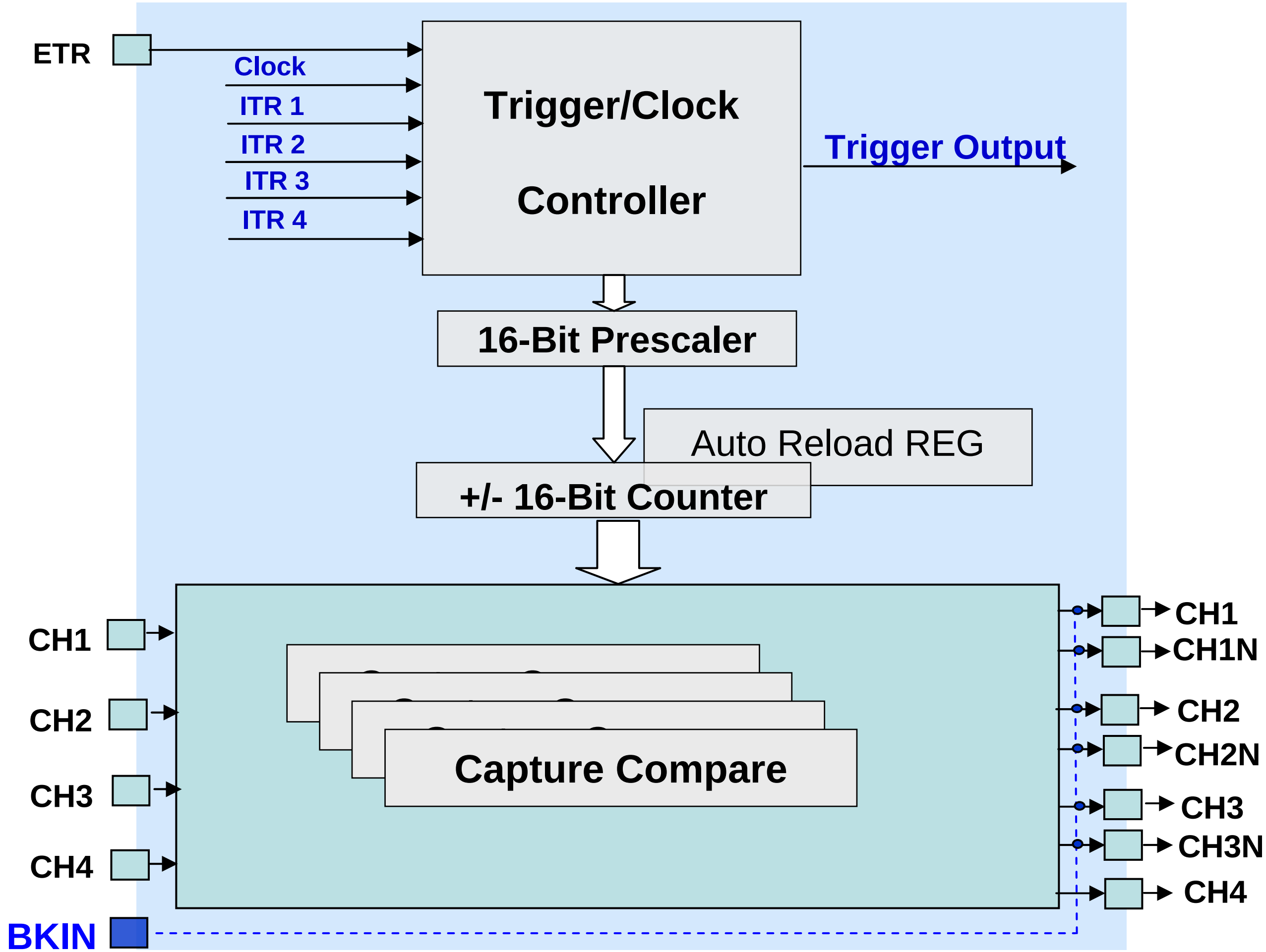
2007 1987

20 years dedicated to the future

Plan

- PWM generation
- Speed / position feedback
- Multi timer configuration
- Analog to Digital converter
- Current sensing and ADC synchronization
- Field Oriented Control
- Motor Control Tools

Advanced timer Features overview

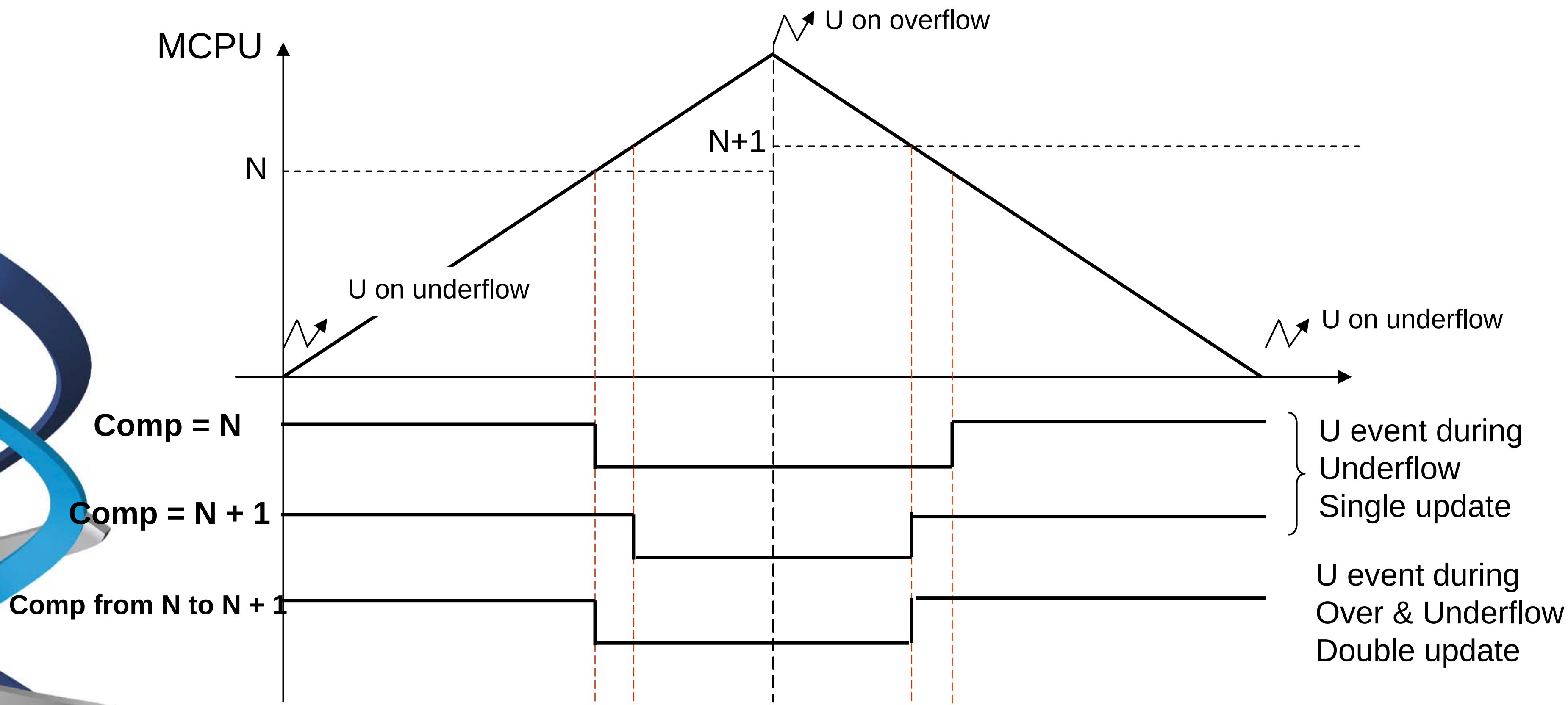


High-resolution PWM generation

- Motor Control Timer clock
  - Can be 2x the APB bus frequency
  - Max input clock is 72MHz to provide 13.8ns edge resolution (12-bit @16kHz edge-aligned PWM)
- Edge or center-aligned patterns
- Double-update mode (cf next slide)
  - No loss of resolution in center-aligned mode
  - Done thanks to an additional interrupt per PWM cycle or DMA transfers

Double Update Mode

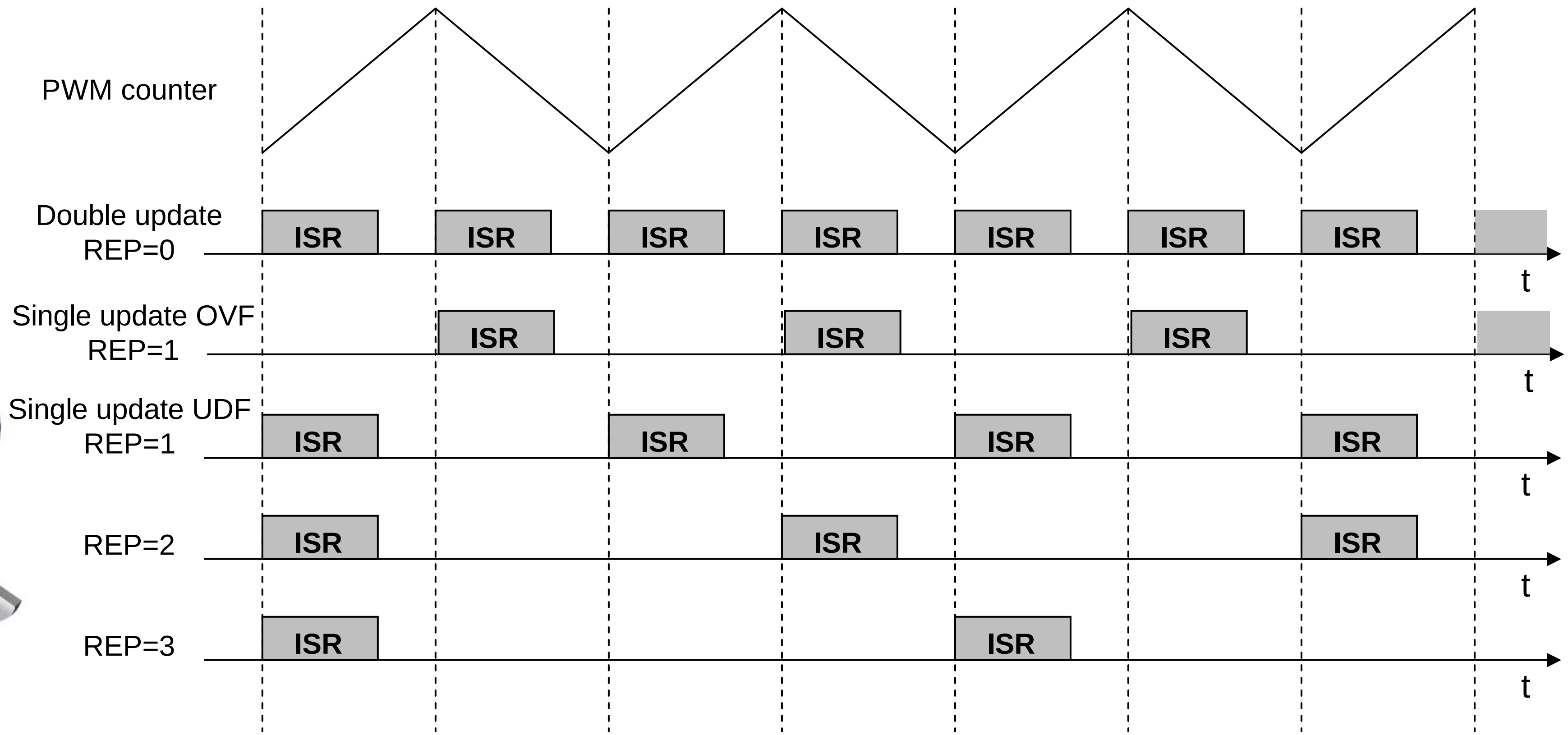
- An Update event (U) during the Overflow of the PWM counter improves duty cycle resolution.



PWM main Interrupt Service Routine

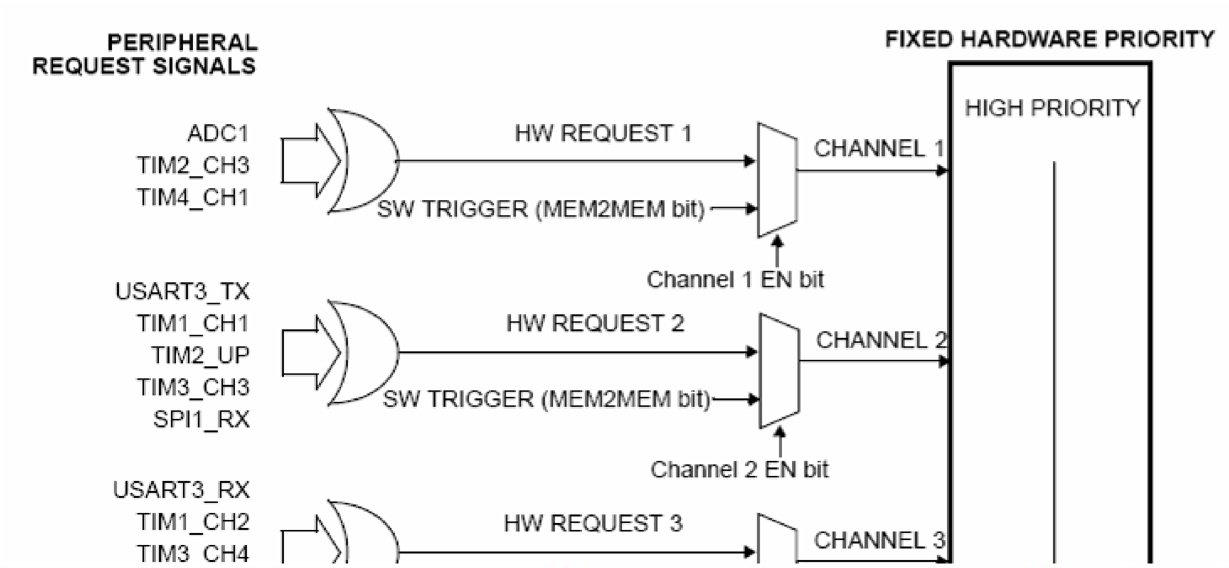
- So-called U (Update) event
  - Synchronously transfers all preload into active registers
    - 3 (4) compares for duty cycles
      - Preload mechanism can be disabled if needed
    - 1 Auto Reload for PWM switching period
      - allows changing on-the-fly the PWM frequency while maintaining duty cycles
    - PWM clock pre scaler
- Adjustable U event rate
  - programmable through a 8-bit repetition counter
  - Allows to choose Overflow/Underflow or both for update

Repetition Counter



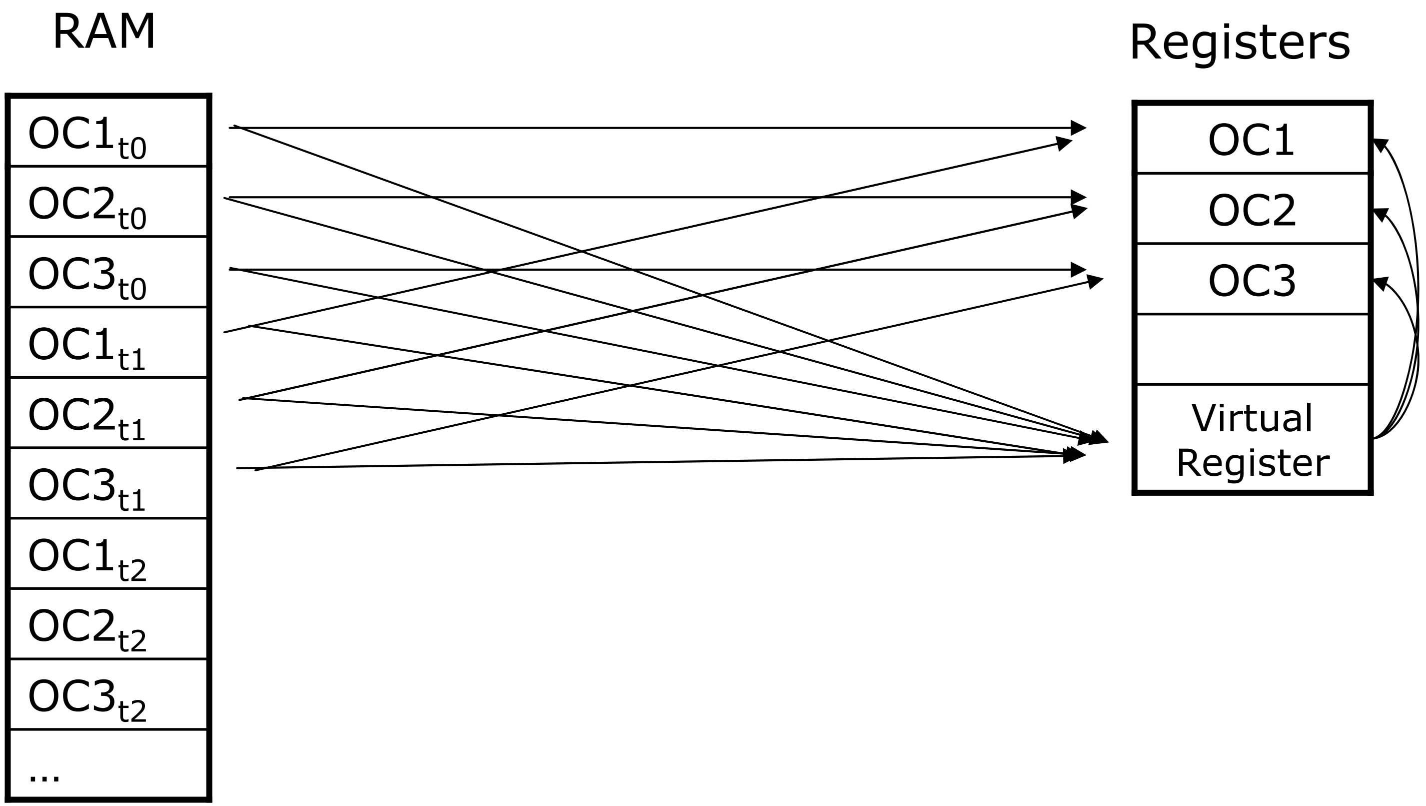
Other interrupts and DMA

- Other interrupt sources available on PWM timer
  - Each Compare match (up or down counting selectable) or capture
  - Trigger events
  - Emergency Stop
- Some events are also mapped on the DMA controller



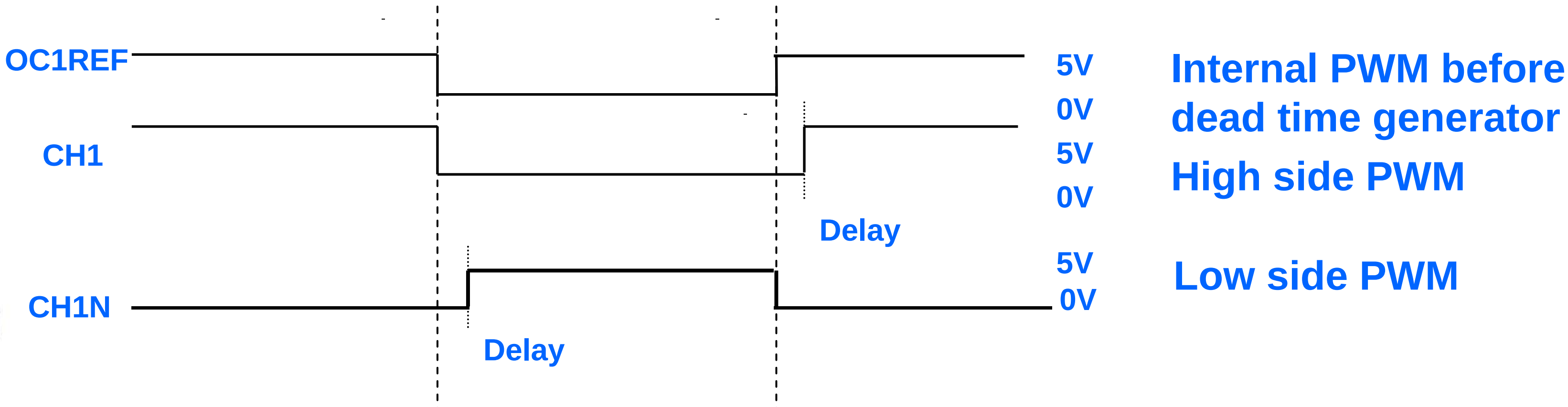
PWM's DMA burst transfer

- Allows to update several registers with a single DMA event
  - Efficient use of DMA (a single stream is required)



PWM outputs management

- Programmable hardware deadtime generation
  - 8-bit register with 13.8ns max resolution at 72MHz (from 0 to 14µs, non-linear)



- Individually selectable polarity selection
- Dedicated emergency stop input
  - Shuts down the 6 PWM outputs and issues an interrupt
  - **Asynchronous** operation (operates without clock source)

Versatile PWM redirection circuitry 1/2

Table 40. Output Control of Complementary OCx and OCxN Channels

Control Bits					Output State	
MOE bit	OSSI bit	OSSR bit	OCxE bit	OCxNE bit	OCx output state	OCxN output state
1	x	0	0	0	Output disabled	Output disabled
	x	0	0	1	Output disabled	OCREF + Polarity (OCREF xor OCxP)
	x	0	1	0	OCREF + Polarity (OCREF xor OCxP)	Output disabled
	x	0	1	1	OCREF + Polarity + dead-time	Complementary to OCREF (not OCREF) + Polarity + dead-time
	x	1	0	0	Off-State (output enabled with inactive state)	Off-State (output enabled with inactive state)
	x	1	0	1	Off-State (output enabled with inactive state)	OCREF + Polarity (OCREF xor OCxNP)
	x	1	1	0	OCREF + Polarity (OCREF xor OCxP)	Off-State (output enabled with inactive state)
	x	1	1	1	OCREF + Polarity + dead-time	Complementary to OCREF (not OCREF) + Polarity + dead-time
0	0	x	0	0	Output disabled	
	0	x	0	1		
	0	x	1	0		
	0	x	1	1		
	1	x	0	0	Off-State (output enabled with inactive state)	
	1	x	0	1		
	1	x	1	0		
	1	x	1	1		

PWM timer used as a GP timer

Motor Control (sinewave)

Motor Control (6-steps)

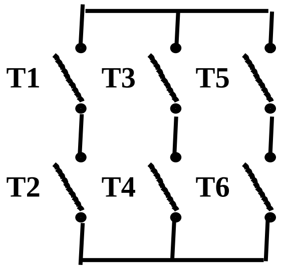
Motor Control (sinewave)

Outputs disconnected from I/O ports

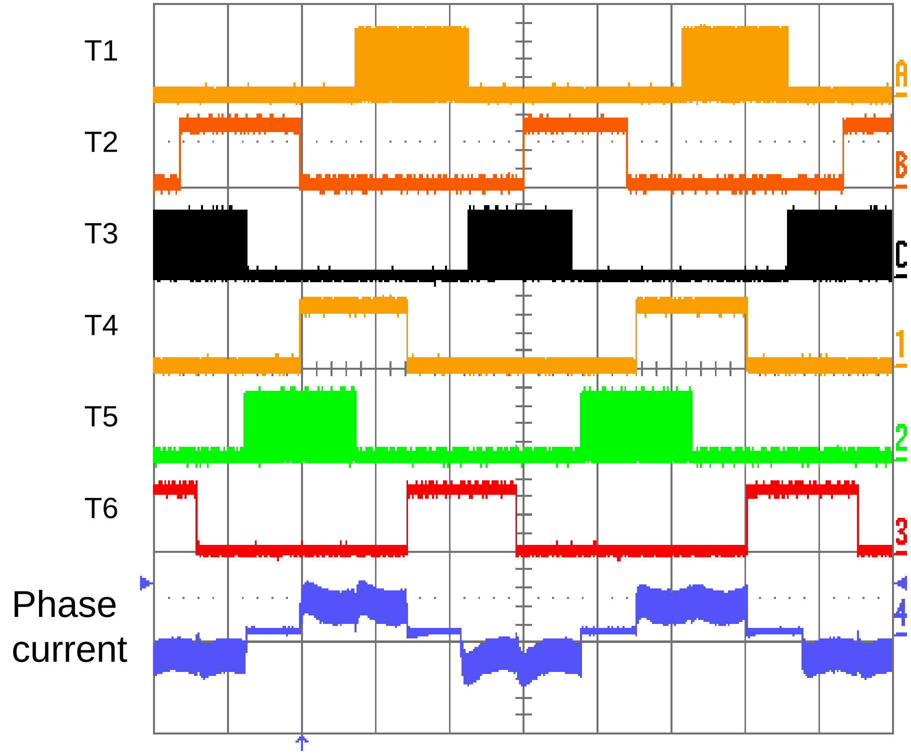
All PWMs OFF (low Z for safe stop)

Versatile PWM redirection circuitry 2/2

- Example: 6-steps (or block commutated) drives



Step	High	Low	OC1	OC1N	OC2	OC2N	OC3	OC3N
1	T1	T4	oc1ref	0	0	1	0	0
2	T1	T6	oc1ref	0	0	0	0	1
3	T3	T6	0	0	oc2ref	0	0	1
4	T3	T2	0	1	oc2ref	0	0	0
5	T5	T2	0	1	0	0	oc3ref	0
6	T5	T4	0	0	0	0	oc3ref	0



Break input

- A break event can be generated by:
  - The BRK input which has a programmable polarity and an enable bit BKE
  - The Clock Security System

- When a break occurs:
  - The MOE bit (Main Output Enable) is cleared
  - The break status flag is set and an interrupt request can be generated
  - Each output channel is driven with the level programmed in the OISx bit
    - For instance all low side switches ON for PM motors in field weakening mode

- Break applications:
  - If the AOE is Reset, the MOE remains low until you write it to '1' again
    - Normally used for security with break input connected to an alarm feedback from power stage, thermal sensors or any security components.
  - If the AOE (Automatic Output Enable) bit is set, the MOE bit is automatically set again at the next update event UEV
    - Typically be used for cycle-by-cycle current regulation
    - Current regulation can also be performed using External trigger input (ETR)

Smoke inhibit protections

- Safety critical registers can be “locked”, to prevent power stage damages (software run-away,…)
  - Dead time, PWM outputs polarity, emergency input enable,…
- All target registers are read/write until lock activation (and then read-only if protected)
  - Once the two lock bits are written, they cannot be modified until next MCU reset (write-once bits)
  - 4 lock levels offer full flexibility depending on the application (e.g. 6-steps vs sine)
- GPIO configuration can be locked to avoid having the PWM alternate function outputs reprogrammed as standard outputs

Debug feature

- Motor control applications are usually tricky to debug using breakpoints
  - Standard breakpoints may damage the power stage
  - Closed loop systems can hardly be stopped and re-started
- A configuration bit allows to program the behavior of the PWM timer upon breakpoint match
  - Normal mode: the timer continues to operate normally
    - May be dangerous in some case since a constant duty cycle is applied to the inverter (interrupts not serviced)
  - Safe mode: the timer is frozen and PWM outputs are shut down
    - Safe state for the inverter. The timer can still be re-started from where it stops.

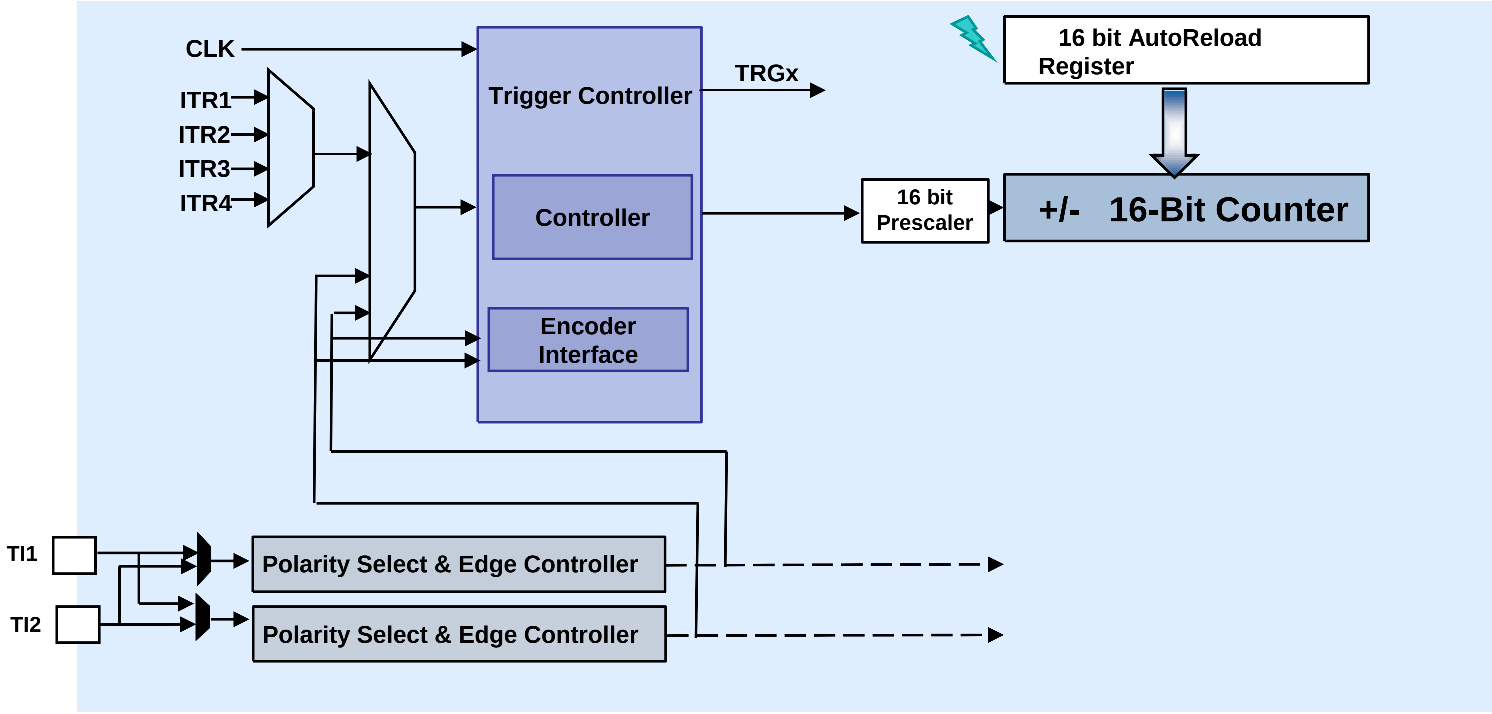
Plan

- PWM generation
- Speed / position feedback
- Multi timer configuration
- Analog to Digital converter
- Current sensing and ADC synchronization
- Field Oriented Control
- Motor Control Tools

Speed Feedback

- Handled by the general purpose timers, with dedicated modes
  - These functions are available on all timers
- Hall sensors
  - Hall Sensor interface (XOR'ed inputs)
- Encoder
  - Encoder modes 1, 2 & 3 (2x, 4x)
- Tacho feedback
  - Clear on capture to measure exact period

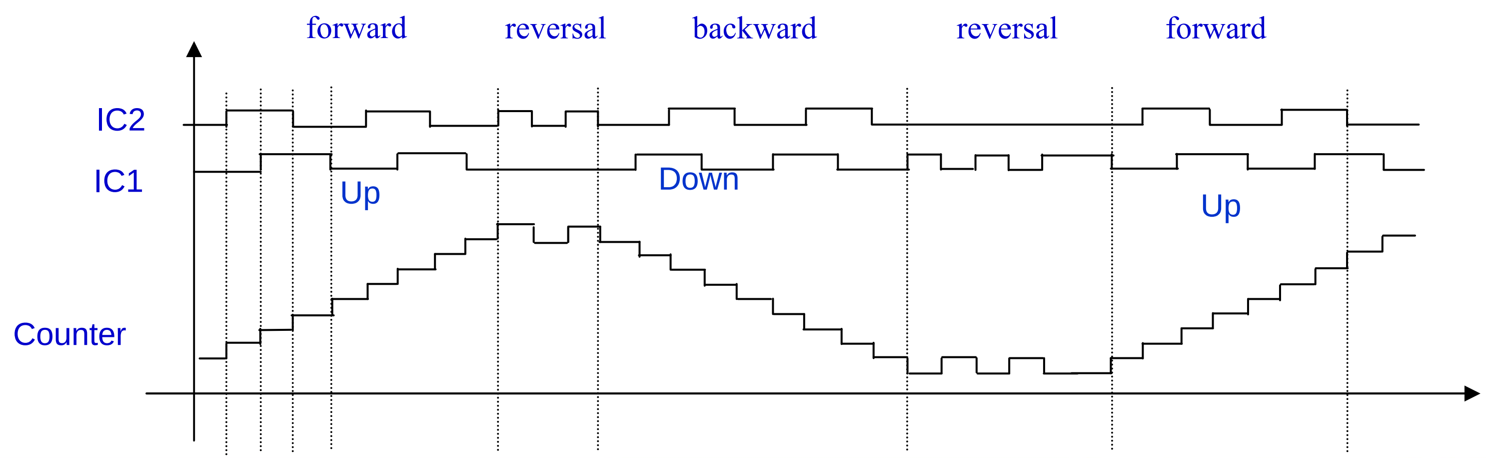
TIM Block Diagram in encoder mode



Interfacing a TIM timer with an encoder

- Encoders and STM32 connection example:
  - An incremental encoder can be connected directly to the MCU without external interface logic.
  - The third encoder output which indicates the mechanical zero position (Z or index), may be connected to an external interrupt and trigger a counter reset

Example of counter operation in Encoder Interface mode



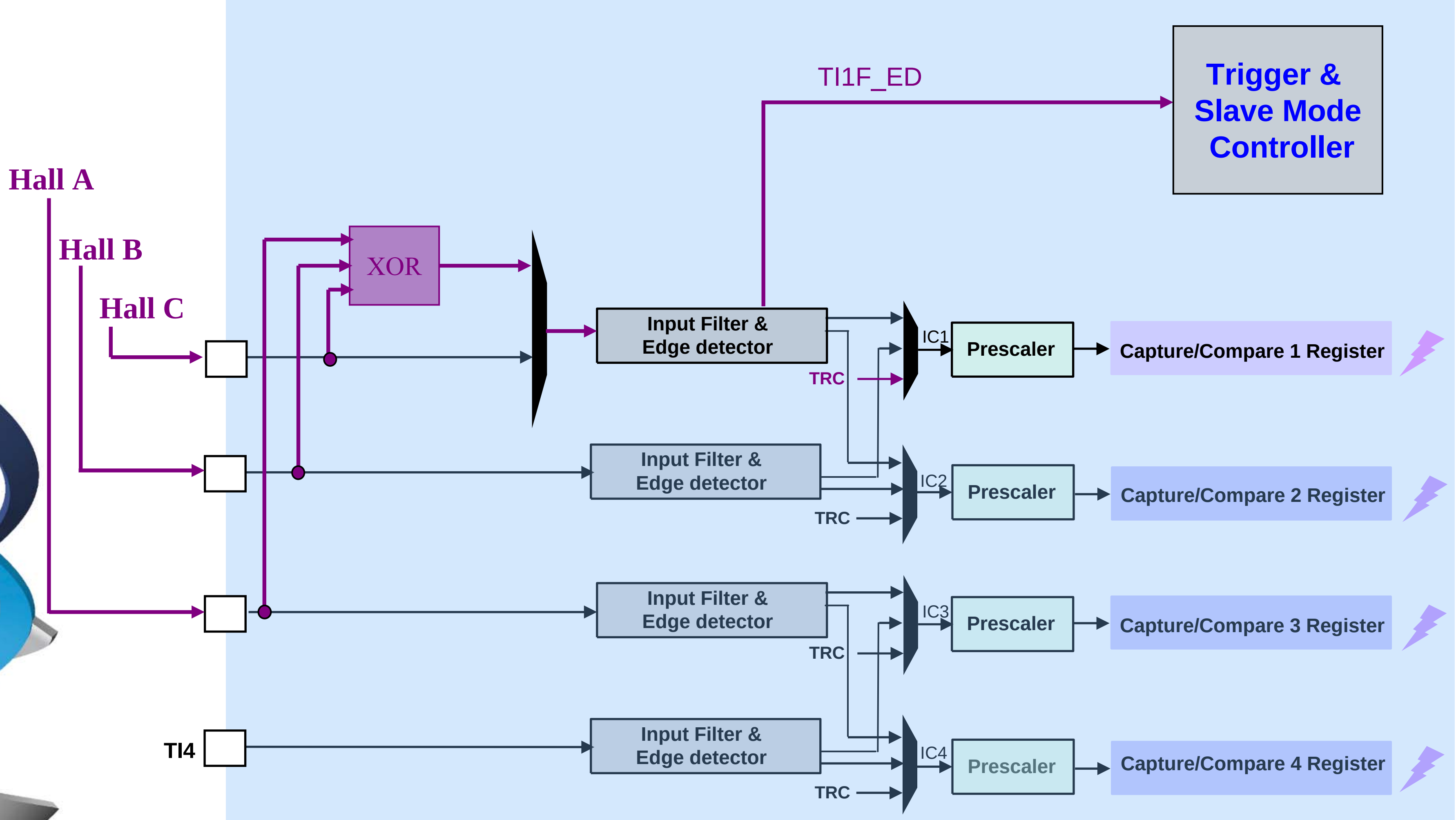
Key encoder features

- Programmable counting rate
  - x4: normal mode, all edges active
    - a 1000 lines encoder will give 4000 counts per revolution
  - x2: counts on input A (or B) only, but direction still determined with A and B
  - "velocity mode": encoder clock can be further prescaled if needed

- Programmable encoder resolution
  - When programming the autoreload register with the number of counts per revolution, the counter register directly holds the angle or the position
    - No need to do the difference vs previous counter value
  - If set to 0xFFFF, can be made compatible with previous designs using a free-running counter

- Possibility to generate one/multiple interrupts per revolution:
  - once every 360°
  - once 60°, 90°,… (depending on autoreload register setting)

Hall sensor Interface

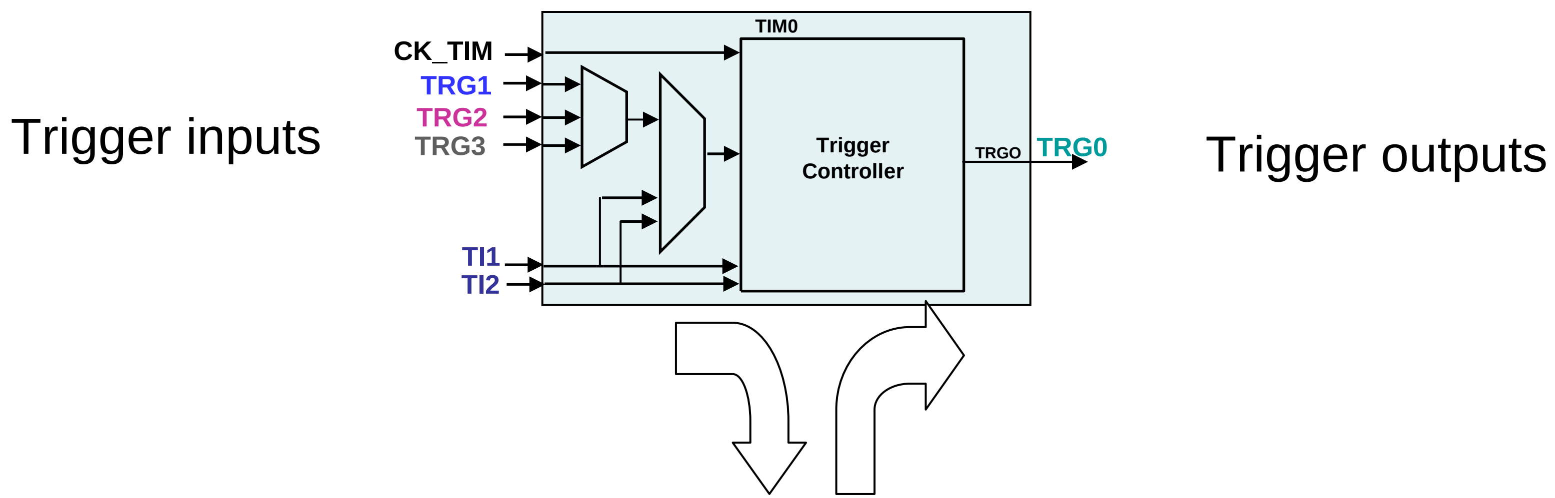


Plan

- PWM generation
- Speed / position feedback
- Multi timer configuration
- Analog to Digital converter
- Current sensing and ADC synchronization
- Field Oriented Control
- Motor Control Tools

Timer Link system

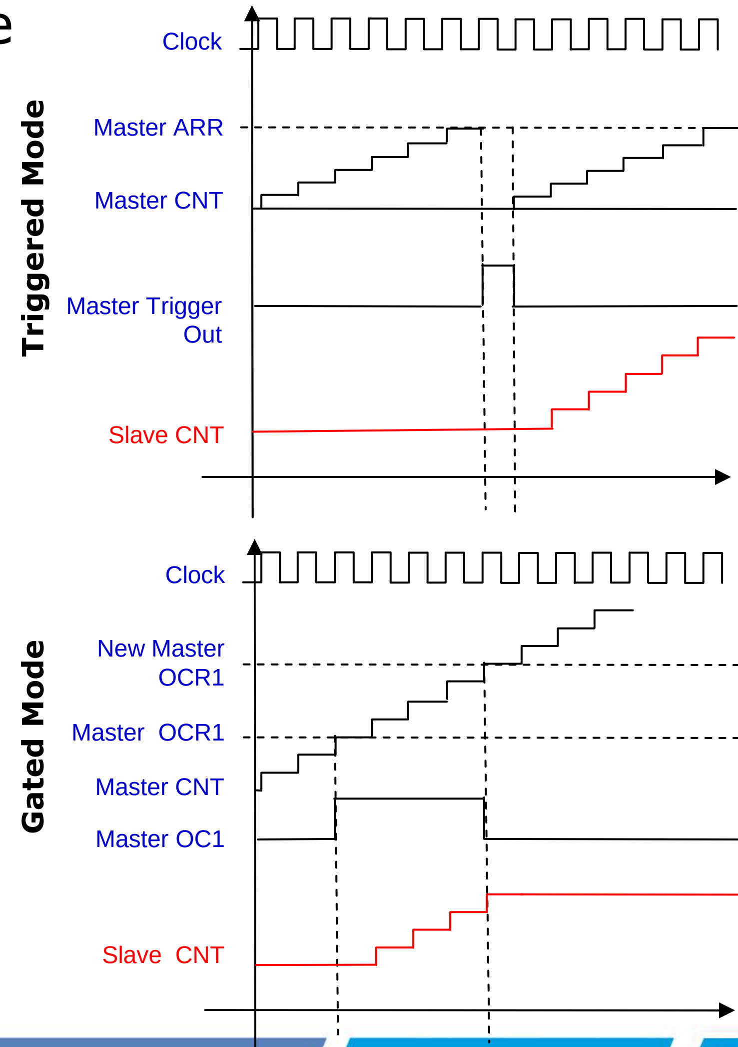
- The three general purpose and the advanced timers are linked together and can be synchronized or chained, thanks to a Trigger output and several selectable trigger inputs.
- For TIM2:0, the input pins(TI1 and TI2) can also be used as triggers



Timer control signals: clock, reset, update, enable,…

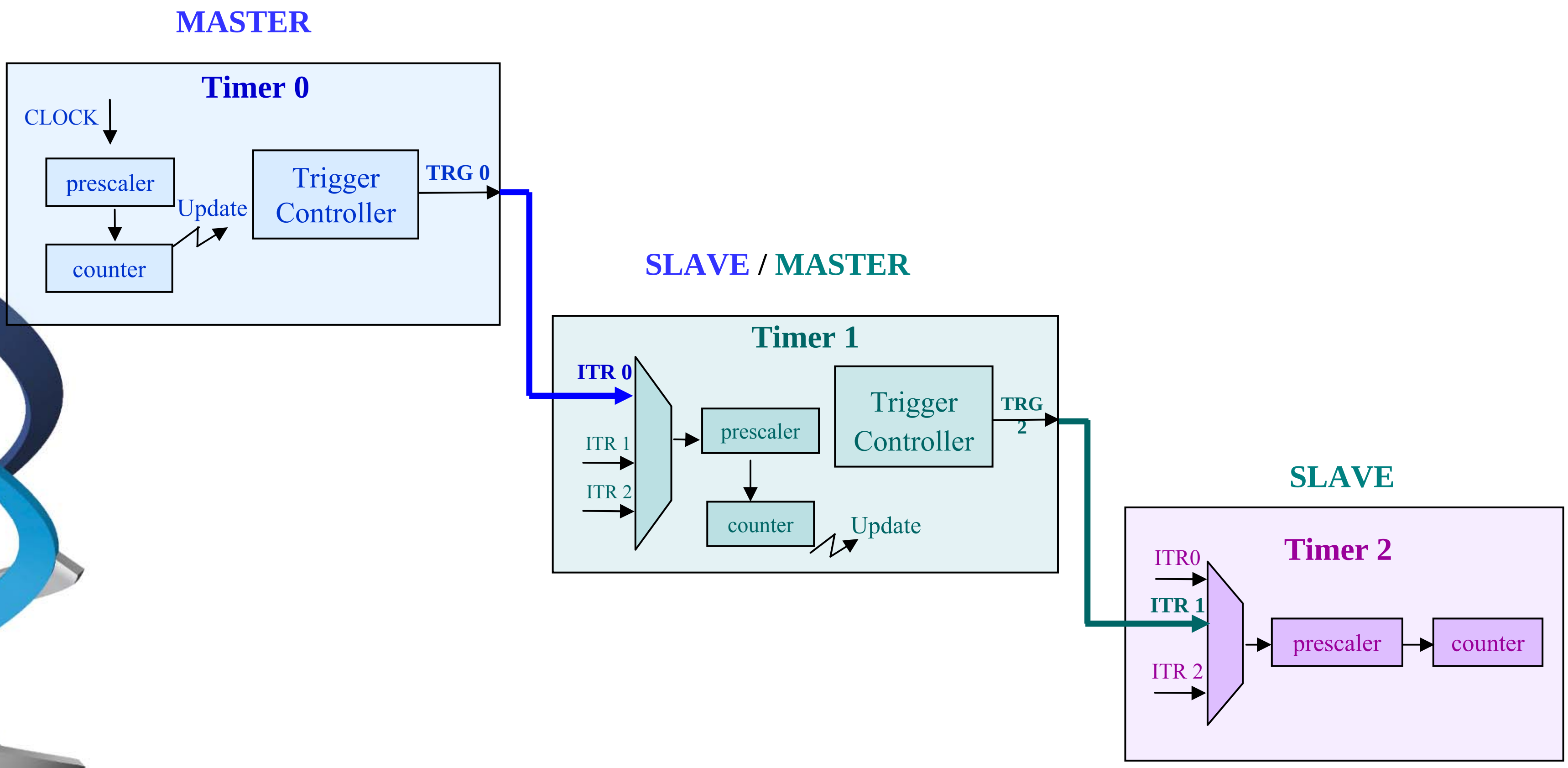
Synchronization Mode Configuration

- When in master mode, the trigger output can be:
  - Counter reset
  - Counter enable
  - Update event
  - Output Compare signal
- When configured as slave, the timer can work in the following modes:
  - Triggered
  - Gated
  - Reset
  - External clock

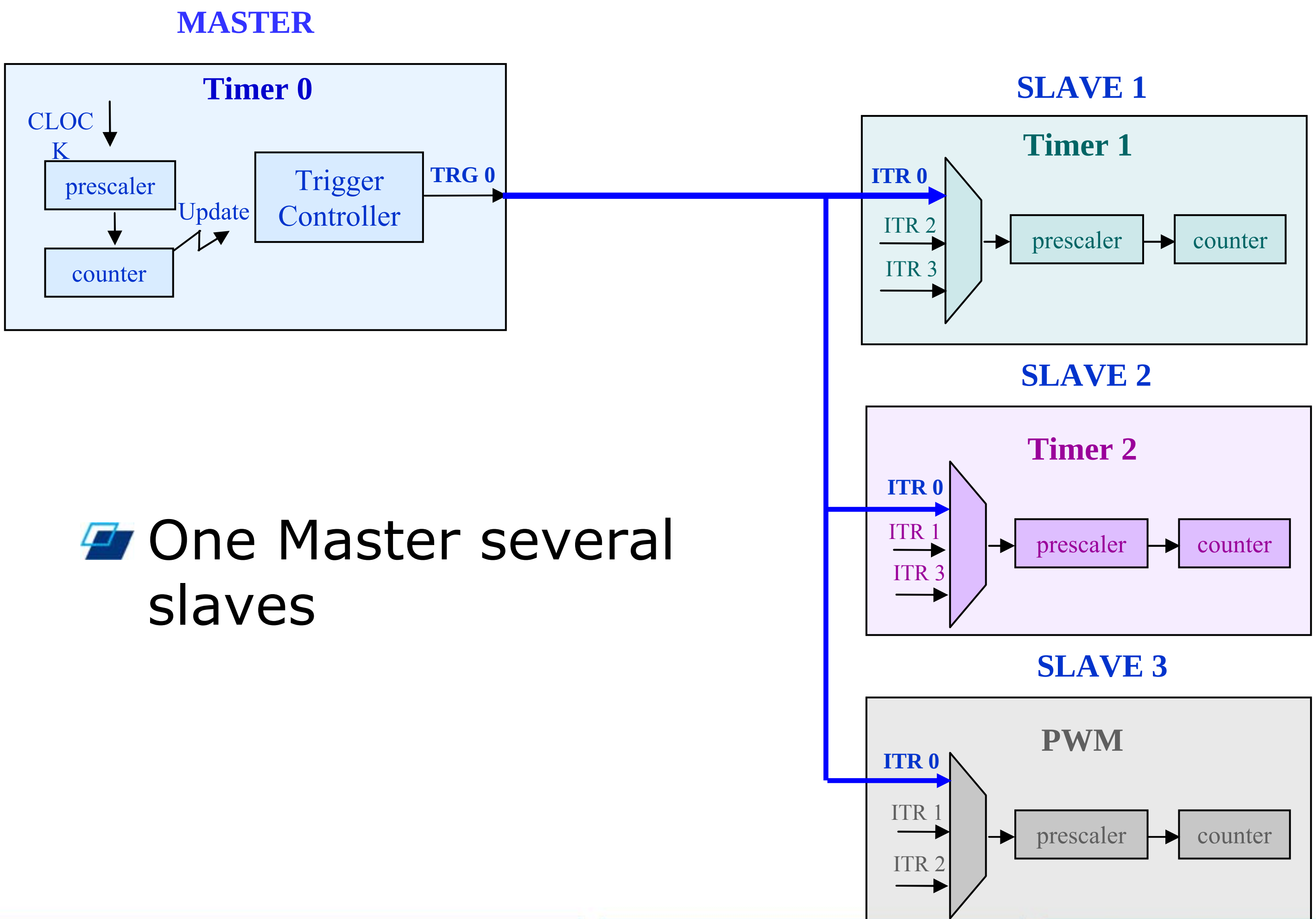


Example 1/3: chained timers

- Cascade mode (for instance, chained time bases)



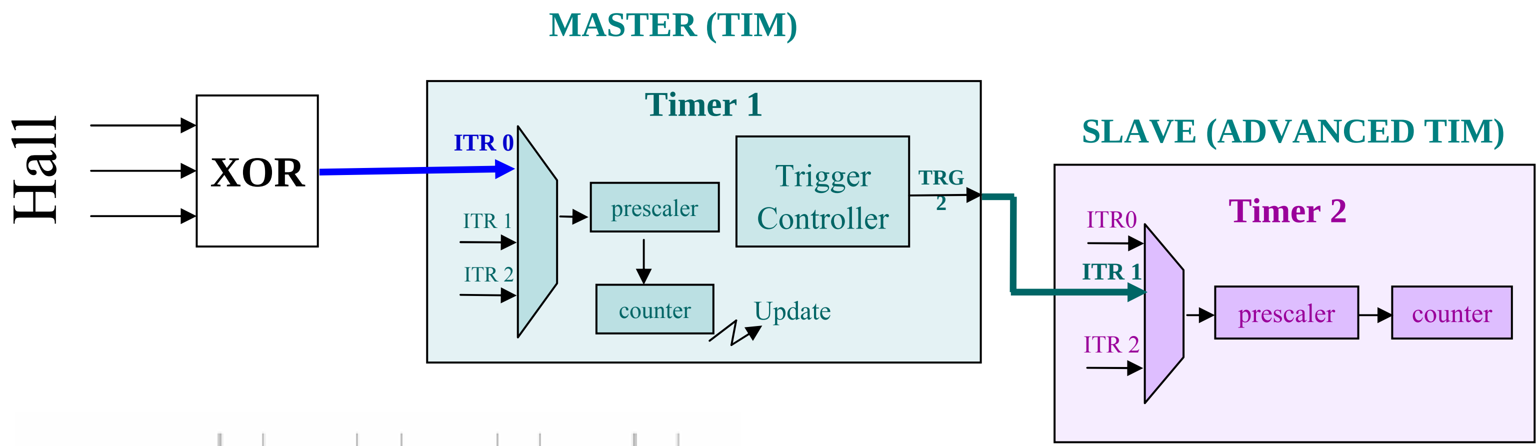
Examples 2/3: synchronized start

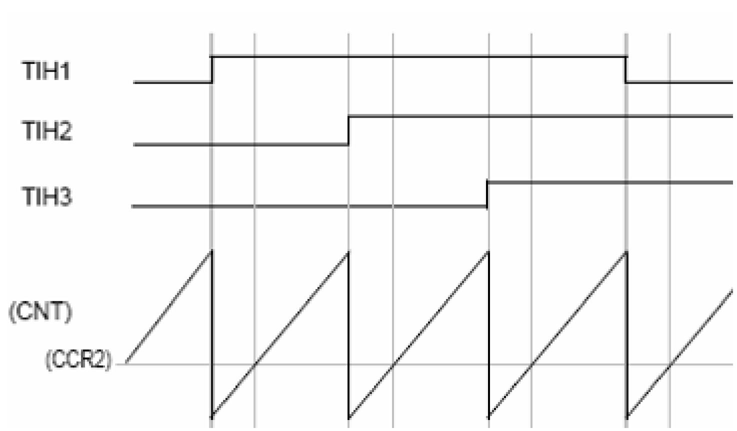


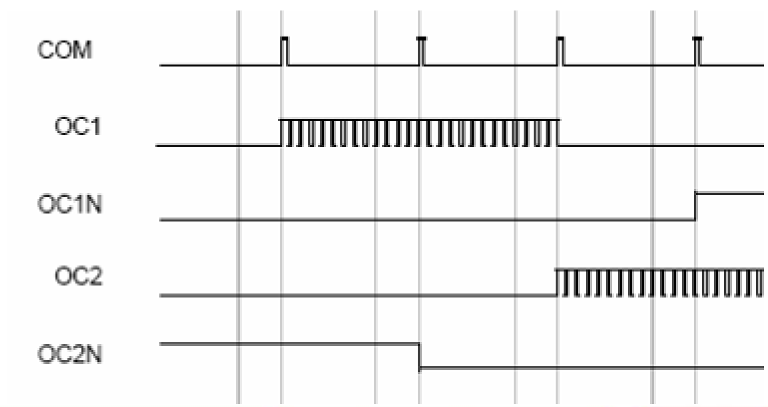
- One Master several slaves

Examples 3/3: block commutation

- A TIM timer handles Hall feedback and triggers an advanced timer for step commutation







Plan

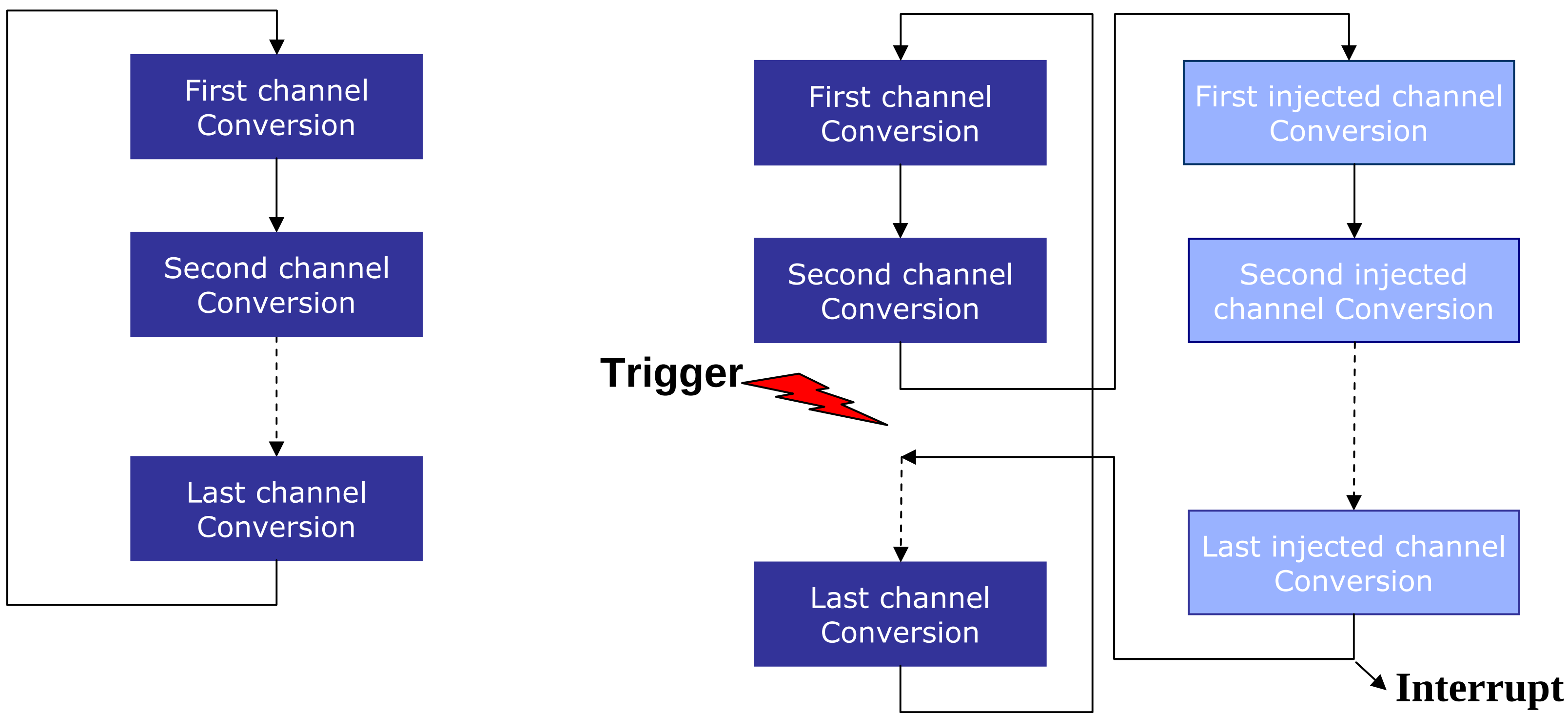
- PWM generation
- Speed / position feedback
- Multi timer configuration
- Analog to Digital converter
- Current sensing and ADC synchronization
- Field Oriented Control
- Motor Control Tools

ADC Features (1/3)

- ADC conversion rate 1 MHz and 12-bit resolution
  - 107ns min sampling time
- ADC input range: 0 ≤ VIN ≤ VREF+ (VREF+ only on LQFP100 package)
- Up to 18 multiplexed channels:
  - 16 external channels
  - 2 internal channels: Temperature sensor and voltage reference
- Interrupt generation
  - End of Conversion, End of Injected conversion, Analog watchdog
- DMA capability
  - On ADC1, but possibility to transfer also ADC2 result if sync'd
- Channels conversion groups:
  - Up to 16 channels regular group
  - Up to 4 channels injected group

ADC Injected Conversion

- Regular Scan mode
- Scan mode with injected conversion



ADC Features (2/3)

- Analog Watchdog (1 channel or all regular or all injected)

- Sequencer-based scan mode
  - Any channel, any order (e.g. Ch3, Ch2, Ch11, Ch11, Ch3)
  - up to 16 regular conversion (transferred by DMA)
  - up to 4 injected conversion stored in internal registers

- Multiple trigger sources for both regular and injected conversion
  - Each group can be started by 6 events from the 4 timers (compare, over/underflow)
  - External event and software trig also available

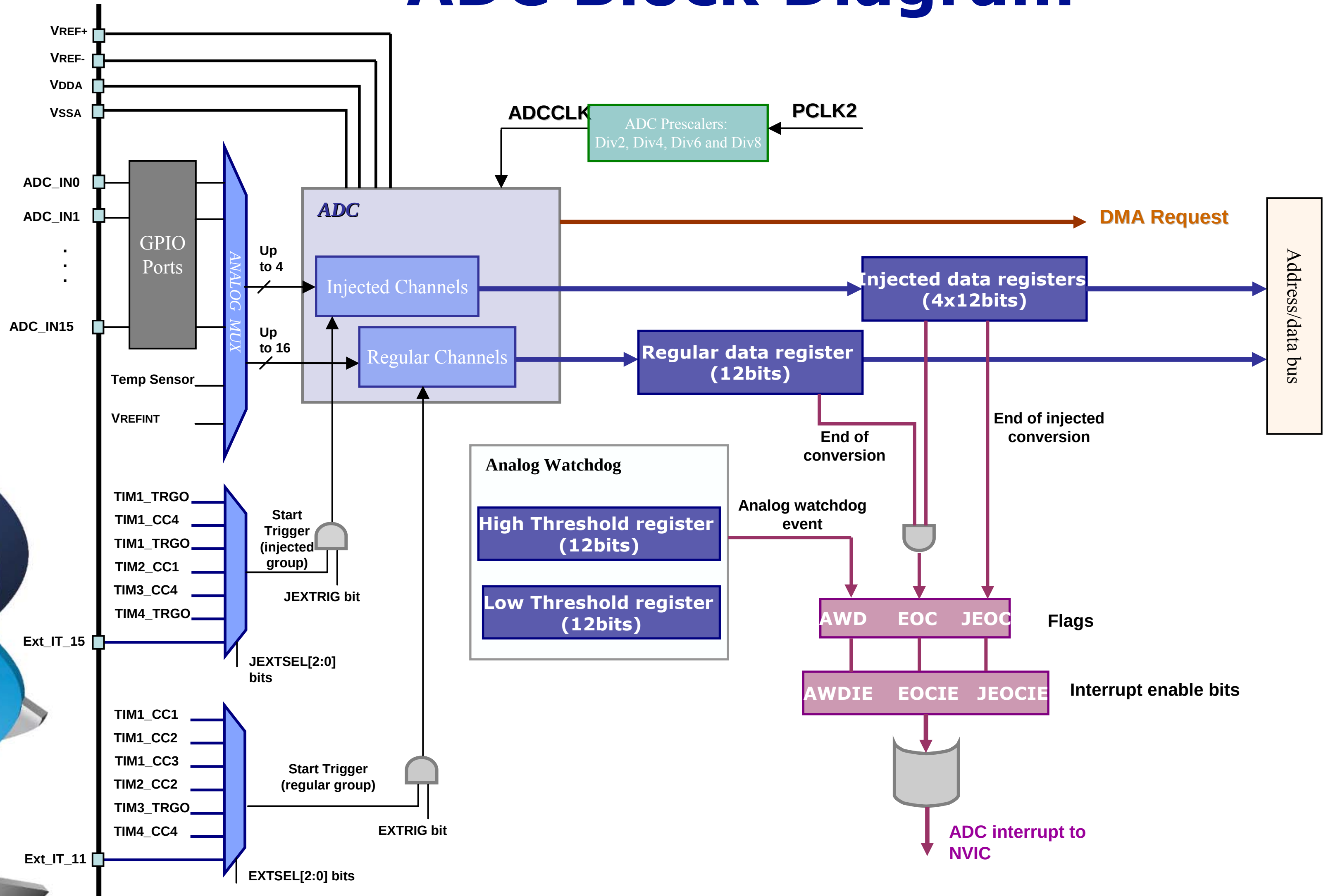
ADC Features (3/3)

- Left or right Data alignment with inbuilt data coherency

- 4 offset compensation registers
  - Compensates external conditioning components offsets (such as Operational Amplifiers). Provides signed results if needed.

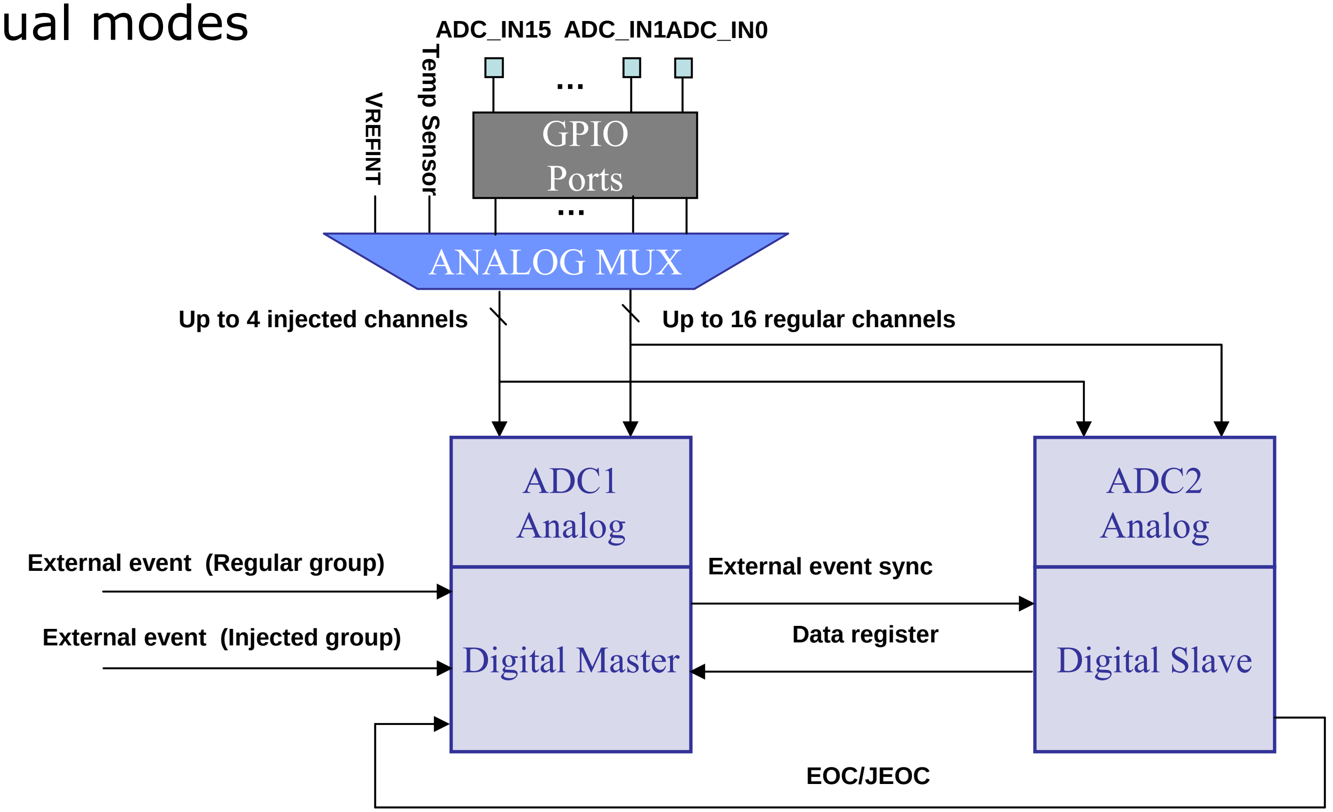
- Channel-by-channel programmable sampling time to be able to convert signals with various impedances
  - From 1µs (for Rin < 1.2KΩ) to 18µs (Rin < 350KΩ), 8 values
  - External voltage follower not mandatory when converting at 1MSps

ADC Block Diagram



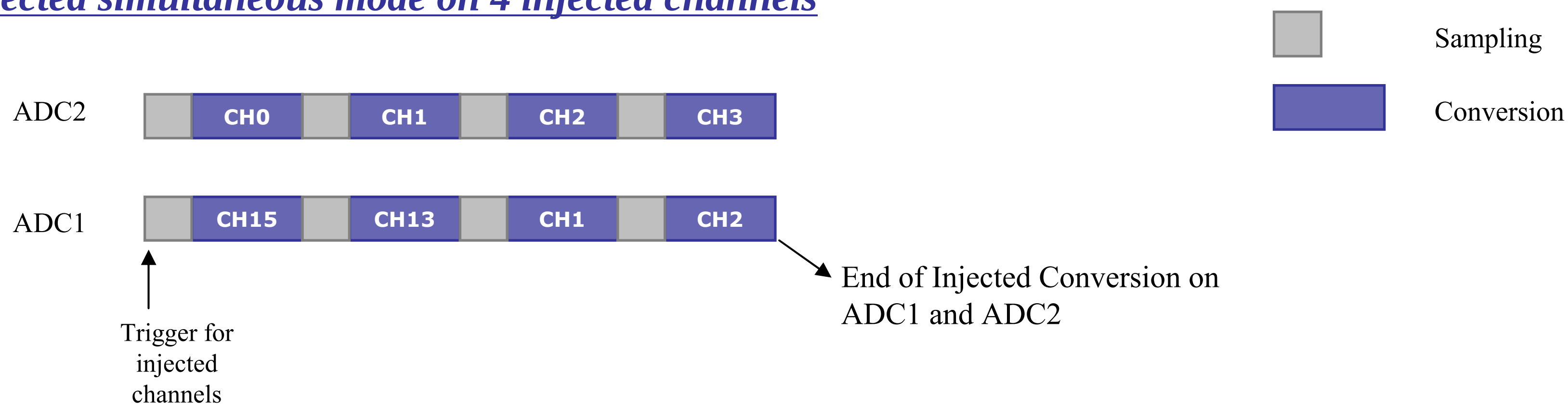
ADC dual modes (1/2)

- Available in devices with two ADCs (Performance line)
  - ADC1 and ADC 2 can work independently or coupled (master/slave)
- 8 ADC dual modes

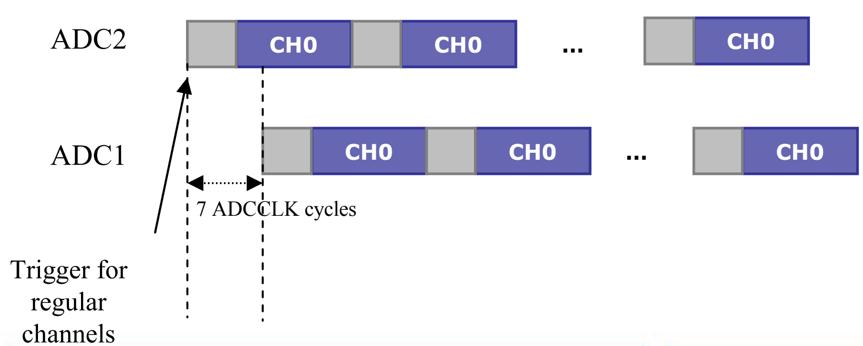


ADC dual modes example (2/2)

Injected simultaneous mode on 4 injected channels



Fast Interleaved mode on 1 regular channel in continuous conversion mode

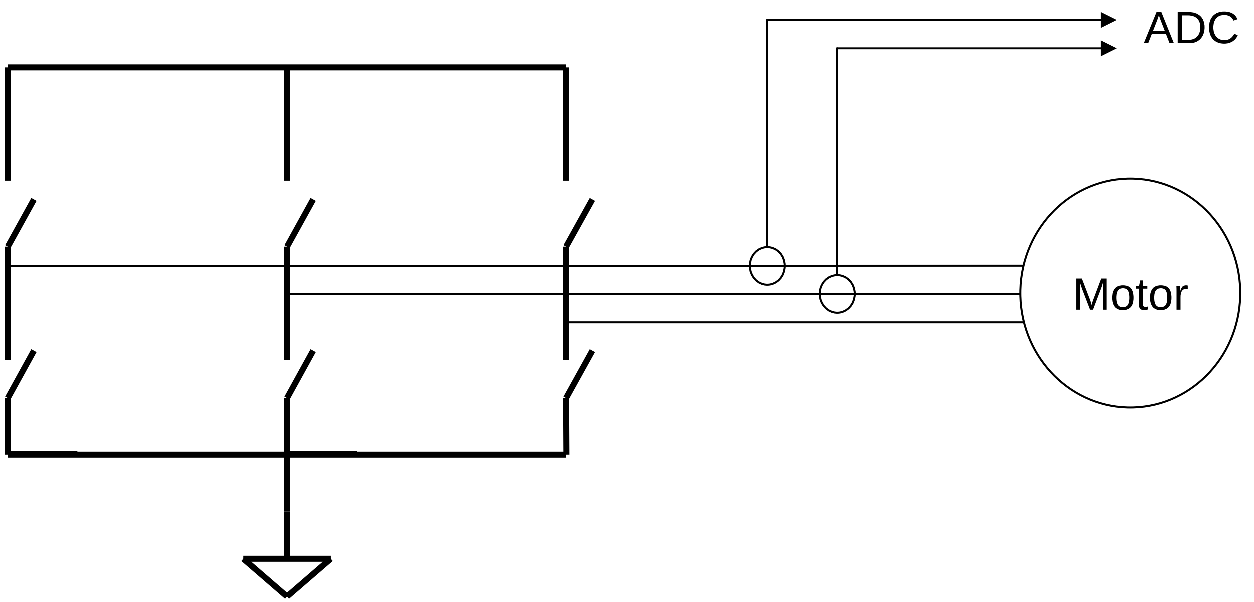


Up to 2 MSps continuous data throughput (DMA-based)

Plan

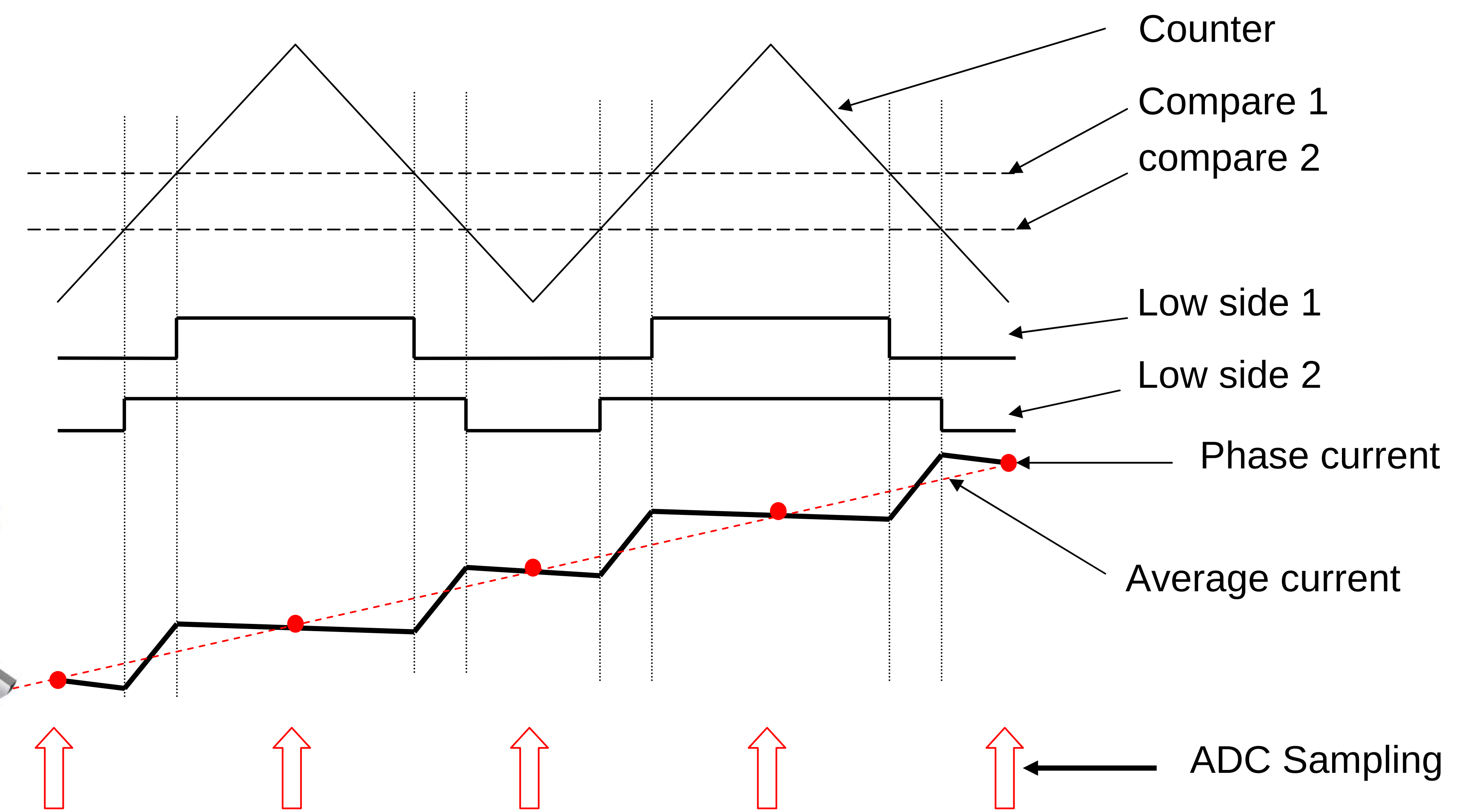
- PWM generation
- Speed / position feedback
- Multi timer configuration
- Analog to Digital converter
- Current sensing and ADC synchronization
- Field Oriented Control
- Motor Control Tools

Isolated Current transducers 1/2

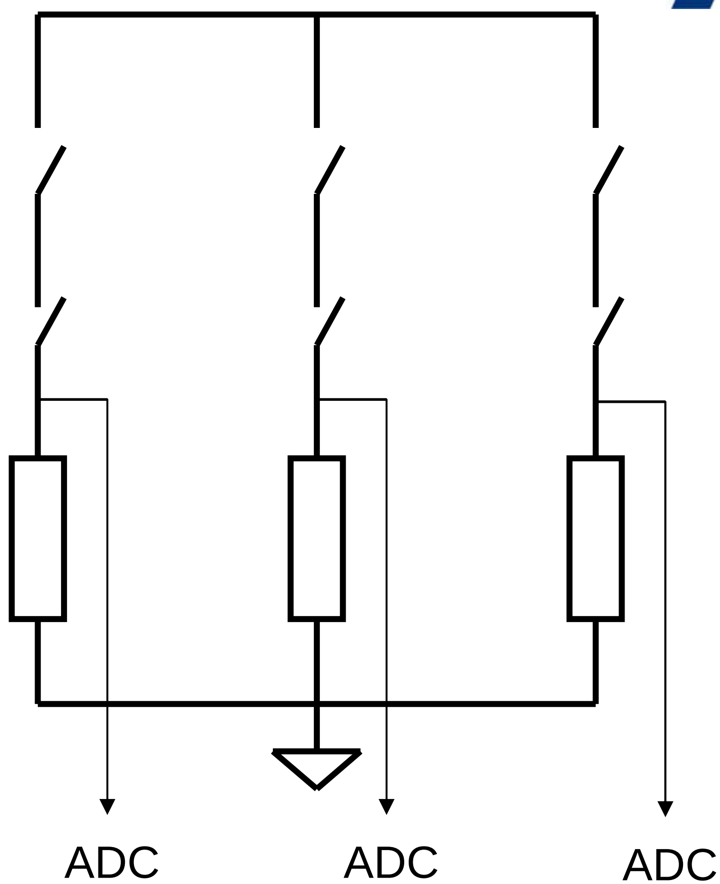


- Isolated / floating sensors
  - PWM synchronization is possible when all low sides and / or all high sides are ON ("crest" or "valley")
  - Two sensors are enough (currents are always readable)
- The current can be read twice per PWM period

Isolated Current transducers 2/2

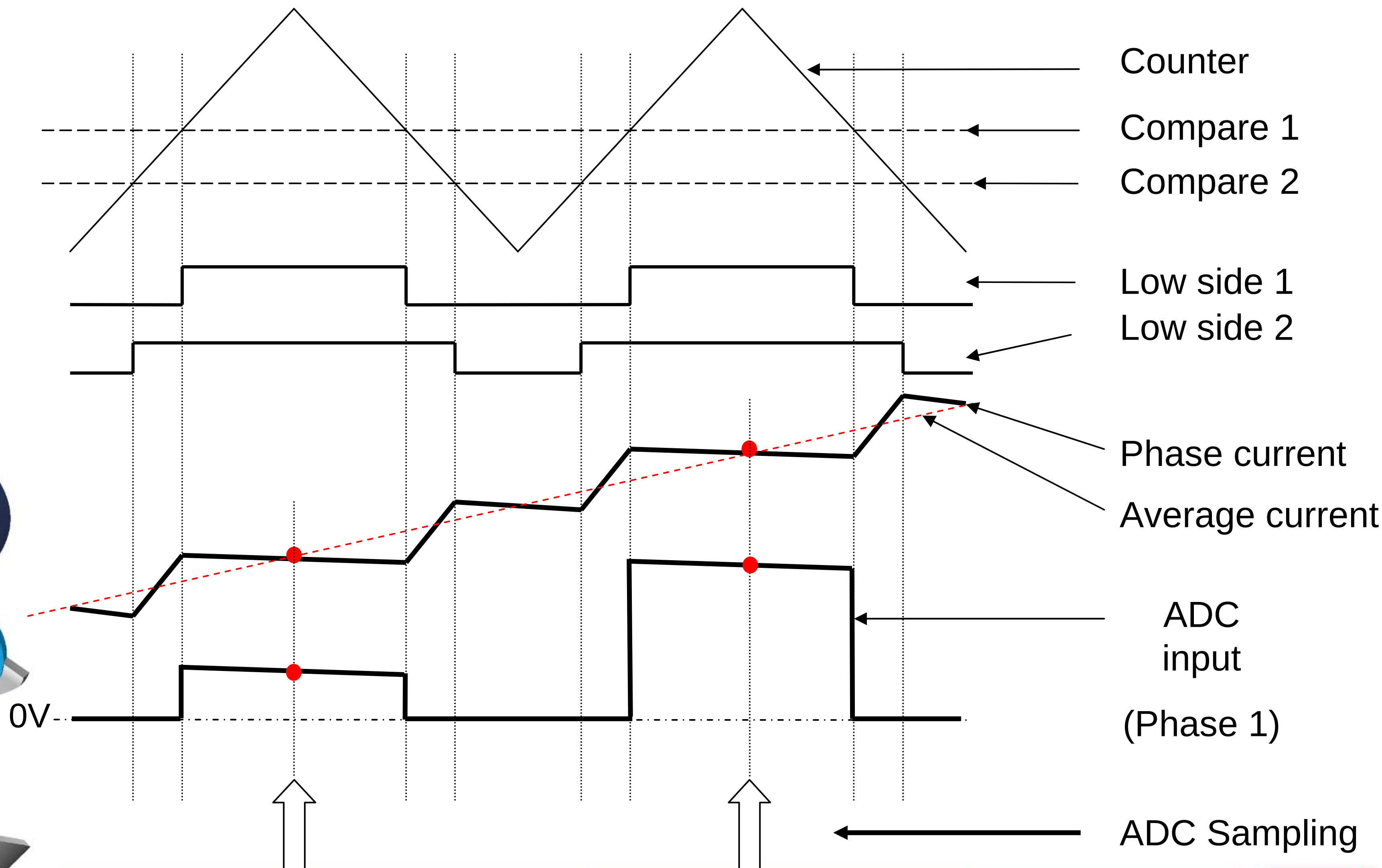


Shunt based current sensing 1/2



- Using 3 shunts
  - PWM synchronization mandatory
  - Need to sample when all low side switches are ON, in the middle of PWM period ("crest")
  - Current cannot be read during 33% of sine period, but two phases at least are readable
    - The third one can be reconstructed (Ia = -Ib-Ic)

Shunt based current sensing 2/2

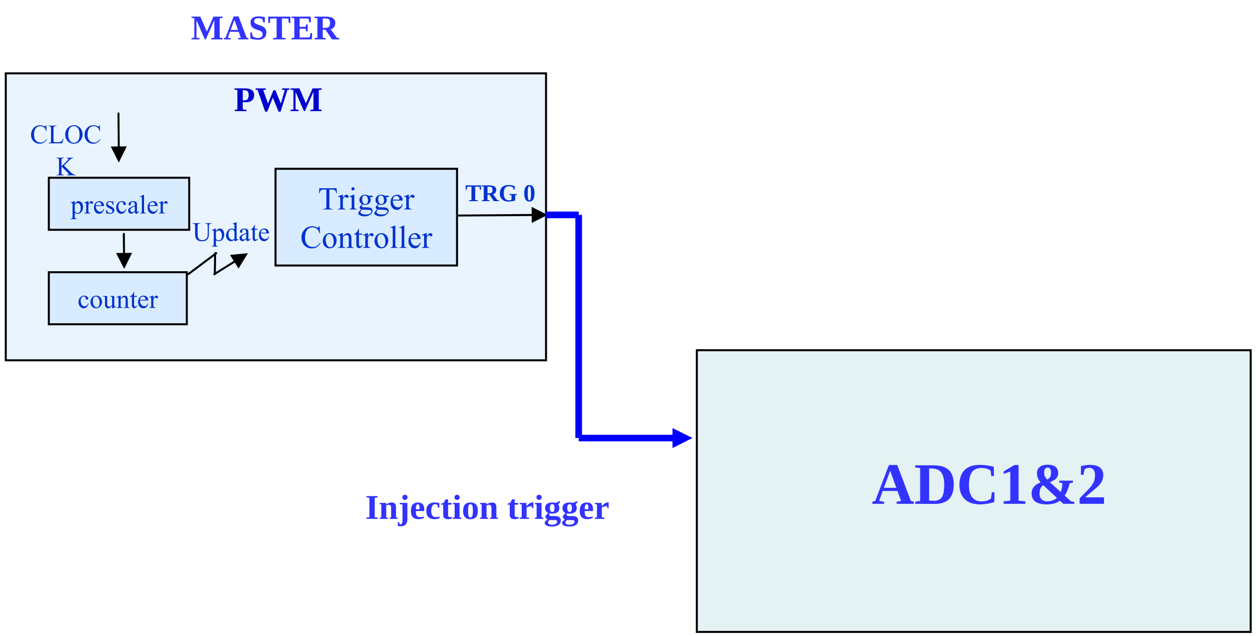


ADC synchronization in STM32

- Done thanks to a synchronization unit embedded in the PWM timer.
- 2 options available:
  - Direct synchronization on PWM crest, valley, or both.
  - Delayed synchronization with the 4^{th} Compare channel
- The ADC results can be then processed with an end of conversion interrupt or transferred by DMA.

Direct synchronization

- The PWM timer “update” signal triggers Simultaneous injected conversions on both ADCs
  - No error due to sequential phase sampling



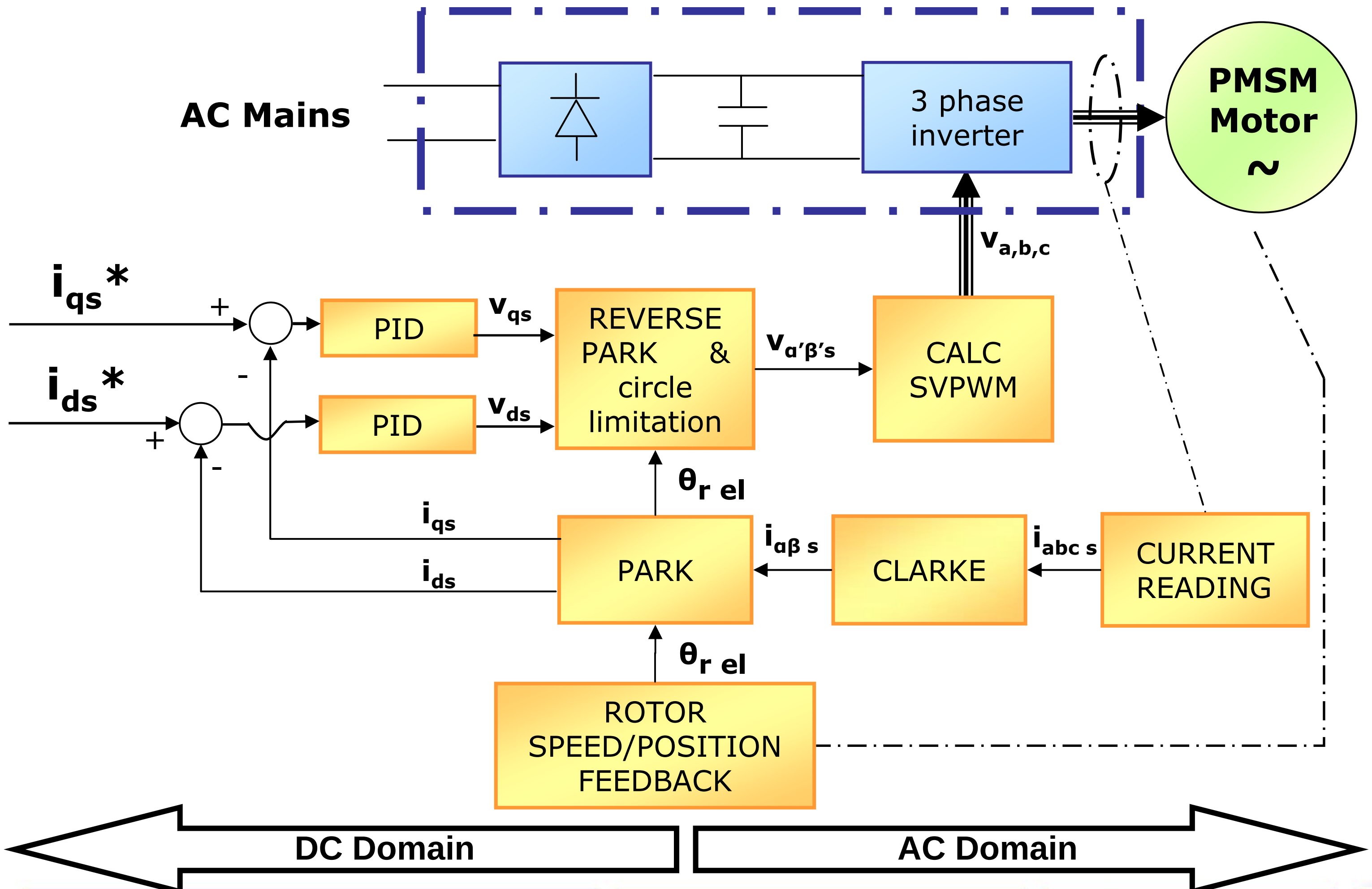
Plan

- PWM generation
- Speed / position feedback
- Multi timer configuration
- Analog to Digital converter
- Current sensing and ADC synchronization
- Field Oriented Control
- Motor Control Tools

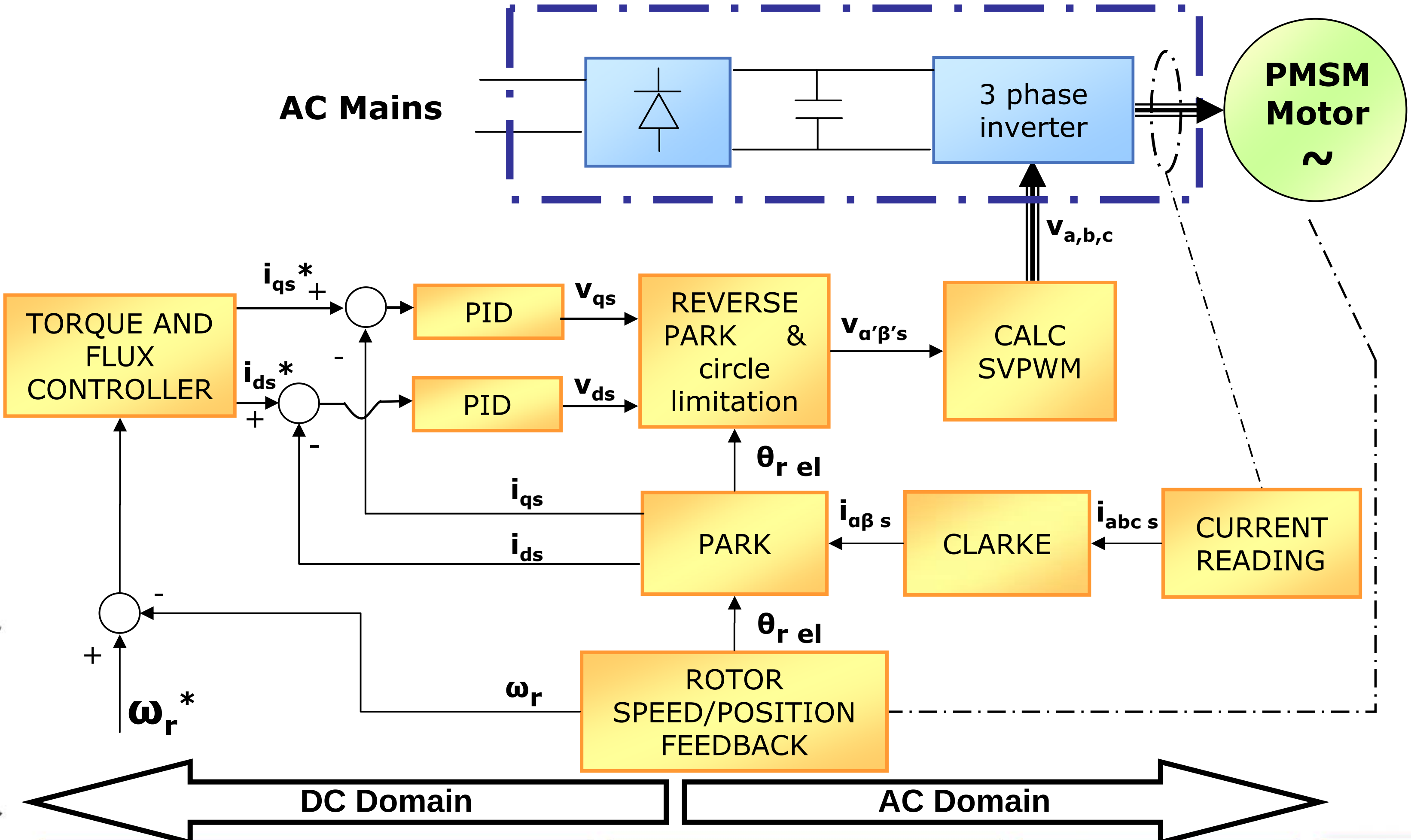
Field oriented control (FOC): a quick overview

- Mathematical technique utilized for achieving decoupled control of the flux and torque in a three-phase machine (ACIM or PMSM)
- Stator current is decomposed into:
  - the magnetizing current Ids, producing a magnetic field algebraically added to the one of the rotor
  - The quadrature current Iqs which controls torque just like the armature current does in the DC motor
- Benefits (vs scalar control)
  - Precise and responsive speed control when the load changes
  - Optimized efficiency even during transient operation
  - Allows position control (through instantaneous torque control)

FOC in torque control (Open loop)



FOC in speed control (Closed loop)

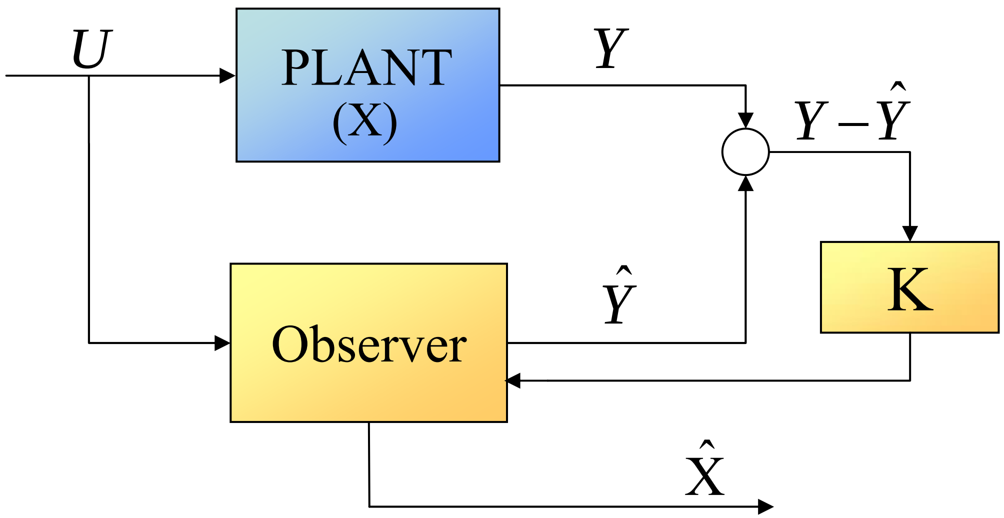


FOC computational requirements

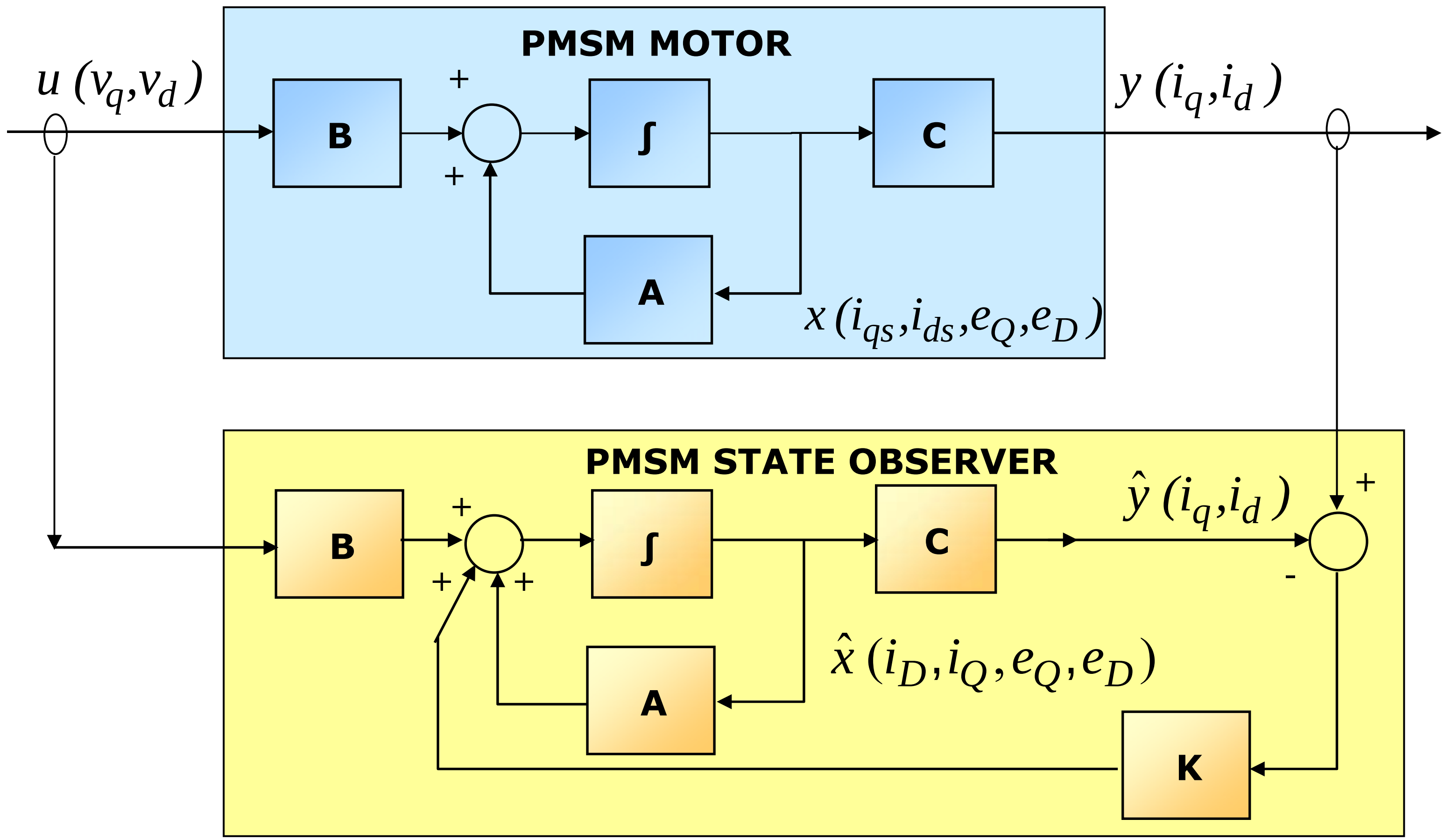
- The complete vector control algorithm must be continuously recomputed, at a rate of between 1 and 10kHz (1ms down to 100µs loop time, depending on the final application)
- 16-bit is the minimum required accuracy for the main control variables, with a need for 32-bit calculations
- The algorithm intensively requires math computations (trigonometric functions, PID regulator, real-time flux and torque estimation based on motor parameters)

A sensorless control method: the B-emf observer

- In control theory a system is **observable**, if it is possible to fully reconstruct the system state from its output measurements
- The **state observer** is a system that provides an estimation of the internal state of the observed system given its input and output measurements.



Luenberger Observer for PMSM FOC



Getting the rotor angle

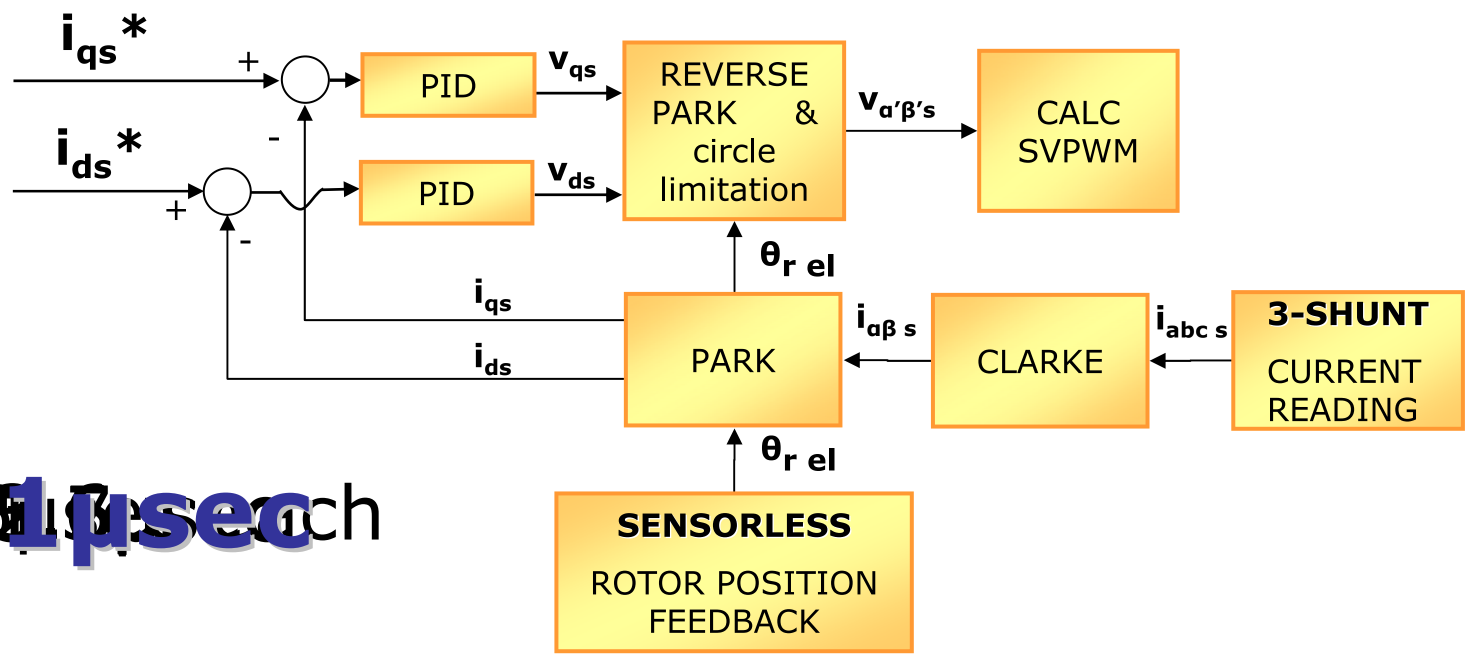
- Once $\hat{e}_\alpha$ and $\hat{e}_\beta$ have been determined, rotor angle position could be simply computed by formula:

$$\theta_r = arctg\frac{\hat{e}_\alpha}{\hat{e}_\beta}$$

- And thus the speed could be computed as derivative of rotor angle
- Rotor angle can also be estimated with a software PLL solution to avoid arctg function (low accuracy at 90°) and derivative (noise sensitive)

FOC algorithm execution time

- With Cortex-M3 running at 72 MHz from embedded flash, fully code in C (optimized for speed)



21µsec

For reference, Sensored FOC is ~17µs (vs 25µs with ARM7-based STR750, ie ~30% gain)

FOC software library memory footprint

- Thanks to the high density of Thumb2 instruction set, the preliminary overall size of PMSM FOC software library is 26Kb

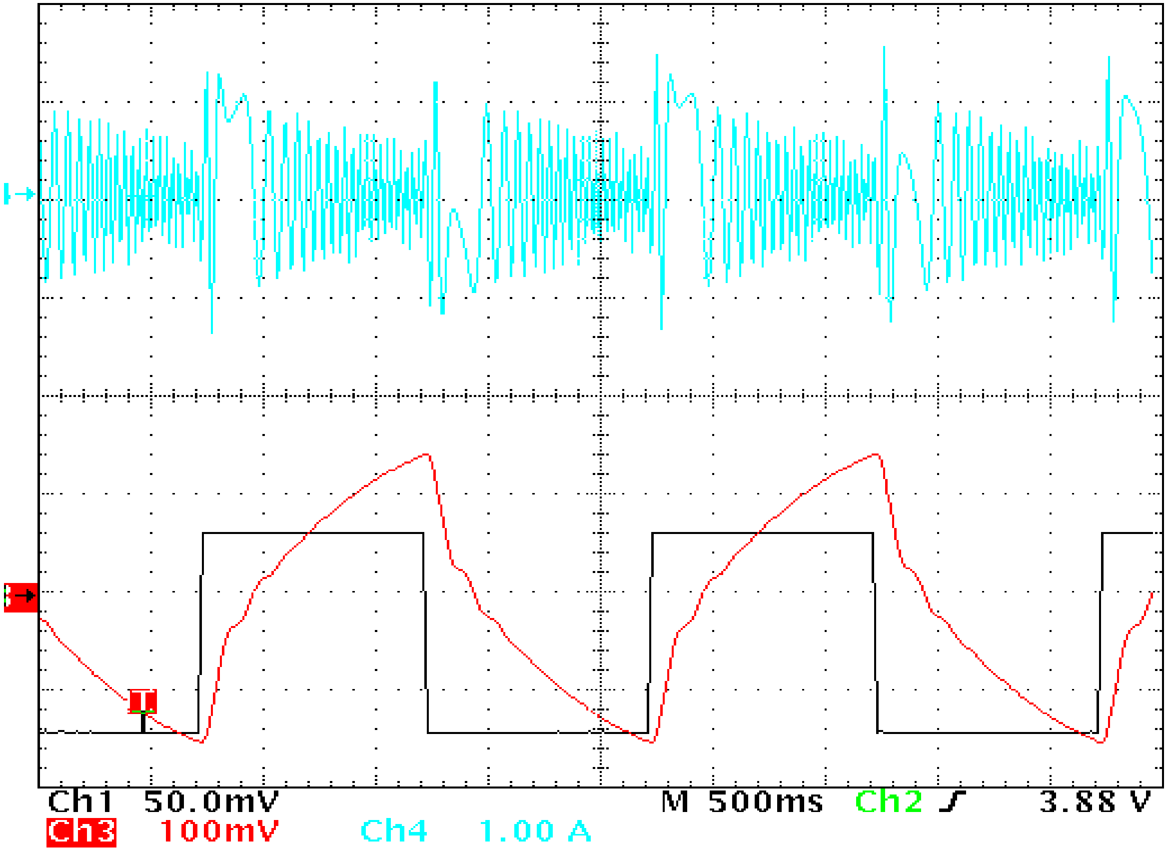
- Excluding only the LCD and Joystick management the overall code size falls to

16Kb

Preliminary, Code optimized for speed

Practical results

- 700W AC induction motor, sensored field oriented control



Plan

- PWM generation
- Speed / position feedback
- Multi timer configuration
- Analog to Digital converter
- Current sensing and ADC synchronization
- Field Oriented Control
- Motor Control Tools

STM32 Software library for PMSM FOC (1/2)

- Supported current sensing methodologies:
  - Isolated Current sensing
  - Three shunt resistors
  - Single shunt resistor (future development)

- Supported rotor position feedback:
  - Encoder
  - Hall sensors:
    - 60° and 120° placement
  - Sensorless

STM32 Software library for PMSM FOC (2/2)

- Developers' support
  - Progressive system development for guiding users during their own development
  - DAC functionality for tracing the most important software variables
  - User interface for real time tuning of PIDs and observer gains (via LCD and joystick)
- MISRA 2004 compliant
- Free of charge and open source
- Demonstration kit available e/o Oct 07

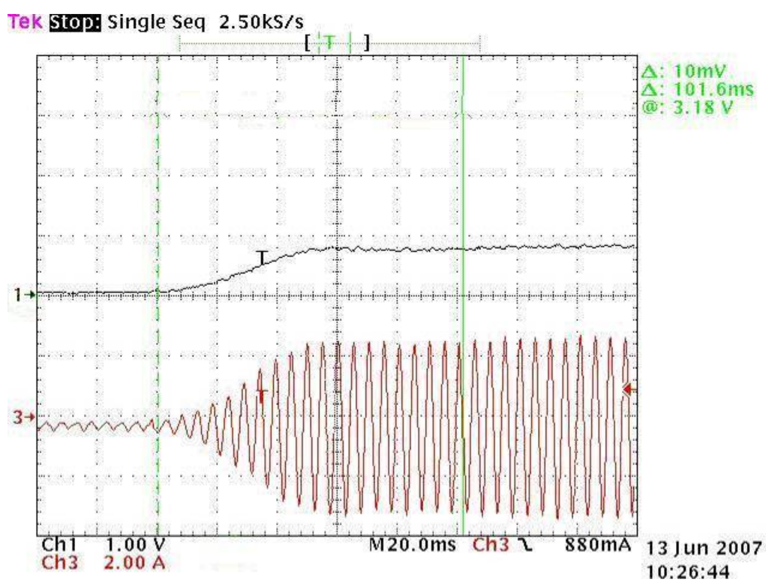
Progressive system development

- Guide user in his development, gradually take him towards sensorless solution
- Allows to avoid the inclusions of the code lines implementing not used functionalities

```
/************** Current sensing by ICS (Isolated current sensors) ************/
//#define ICS_SENSORS
/************** Current sensing by Three Shunt resistors ******************/
#define THREE_SHUNT
/************** Position sensing by Incremental encoder ******************/
//#define ENCODER
/********************** Speed sensing by Hall sensors  *****************/
//#define HALL_SENSORS
/****************************  No speed sensors  *******************/
#define NO_SPEED_SENSORS
//#define VIEW_HALL_FEEDBACK
//#define VIEW_ENCODER_FEEDBACK
/******************** PI + Differential term for Id & Iq regulation **********/
#define Id_Iq_DIFFERENTIAL_TERM_ENABLED
/***************** PI + Differential term for speed regulation **************/
//#define SPEED_DIFFERENTIAL_TERM_ENABLED
/********************** PIDs Parameter regulation software **************/
//#define FLUX_TORQUE_PIDs_TUNING
#define OBSERVER_GAIN_TUNING
/********************** PIDs Parameter regulation software **************/
#define DAC_FUNCTIONALITY
```

DAC functionality

- Implemented using two out of the four TIM3 output compare channels
- Allow the simultaneous monitoring of up to two software variables selectable in real-time using a dedicated menu
- Can be disabled simply commenting one code line



STM32 Motor Control
PMSM FOC ver 0.2

Signal on PB0
Iqref

Signal on PB1
Ia

←→ Move ↑↓ Change

User interface

- Real time tuning of torque, flux and speed PIDs
- Observer gains tuning (in case of sensorless)
- Variation of target speed (speed control) or target torque and flux (torque control)
- Bus voltage and power stage temperature monitoring
- Selection of variables to put on output for DAC functionality implementation

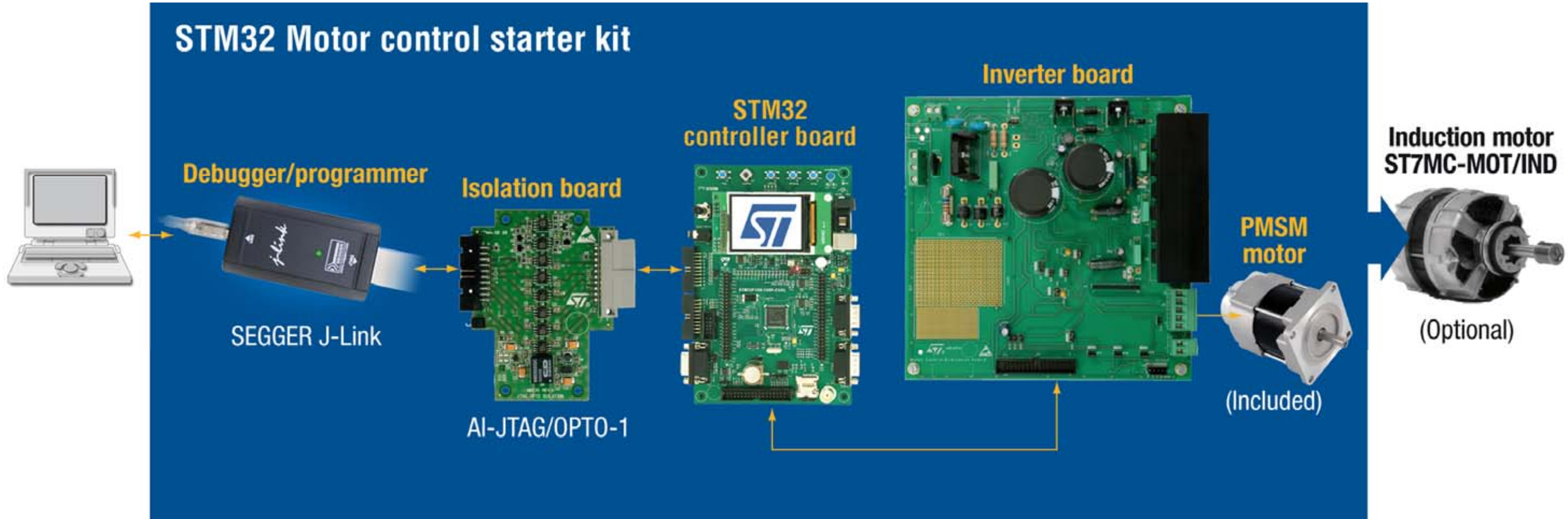
STM32 Motor Control
PMSM FOC ver 0.2

Closed Loop
Speed (rpm)

Ref	Meas
02500	00000

Speed control mode
←→ Move ↑↓ Change

STM32 demonstration kit

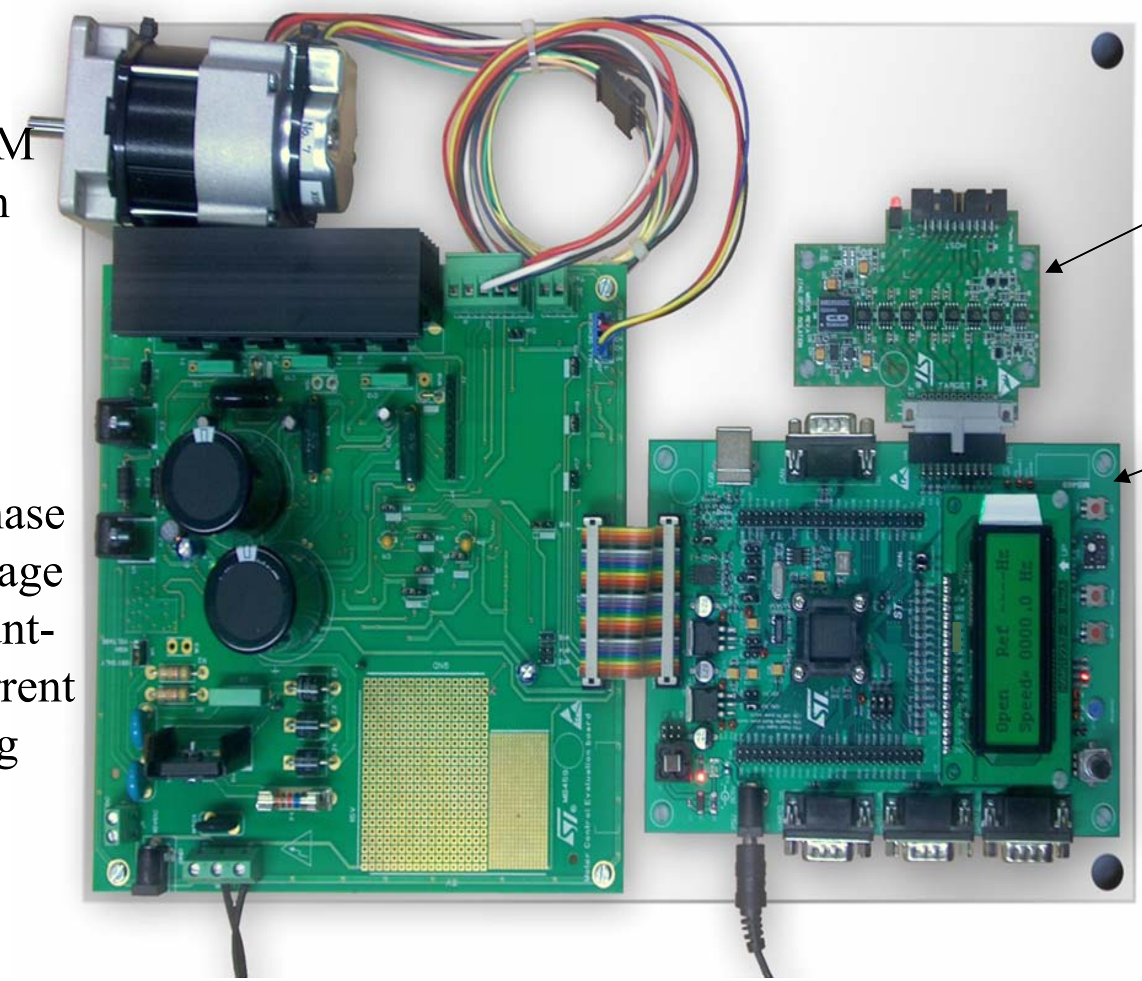


- **Three-phase power stage with shunt-based current reading**
- **Complete source files software libraries for 3-PH Induction and PMSM motors provided**
- **Brushless PM Motor with encoder included**

STM32-MCKIT (alpha version)

Brushless PM Motor with encoder

Three-phase Power stage with shunt-based current reading



Opto-isolated JTAG

Evaluation board (final STM32 version has a color LCD)