

Automotive Control Solution for Brushless DC Motors

TTTech provides solutions for setting up distributed systems with brushless DC motors. Today brushless DC motors are used in a variety of applications. In the future they will be used in cars for by-wire applications such as brake-by-wire and steer-by-wire. A by-wire system in a car substitutes mechanics and hydraulics for electronics with adequate sensors and actuators. This article gives information on the possibilities of setting up a complete system including control of brushless DC motors, connection of various sensors, and data transfer via the Time-Triggered Protocol (TTP®).

TTP By-Wire Box – The Electronic Control Unit for Brushless DC Motors

The TTP By-Wire Box is an actuator control unit that offers full hardware and software support for direct control of a brushless DC motor. Therefore, it is ideally suited for implementing by-wire functionality, such as brake-by-wire, steer-by-wire, or clutch-by-wire. Additionally, TTP By-Wire Box is an advanced automotive development system for a wide range of standard I/O interfaces that are driven by the automotive-qualified Freescale MPC555 PowerPC® microprocessor. The TTP communication controller AS8202NF and the TTPTools software development suite provide all the facilities needed to integrate several TTP By-Wire Boxes into a hard real-time architecture.

The TTP By-Wire Box is designed for use in a rough environment as found in cars and works with 12 to 42 Volt power supplies. The control unit has a watertight high-quality aluminum housing with cooling fins and connectors for the wire harness in the automobile.

The Use of Brushless DC Motors

While brush type motors are inexpensive, reliable, accurate machines that still play a role in today's industrial workplace, the commutation brush, as a wear item, needs replacement.

Brushless DC motors do not have the limitations of a physical commutator, the commutation is performed by control electronics instead. Sensors for measuring the rotor's position are required to determine the right moment for commutation. Depending on the application area there are two types of the TTP By-Wire Box, supporting either 6-step or sinusoidal motor control. They differ in their complexity of the motor control and therefore in the required computing power and sensor precision. In both types the effective value of the voltage is adjusted by the duty cycle of the signals in pulse width modulation (PWM). The power output is designed for a maximum of up to 1kW.



6-Step Commutation – Position Measurement with Hall Sensors

For 6-step commutation the TTP By-Wire Box is equipped with inputs for three Hall effect sensors to measure the rotor's position. The three Hall-effect sensors are typically mounted at an angle of 120 degrees giving a position resolution of 60 degrees (see Figure 1).

A brushless DC motor consists of three phases, wired in star configuration. For 6-step commutation the current is forced into one phase by applying a PWM voltage, and removed from another by holding it at GND with the third phase left open-circuit (see Figure 2).

After the motor rotated 60 degrees, the phases are switched (e.g., the current is then forced into the second phase and removed from the third, while the second phase is disconnected).

Thus, the three phases of the motor are connected differently six times in a commutation cycle for each pole pair (see Table 1).

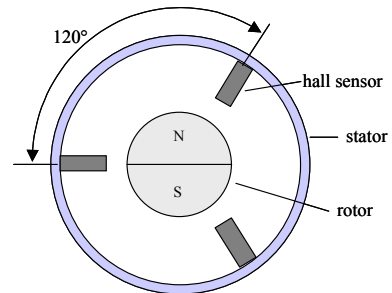


Figure 1: Mounting of hall sensors

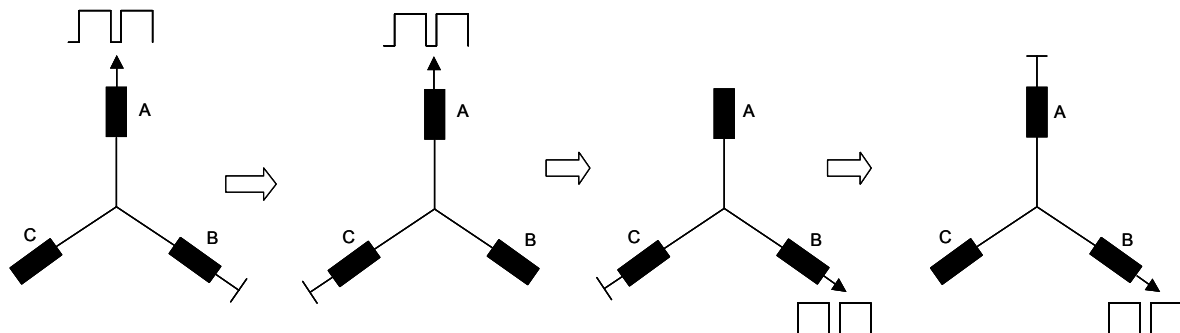


Figure 2: 6-step commutation

Hall 1	1	1	1	0	0	0
Hall 2	0	0	1	1	1	0
Hall 3	1	0	0	0	1	1
Phase A	PWM	PWM	Hi-Z	GND	GND	Hi-Z
Phase B	GND	Hi-Z	PWM	PWM	Hi-Z	GND
Phase C	Hi-Z	GND	GND	Hi-Z	PWM	PWM

Table 1: Controlling the motor with 6-step commutation
(PWM – Pulse Width Modulation, Hi-Z – High Impedance, GND – Ground)

A disadvantage of the 6-step communication is the resulting torque ripple caused by the low position resolution achieved with the three hall-effect sensors: The desired lead angle between electromagnetic stator field and the permanent magnet rotor field is 90 degrees. In this case the supplied current is completely converted into shaft torque. With a position resolution of 60 degrees the effective lead angle between the magnetic fields will vary between 60 degrees and 120 degrees, reducing the available torque to

only 87 per cent. This results in a torque ripple as depicted in Figure 3, which causes vibration, noise, and reduced performance.

To fully optimize the conversion of current into shaft torque, the amplifier needs to vary the applied current continuously based on a precise measurement of the rotor position. This is achieved with sinusoidal motor control as described in the next section.

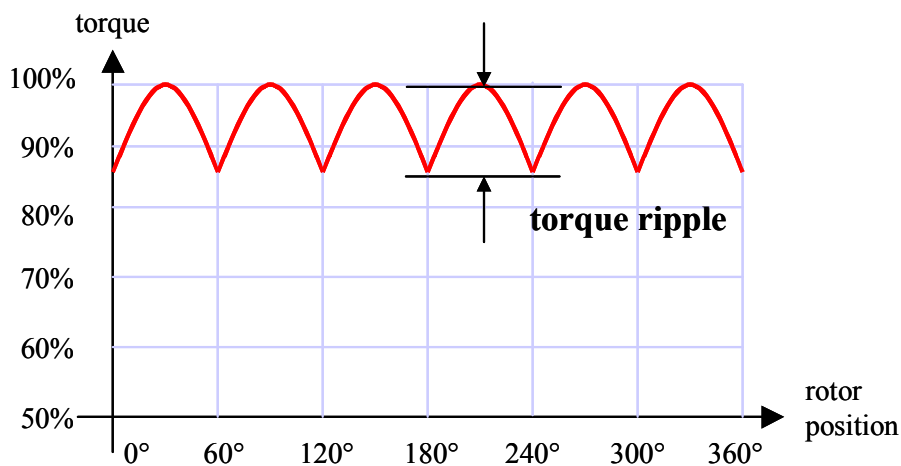


Figure 3: Torque ripple of 6-step commutation

In the TTP By-Wire Box the 6-step commutation and current control of the brushless DC-motor is done by a Complex Programmable Logic Device (CPLD). The application software is loaded into the Freescale MPC555 PowerPC (see block diagram in Figure 4).

The CPLD gets the following parameters from the application software at runtime:

- motor on/off
- two current set-points (min- and max-thresholds) for current control
- motor direction (forward / backward)
- motor brake

Furthermore, for safety reasons, the application is required to toggle a dedicated “watchdog” pin periodically at runtime. If, e.g. caused by an application software failure, this watchdog pin is not toggled at the required frequency, the CPLD stops the motor.

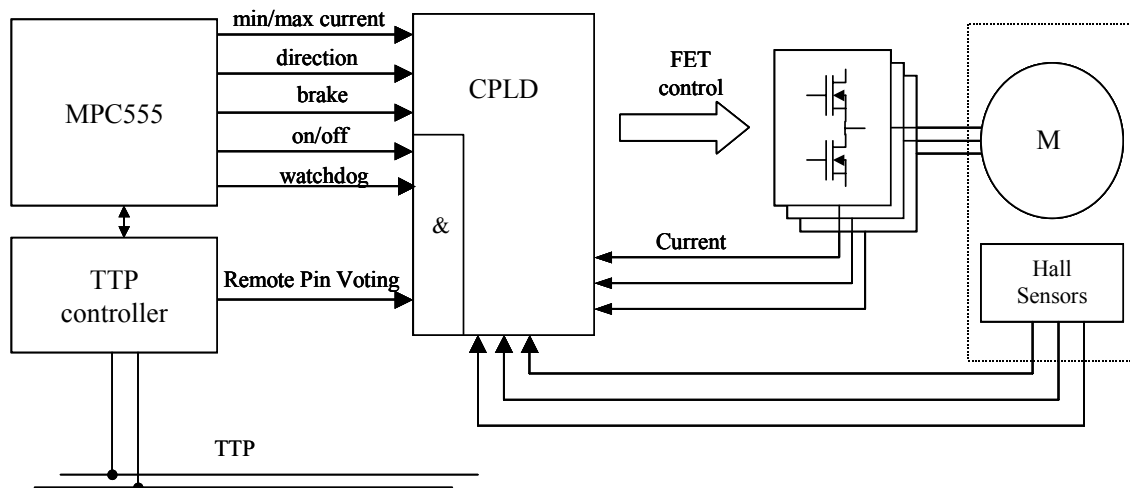


Figure 4: ^{11P}By-Wire-Box block for 6-step commutation

Sinusoidal Control – Position Measurement with Resolver or Encoder

With sinusoidal commutation the current of the three motor phases is continuously varied in sinusoidal waveforms, thus keeping a constant 90 degrees offset between the stator field and the rotor. This technique ensures that the static torque produced by the motor (for a given torque command) does not vary based upon the shaft's position. The motor thus achieves optimum efficiency and minimum torque ripple.

For sinusoidal commutation a high resolution resolver or encoder is required for delivering precise motor position information. Furthermore, more processing power is required for the motor control. This makes the sinusoidal solution more expensive than the 6-step commutation, but in addition to the reduced torque ripple it also allows precise motor position control which is required for many by-wire applications. A typical application for sinusoidal motor control is force feedback control in a steer-by-wire vehicle.

TTTech has developed a dual-CPU ^{TTP}By-Wire Box with two CPUs for sinusoidal motor control. While a DSP controls the motor, the MPC555 host CPU executes the application software and controls TTP communication. Communication between MPC555 and DSP is implemented by a serial interface (SPI ... Serial Peripheral Interface).

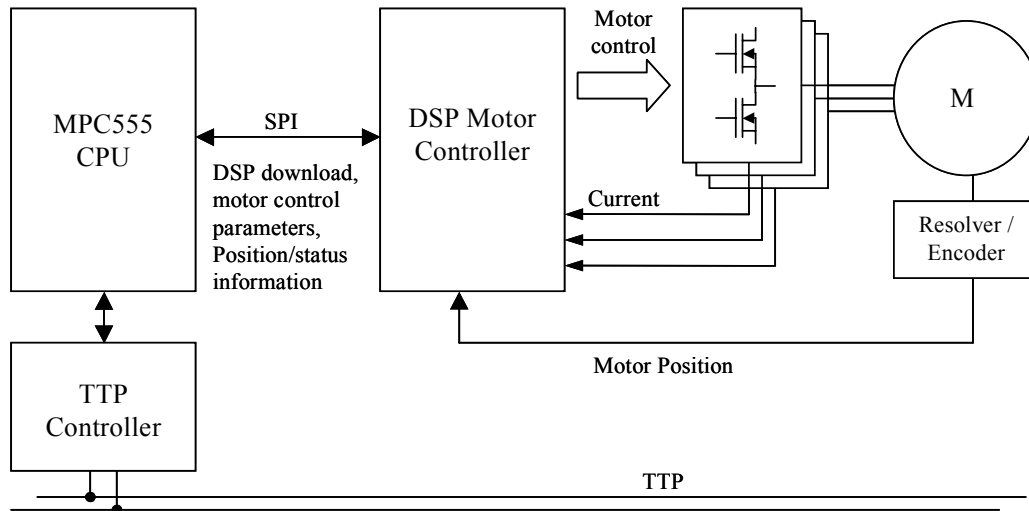


Figure 5: TTP By-Wire Box for sinusoidal motor control

Three different sensor types delivering motor position can be chosen when using the TTP By-Wire Box with DSP:

- Incremental Encoder
- Resolver
- Electric Encoder™

Incremental Encoder

An encoder converts an angular movement into a series of electrical digital impulses (see Figure 6). It produces two squared waves that are out of phase for 90 degrees, which are usually called channel A and channel B. One channel gives information in relation to the rotation speed, while through acquisition of the second channel the sense of rotation is given by the produced state sequence.

With encoders, only incremental shaft movement is tracked directly, and absolute shaft position is determined sensing a unique position once per revolution of the device (Z or zero channel). The result of this is that when power is first applied, an incremental encoder-based system does not know

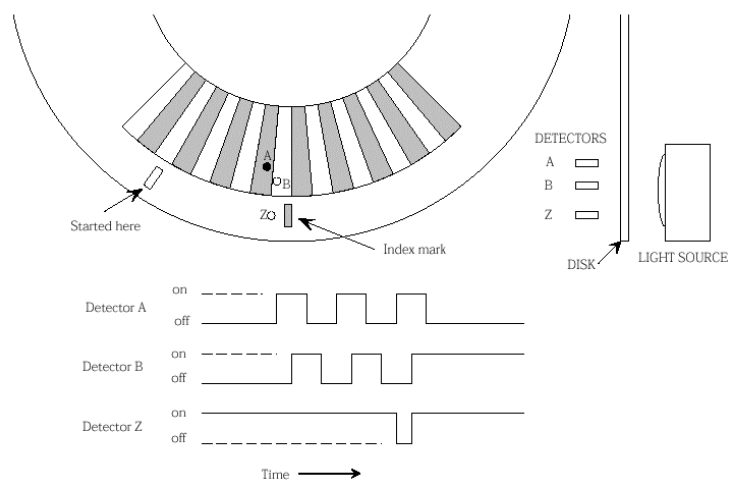


Figure 6: Incremental encoder

absolute shaft position until the encoder is moved far enough to pass the first zero reference position. Resolution in the encoder is based on the number of divisions or line counts on the encoder disk.

Resolver

A resolver is a mechanical device mounted on a rotating shaft of a motor to give the exact position of the shaft in the form of sine and cosine signals.

Resolvers are basically rotating transformers. The rotary transformer is wound with two secondary windings oriented 90 degrees to one another which are stationary and mounted in a housing. These are called stators. The primary winding is located on the shaft of the resolver and is called the rotor.

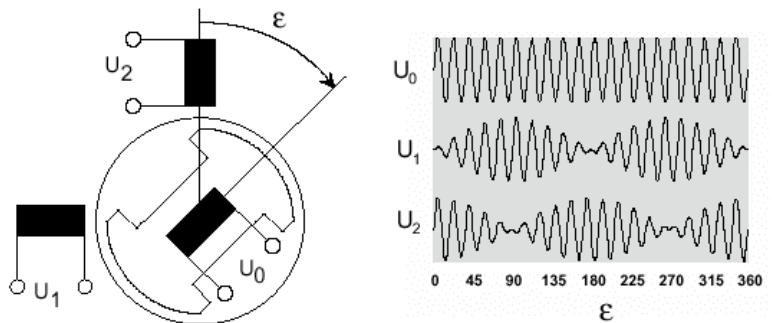


Figure 7: Resolver

An AC voltage, the reference signal, is coupled into the rotor winding and provides primary excitation. The two orthogonal stator coils are wound, so that when the rotor shaft turns, the amplitude of the output signals is modulated with the sine and cosine of the shaft angle ϵ . Hence the shape of the resolver output signals U_1 and U_2 is equal to the sine and the cosine of the mechanical angle.

Electric Encoder

The rotary Electric Encoder provides a continuously varying voltage proportional to the sine and cosine of the measured angle. Like the resolver signals, the Electric Encoder sine and cosine signals also provide absolute position information, but in contrast to the resolver signals there is no AC voltage used for sine-/cosine-amplitude-modulation and therefore the Electric Encoder does not need AC excitation.

The operation of the Electric Encoder is based on a non-contact capacitive technology in which an electric field is modulated by a relative displacement.

The Electric Encoder can be driven in two operation modes, coarse and fine. In coarse mode, the sine and cosine signal repeats only once over a full revolution (similar to the resolver) providing a coarse absolute position. In fine mode, the signals repeat many times providing a fine absolute position.

Other I/O Control

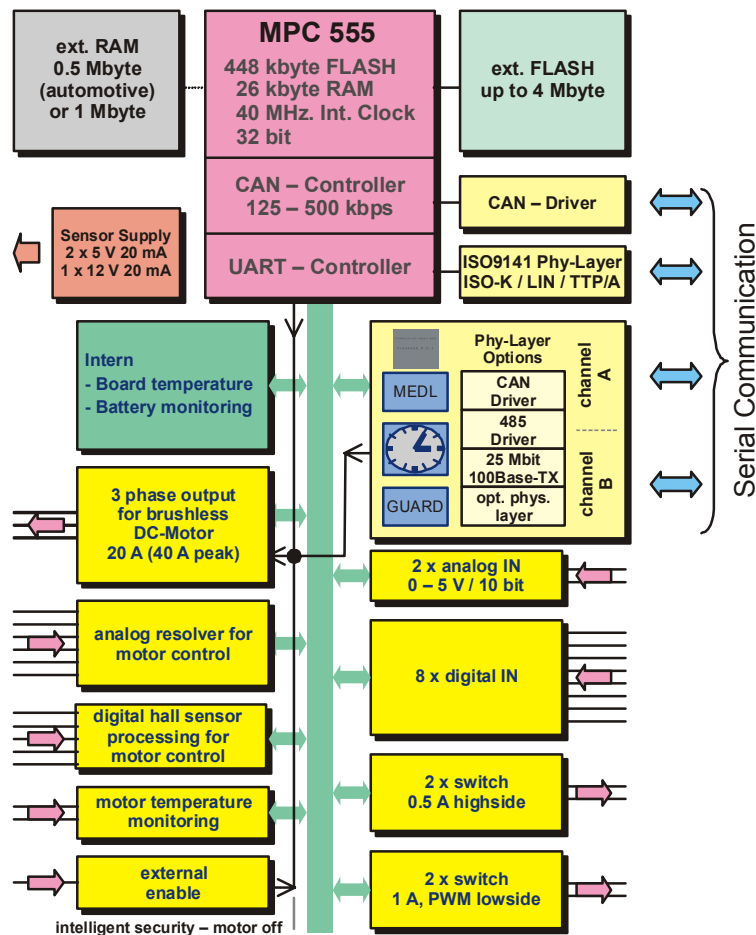


Figure 8: Block diagram of the TTP^{By-Wire} Box (single-CPU variant)

As shown in the block diagram in Figure 8, TTP^{By-Wire} Box offers – in addition to the mentioned I/Os for motor control – a wide range of standard I/O interfaces suited for a variety of different sensors and actuators, like

- ABS type wheel speed sensor input
- Digital inputs
- PWM-controlled high-side and low-side switches
- Analog inputs 0-5V,
- temperature sensor inputs

Communication interfaces:

- redundant TTP interface with CAN, RS-485 or MII physical layer

- ISO 9141 physical layer suitable for TTP/A, LIN, and ISO-K
- 2x CAN (125 – 500 Kbit/s)

An Exemplary Brake-by-Wire System

Figure 9 illustrates the use of the TTP^{By-Wire} Box in a brake-by-wire system.

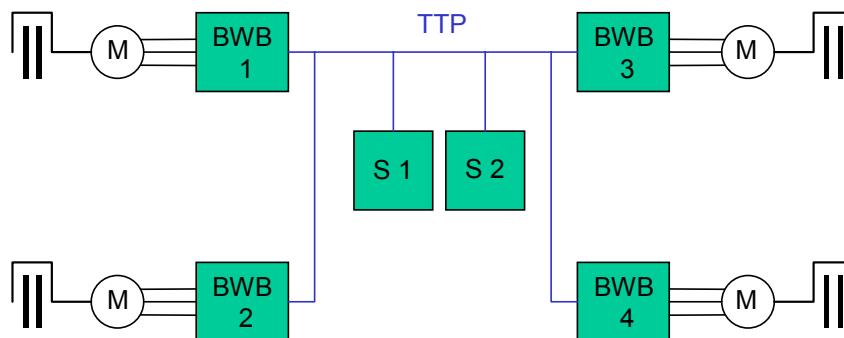


Figure 9: Diagram of a brake-by-wire car
(BWB – TTP^{By-Wire} By-Wire Box; S1, S2 – redundant brake pedal sensors;
M – motor, actuator; TTP – time-tiggered protocol as communication system)

If the driver operates the brake pedal, the pedal travel is calculated by the redundant sensors S1 and S2. The sensor puts the value from the brake pedal on the bus, and each actuator receives it. The TTP protocol ensures a consistent and timely transmission of the messages. The actuator gets the desired brake power and accordingly triggers the electric motor that operates the brake shoes. The brake system can be expanded continuously by adding necessary sensors and software modules.

The brake system in cars represents one of many possible applications. It is given here to illustrate the design of a distributed computer architecture.

The Benefit of Distributed Control Systems

Distributed control systems are becoming more and more important in the automotive and automation industry. Central architectures are limited in computing power, complexity, and wiring expenditure. Distributed control systems assign tasks to control units of a manageable size.

Distributed control systems have the following properties:

- Electronic wiring replaces many mechanic and hydraulic parts.
- The computing power for the overall system can be distributed to all nodes in the system.
- The number of sensors can be reduced because their measuring data are available in the entire network.
- The software can be expanded with convenience and safety functions if adequate sensors are implemented.

The Time-Triggered Protocol

Communication among nodes has to be guaranteed in any circumstance so that the system can meet the requirements of safety-critical real-time systems. Specifically designed for applications in this area, the Time-Triggered Protocol (TTP) is ideally suited for reliable data transmission in real time.

The messages are transmitted in a strictly periodic way. The developer specifies the transmission frequency of each message in advance. This makes the behavior of each running node absolutely predictable. This property is ideally suited for detecting a fault and taking immediate measures in case of failure. The nodes control each other. A specific algorithm ensures that every node has the same status information about all other nodes. If the dropout of a component is detected, a dropout strategy allows a continuous operation of the system. If the components are redundant, the so called "fault-tolerant layer" provides a consistent handling of the replicas. In case a TTP By-Wire Box drops out, another one takes over. If hardware and motors are not to be redundant, it is possible to switch over to another operational mode. In the exemplary brake-by-wire system there would be the option to switch over to a two-wheel diagonal brake system in case one brake fails.

Remote Pin Voting

TTP offers a special service called Remote Pin Voting that can also be used with the TTP By-Wire Box to deactivate a motor that got out of control due to a defective CPU or erroneous software:

If, for example, the motor connected to BWB 1 in Figure 9 gets out of control and the other electronic control units (ECUs) in the TTP network detect this error condition by e.g. monitoring the TTP messages sent by this node, the other ECUs BWB 2, BWB 3 and BWB 4 can initiate a shutdown of the motor of BWB 1 by sending a special, remote pin voting message. If the majority of the other ECUs in the network decide to shut down the motor, the TTP controller in BWB 1 will set its remote pin voting signal to low (see Figure 4) which causes the motor to stop. For this remote deactivation no interaction of the defective MPC555 CPU is needed.

TTP Tools – The Development Environment for Fault-Tolerant Real-Time Systems

The TTP By-Wire Box is designed to be used in combination with the TTP Tools, the software development suite for TTP. This toolset supports rapid prototyping and algorithm testing for vehicle dynamics models and control systems.

High-quality software tools for simulating and programming a TTP network are part of this TTP toolset. These tools are designed for configuration of a TTP communication system. Their principal parts are:

- TTPPlan – The cluster design program

This tool specifies the parameters of the TTP network (cluster). It defines the number of the nodes in the system and the temporal behavior of all messages on the bus. The static reiteration frequency is established prior to the startup and cannot be changed at runtime.

- **TTPBuild** – The node design program

This tool is used for configuration at the node level. The operating system **TTPOS** is configured and the “fault-tolerant layer” is generated. This fault-tolerant-layer ensures a consistent handling of replicated nodes in the system.

These two configuration programs are crucial to TTP programming and are integrated in the **TTPMatlink** environment, which covers the application-sided part. **TTPMatlink** is based on MATLAB®/Simulink® and has options for

- simulating the control algorithms and the behavior of the TTP messages. **TTPMatlink** models can simulate the behavior of the future system before the final implementation.
- generating the C code of the application algorithms with the Real-Time Workshop® Embedded Coder. The source code for the application is generated on the basis of the model derived from **TTPMatlink**.

TTPBy-Wire Box also comes with an I/O blockset for MATLAB/Simulink called I/O Toolbox. With the blocks of the I/O Toolbox the I/O control of the **TTPBy-Wire Box** can be integrated directly into a Simulink model. Additionally, it allows simulating the behavior of the I/Os.

The entire development environment allows the software engineer to fully concentrate on the design of the system architecture and algorithms.

Figure 10 shows an example **TTPMatlink** model for distributed motor position control. The two blue blocks in the upper window represent two subsystems running on two different nodes, one subsystem implements the position control algorithm, the other the actual motor control. The pentagonal yellow blocks depict the messages sent over and received from the TTP bus. The lower window shows the model part inside the motor control subsystem, the green block represents the I/O Toolbox motor control block for sinusoidal motor control.

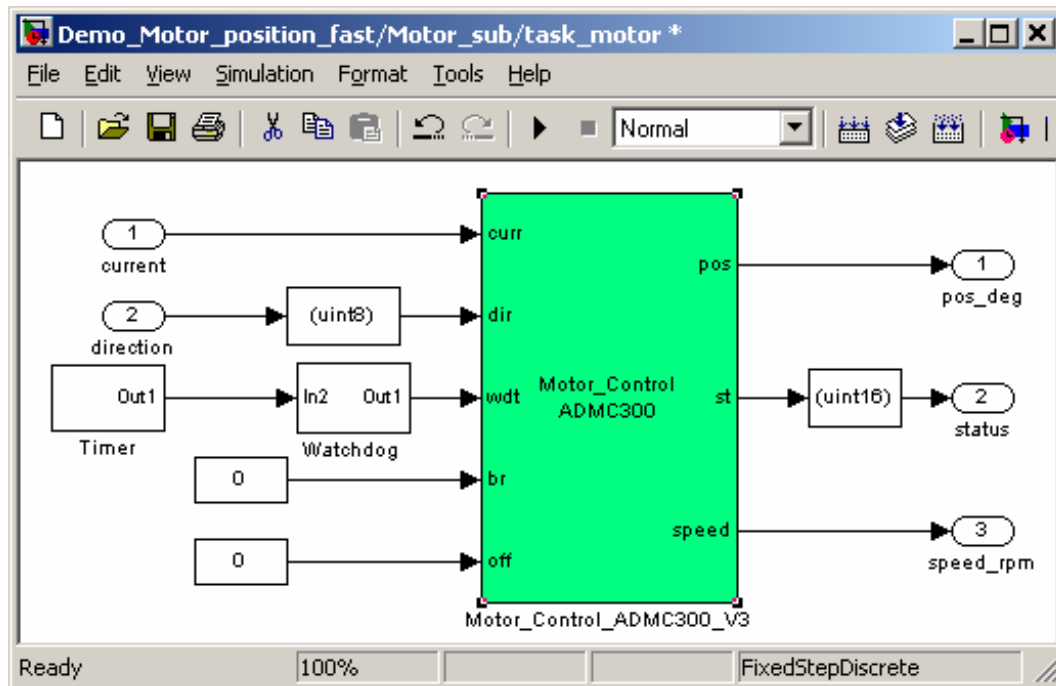
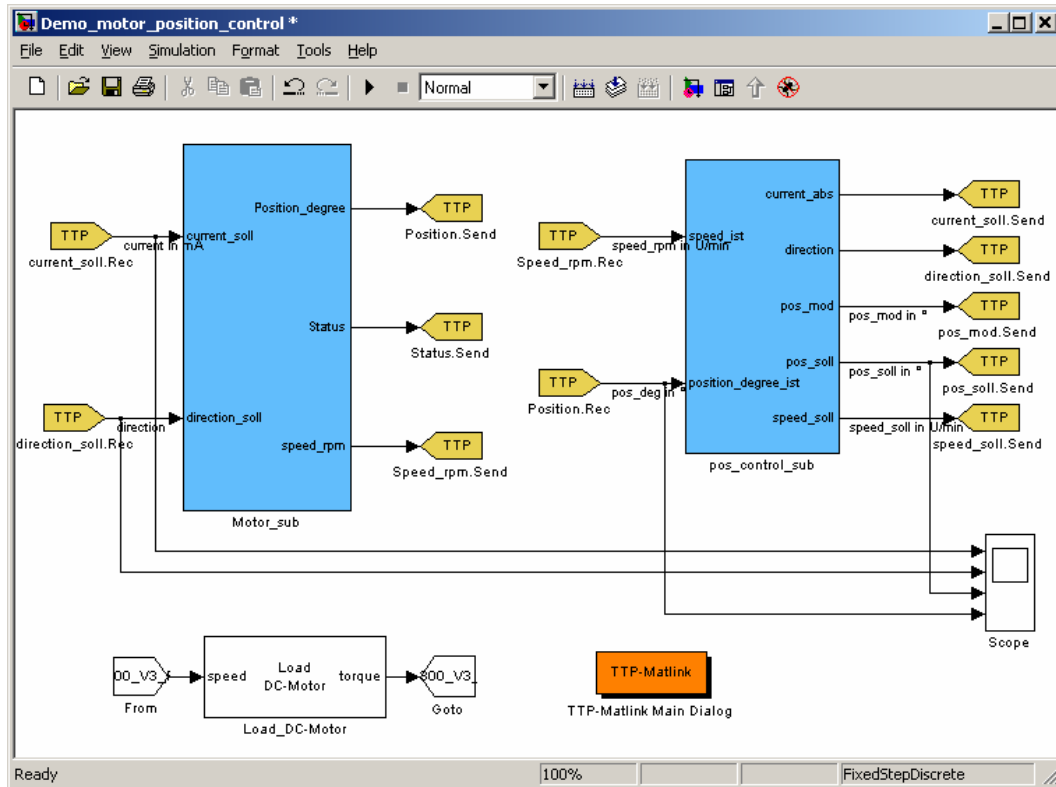


Figure 10: TTP Matlink model with distributed motor position control

Figure 11 illustrates the simulation of the messages of the TTP Matlink model in Figure 10 (contents of the scope block). Plot 3 shows the set value for the motor position, plot 4 the measured position in degrees. Plot 1 and plot 2 show the current applied to the motor and the motor direction respectively.

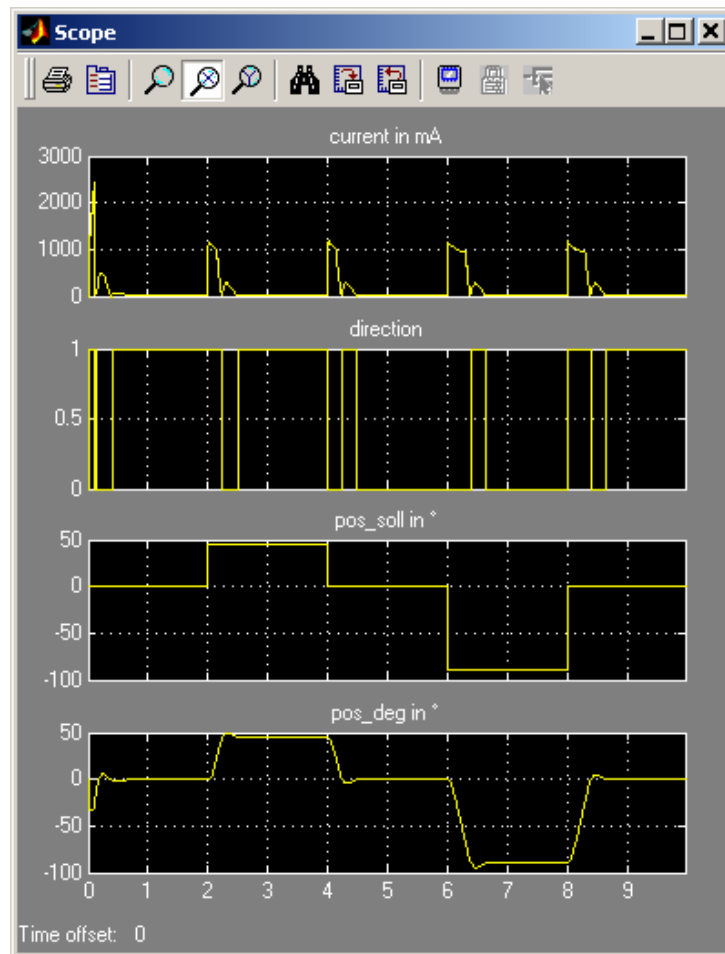


Figure 11: Simulation of the TTP Matlink model shown in Figure 10

Conclusion

TTTech provides innovative solutions for setting up distributed systems with brushless DC motors. The TTP By-Wire Box is an actuator control unit with full hardware and software support for direct control of a brushless DC motor. In combination with the fault-tolerant Time-Triggered Protocol (TTP), it is ideally suited for implementing by-wire functionalities in cars, such as brake-by-wire, steer-by-wire, or clutch-by-wire. Depending on the application area the TTP By-Wire Box is available in two versions, supporting either 6-step or sinusoidal motor control. These two type of the actuator control unit differ in their complexity of the motor control and the required computing power and sensor precision. Additionally, the TTP By-Wire Box can be used as an advanced automotive development system with a wide range of standard I/O interfaces that are

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