The TwinCAT real-time extension for Windows

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PC-based control is the combination of generally available technology from the IT world with specialized functions for automation technology. In this way, automation technology can participate in the rapid development of hardware and software in the IT world, and at the same time use the available computing power for automation tasks. A standard operating system and standard PC hardware are used for this purpose. The de-facto standard for operating systems in the business sector is Microsoft Windows, which has been upgraded for automation technology with a powerful real-time extension and TwinCAT.

Windows provides extensive software support for hardware components available on the market. However, an essential prerequisite for automation technology is the processing of programmed functions in real time. Windows is "by design" not real-time capable, i.e., a long print job, for example, can cause significant delays in the execution of other functions (delta t > 500 ms). 500 ms latency may not even be noticed on an office PC, but usually means a catastrophic failure for a controller system.

Due to its general availability, widespread use and stability, Beckhoff selected the Microsoft Windows NT operating system (then NT 4.0) for its PC-based control technology in 1996. Drawing on the experience of many years of the real-time solution under MS-DOS, a real-time extension for Windows was developed. The goal was to extend a generally available, widely used operating system with real-time functions for use in automation technology. The idea was that the real-time functions – such as a PLC – should appear like a printer driver to the operating system. This approach has been and continues to be developed across all versions of Windows, including Windows 10. Beta versions of Windows 11 with TwinCAT are currently being tested in the development lab and by the first customers.

In the beginning there was the timer interrupt

The foundation of PC Control technology from Beckhoff is the central timer interrupt, from which all time-controlled functions are derived. The main function of the timer interrupt is the cyclic activation of the TwinCAT real-time scheduler, whose tasks execute the required real-time functions of the automation system.

The central timer for Windows NT on a 1996 PC was the PC Timer 0 of the Intel 8254 timer module. For the proof of concept, the interrupt of the PC Timer 0 was used in such a way that a proper function of the Windows NT system was given at any time. The implementation was validated with the help of Microsoft employees in a Microsoft lab in Paris. Real-time measurements with an external hardware oscilloscope showed a deterministic occurrence of the timer interrupt with low jitter in the programmed intervals.

The basis for the deterministic processing of the highest priority interrupt in the Windows NT system is the general interrupt handling of the NT kernel. The Windows NT interrupt concept provides that interrupt service routines (ISR) process hardware interrupts only for a very short time, acknowledge them and move longer processing processes to the lower-priority level of "deferred procedure calls" (DPC). This ensures that interrupt service routines do not block each other or else, block each other only very briefly.

Switching between Windows and real-time context

A patented property of the TwinCAT real-time solution is what the company refers to as the "double tick". Thus, two interrupts are triggered for each real-time interval. An interrupt is used to switch from the Windows context to the real-time context with subsequent execution of the real-time scheduler. The second interrupt switches back to the Windows context after a programmable timespan. This process is repeated at the programmed interval of the base time. In this way, two underlying time slices are created, each of which is used by Windows functions and TwinCAT real-time functions. In the example of a base time of 1 ms with an 80/20 split, this means that 800 µs are available for TwinCAT real-time applications in each millisecond and 200 µs remain for Windows activities. The base time and the split between Windows and TwinCAT are configurable. The aforementioned PC Timer 0 is ideally suited for this operating mode, since the interval time can be programmed one cycle in advance and the transfer of the new time value takes place without offset.

With the double tick, the computing time on a single processor core can be divided in such a way that timing functions necessary for Windows are retained and Windows cannot be "stalled" by an excessively high real-time load. For example, Windows communication via a serial interface works perfectly even with higher baud rates, which would not be possible without the double tick.

The example of the PC Timer 0 shows the best-possible utilization of the PC system's resources by TwinCAT. However, PC architecture has evolved very quickly over the years. PC Timer 0 is no longer available on modern PCs without legacy support. With the introduction of dual- or multi-core systems, the use of the timers of the i8254 in TwinCAT, for example, was replaced by the timers of the LAPIC (Local Advanced Programmable Interrupt Controller) on a core. The cache architecture and its optimal use play a significant role in the available CPU computing power. To this end, TwinCAT has been adapted and continuously optimized over the years in cooperation with CPU manufacturers.

TwinCAT Scheduler

For the allocation of computing time in the real-time context, TwinCAT uses a scheduler that can currently manage up to 65,535 tasks. The first version of the scheduler from 1996 supported 64 tasks, which were mainly used for PLC and NC.

With the introduction of multi-core technology, the scheduler was also required to distribute real-time control tasks efficiently across the cores configured for TwinCAT. This made scheduling much more complex. In particular, scalability over a larger number of cores (> 16) was a challenge. The TwinCAT real-time scheduler currently supports up to 256 cores, which is a unique selling point in the automation industry. Without multi/many-core support, computationally intensive applications such as XTS, XPlanar or real-time image processing would not be possible. The multi-core support in TwinCAT offers two different operating modes:

- Shared Cores: TwinCAT shares a core as described above, and unused computing time of the TwinCAT context is allocated to the Windows context.
- Isolated Cores: In this case, the Windows configuration limits the number of cores available for Windows. The remaining cores are detected by TwinCAT and can be activated during the TwinCAT configuration. This operating mode can further improve the determinism of the timer interrupt and reserves 100% of the computing capacity of the designated core for TwinCAT real-time tasks.

Conclusion and outlook

Over the last 25 years, the TwinCAT real-time kernel has developed from a timer interrupt with connected scheduler to a real-time system that optimally supports the latest 64-bit CPU architectures with regard to automation technology. Standardized APIs such as OpenMP as well as debugging with Visual Studio® are supported. With the aid of the TwinCAT Real-time Monitor (TE1010), the time behavior of tasks, semaphores and other resources of the real-time system can be recorded and displayed with microsecond accuracy.

Beckhoff has currently started to deliver the alternative operating systems TwinCAT/BSD (combination of FreeBSD and TwinCAT real-time kernel) and TC/RTOS (combination of FreeRTOS and TwinCAT real-time kernel). Other combinations may follow in the future – in any case, there will be many more implementations of TwinCAT on new hardware and operating systems.

More information:
www.beckhoff.com/te1010