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Potential of the DSP-based Method for Fast Precise Event Timing

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Introduction

By the term "event timing" we mean measuring the time instants when some events occur. In addition, we consider the event timing only in the context of the technical applications where events are represented by leading edges of uniform pulses. In this case the event timing is simply a measuring of time at instants when these pulses arrive at the input of a measuring device. The devices of such kind are called event timers.

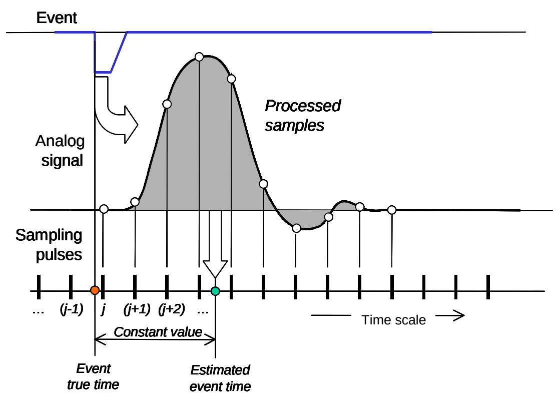
Functionally the event timers cover possibilities of the conventional time interval counters since any time intervals between any events can be further calculated as differences between the corresponding time-tags. Accordingly, the event timers offer significant benefit in applications where complicated signal analysis in Modulation domain is especially needed (e.g., time-of-flight spectrometry).

One of the most important problems for development of advanced event timing technologies is to combine the high measurement precision with high measurement rate. We shall consider this problem solution by an example of one DSP-based method for event timing.

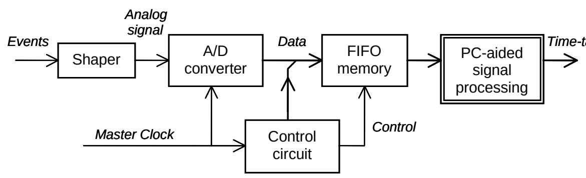
Principles of DSP-based methods for event timing

Usually ones define the timer's precision as the standard deviation of time measurement for single event. Currently the "high" timer's precision means that it is less than tens of picoseconds (although such criterion is not too strict). To achieve so high precision, certain interpolation measurements are used in addition to the coarse time measurements performed in a digital way. Mostly the methods for such interpolation measurement (time interval stretching, vernier method, time-to-amplitude conversion, etc) are similar to the methods conventionally used for the high-precision measurement of single-shot time intervals; full-scale review of these methods may be found in [1]. However, practical implementation of the conventional interpolation methods usually entails considerable hardware complexity, including very careful design and adjusting. For this reason most of the currently available top-quality event timers belong to the class of the custom-made and very expensive instruments.

In addition to the traditional interpolation methods mentioned above, a few new DSP-based methods for high-precision event timing have been recently suggested. General idea of these methods is to generate a specific analog signal at instant determined by the input event, digitise such Event-Initiated (EI-) signal and then digitally process it. When the processing is made in a proper way, it results in an estimate of the EI-signal position (and the input event position respectively) on the time axis (Fig.1).



a)



b)

Fig. 1. Time (a) and block (b) diagrams illustrating the DSP-based methods for event timing

As can be seen, unlike the traditional interpolation techniques, in this case the common-used DSP facilities replace essential part of usually complicated analog circuits, resulting in considerable reducing of hardware complexity.

Conceptually the mentioned approach to high-precision event timing has been offered about ten years ago [2]. Theoretically it can provide the precision as high as is wished, if the EI-signal is absolutely stable and ideally timed to the input event. However, such conditions are not practicable. Correspondingly various specific methods for event timing based on this approach mainly differ in regard to the best practice of EI-signals generation and to the matched algorithms for their digital processing. For example, the EI-signal considered in [2] is generated as a train of triangular pulses with use of re-circulating cable loop. At that time (1998), such method has provided top-level precision (8.5 ps RMS).

Another recently considered DSP-based method for event timing is based on application of the EI-signal in the form of radio-frequency pulse (in response to a SAW filter excitation) and computing algorithm for cross-correlation estimations [3]. In the specific implementation this method demonstrates the currently world's best precision (less than 1 ps RMS), confirming the high potential of the DSP approach as a whole.

However a large amount of signal samples (up to a few thousands) is needed to perform the high-precision event timing in accordance to the above particular methods. That leads to a large dead time between adjacent measurements and, correspondingly, significantly decreases the achievable maximum measurement rate. In addition, this requires essential computing resources for the related DSP.

The mentioned drawbacks considerably limit the application area of DSP-based event timers. For example, in many cases the creating of multi-channel event timer systems is only one way to apply them for the task where small dead time is vitally needed. Evidently, the multi-channel systems are much more complicated, expensive and not too reliable. In view of that it was important to develop the method for event timing that can use a limited amount of the EI-signal samples for further DSP to reduce the dead time.

DSP-based method for fast event timing

The method (called EET, i.e., Enhanced Event Timing), which basically meets the above condition, have been developed and discussed in [4]. Briefly, the method includes the generation of the EI-signal in form of a single Gaussian pulse and the capturing from it only four samples for further processing. Corresponding algorithm for EI-signal processing is based on the conversion of difference between two specifically selected EI-signal samples to the target digital time-tag. Important point of this method is that such conversion is non-linear, resulting in non-uniform time quantizing to reduce the integral non-linearity [5]. The matter is that so small sample amount usually causes noticeable initial integral non-linearity that can considerably decrease the timing precision. Generally such particularity accompanies any method for high-precision event timing when a limited amount of signal samples (up to tens) is used.

At that time (2001), in a specific implementation the EET-method provided precision about 12 ps RMS at measurement rate up to 10 MHz. The achieved precision was quite good for so high measurement speed. Further development of the EET-method and its implementations during next few years considerably advanced the performance characteristics of the high-precision event timers based on it. A great importance in such development had general advancement of DSP technologies, including performance improvement of A/D converters, programmable logical chips and other electronic components.

Although the basic principle of the EET-method seems to be quite simple, there are many essential realisation details to achieve the best final result in its specific implementation and to correctly evaluate the actual potential of the method. For example, there are a lot of routine technical problems concerning stabilization of the EI-signal parameters, generation of the low-jitter clock sequence, etc. In addition, the advanced test methods and means should be applied to reliably evaluate the actual performance characteristics of similar implementations. We shall consider the basic features of EET-method by the example of its implementation in recently performed by us design of Event Timer A032-ET [6].

Example of the EET-method implementation

The most of top-quality event timers represent unique customized products. The A032-ET differs from them in that it was developed as an instrument commercially available. In other words, it should provide not only high performance characteristics but also good reproducibility and low manufacturing cost to be attractive for potential users. In view of all that the EET-method was well suited for the A032-ET design owing to the provided hardware simplicity. Functionally the A032-ET was oriented to applications in Satellite Laser Ranging (SLR), particularly for SLR at KHz rate.

Structurally the A032-ET hardware almost fully conforms to the block-diagram shown in Fig.1. To simplify the hardware design, clock frequency 100 MHz is used. This is quite convenient for reliable operation of the commonly used integral digital components, including Complex Programmable Logic Devices (CPLD) applied for integral implementation of the control circuits. An ordinary cable delay line is used for stabilization of the EI-signal parameters. On the whole that results in compact and relatively simply adjustable hardware (Fig.2).

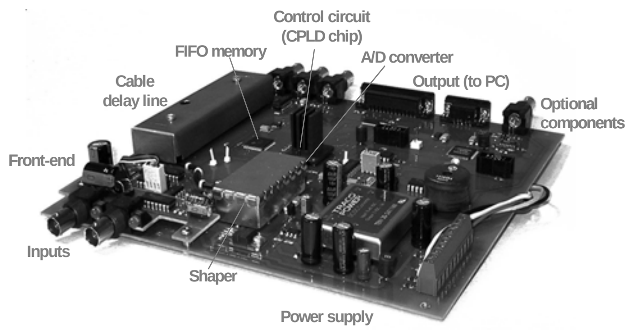


Fig. 2. A032-ET hardware implementation

In the A032-ET hardware 10-bit A/D converter (AD9214) continuously digitises a sequence of the EI-signals, but only four samples of each EI-signal are selected and memorized for further processing. In this case the hardware registers each event during 60 ns. Such small dead time allows measuring the events from different inputs (e.g., START and STOP) in the same measurement channel, providing considerable reducing the hardware complexity. In addition, unlike the multi-channel event timers, such single-channel configuration offers much better stability of precision parameters due to the effect of error compensation in measurements from different inputs.

The algorithm of signal processing requires about fifty PC CPU operations for computation of one time-tag. That is surely less than one microsecond for typical PC. The computation is adapted to the actual parameters of the EI-signal to achieve the best precision. Specifically, there is a special online calibration procedure to correct the data for computation process according to the long-term variation of the ET-signal parameters under time-varying operating conditions.

During last few years about 30 units of such device have been manufactured and carefully tested. Thus, the considered below performance characteristics have to be safe.

Achievable precision for the EET-method implementation

The simplest and demonstrative way how to specify the A032-ET actual precision is to perform direct repetitive measurement of a periodic test signal that has a jitter much smaller than the expected random errors produced by the instrument. In this case cyclical calculation of standard deviation σ_T for time intervals between measured events provides the estimates of the timer's resolution (Fig.3).

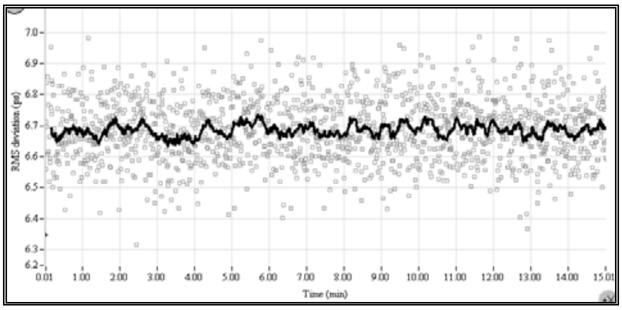


Fig. 3. Typical A032-ET resolution vs. time

Then the target estimates of the timer's precision can be simply obtained as $\sigma_t = \sigma_T / \sqrt{2}$. As the multiple experiments suggest, basically the A032-ET precision is ranged from 4.2 to 5.6 ps for different implementations of the device. This is in the range of the best precisions currently achieved for the commercial event timers.

Generally three basic error components can be noted as the main reasons for precision limitation of the EET-based event timers:

- quantizing errors which directly depends on the resolution of A/D converter;
- integral non-linearity errors which basically are caused by the impact of input signal on the interpolation process through spurious couplings;
- internal noise caused by trigger errors, sampling jitter, induced interferences, etc.

Note that the integral non-linearity errors are considered as systematic ones only in the case of synchronous measurements, otherwise they are like the internal noise [5]. Therefore these three kinds of errors in the most cases can be specified in statistical terms (by standard deviation values).

Standard deviation σ_Q of the quantizing error can be roughly evaluated with use of simple empirical expression $\sigma_Q \approx \frac{T_R}{3 \times 2^N}$, where T_R is the sampling period and N - resolution of the used A/D converter. For the A032-ET the standard deviation σ_Q is equal to 3.3 ps approx.

As for the integral non-linearity errors, it is device-depended and has been evaluated experimentally. Fig.4 illustrates typical A032-ET integral non-linearity obtained with use of the evaluation method considered in [5].

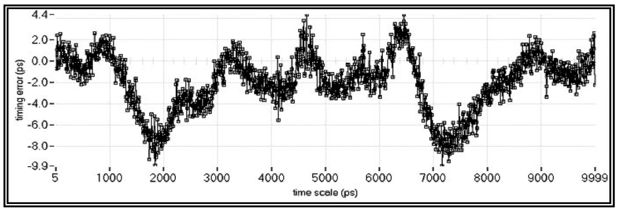


Fig.4. Typical A032-ET integral non-linearity

Typically the standard deviation of such kind of errors is in the range 2.5-2.7 ps.

Since the internal noise is caused by various parasitic sources, it can be evaluated as a complement with respect to the total measurement error, assuming that all mentioned error components are statistically independent. Using the previously estimated value of timer's precision, the RMS value of internal noise can be estimated as of about 2 ps.

Thus, in the considered specific case of EET-method implementation there is the following relative distribution of the error components in the total measurement error:

- quantizing errors – ~50%;
- integral non-linearity errors – ~30%;
- internal noise – ~20%.

On the basis of the above estimates it can be concluded that there are at least two basic ways to improve the precision of EET-based event timers as compared to the A032-ET precision:

1. Minimization of the quantizing errors by using of A/D converters with higher resolution (it is quite available).
2. More careful hardware design to minimize the internal noise (it is always possible in a varying degree).

Our first attempts in these directions show that the precision of the event timers based on EET-method at least can be twice as good.

Achievable operation speed

As can be seen, the operation speed for the EET-based event timers depends on the EI-signal duration and determines the smallest permissible time interval between two adjacent events. The EET-method suggests the minimum duration of EI-signal about 4 periods of clock pulses defining the rate of this signal sampling. In practice it should be a little greater (5-6 periods) taking into account that some time is needed for recovery of the EI-signal shaper. That results in the dead time about 60 ns and the maximum measurement rate about 16-17 MHz when 100 MHz clock frequency is used. The higher clock frequency is possible but within certain limits that depend on the performance of currently available high-speed electronic components. So it seems that the maximum measurement rate at least up to 25-30 MHz is quite practicable.

Conclusion

DSP approach to high-precision event timing seems promising and quite competitive in comparison with more traditional techniques used for that. Specifically, the best precision/ speed ratio for event timers have been achieved just by this approach using the EET-method. It seems that potential of this method is not exhausted and significant improvement of performance for its next implementations is quite possible.

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Yu. Artyukh, V. Bespal'ko, E. Boole. Potential of the DSP-based Method for Fast Precise Event Timing // Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 4(92). – P. 19–22.

General principles of high-precision event timing based on DSP approach are discussed with emphasis made on the particular fast method for such event timing. The latest specific implementation of this method and its main features (basic error components, achievable final precision and operation speed) are considered in more details. By this example it is shown that the method can provide picosecond precision at measurement rate up to tens of MHz. Ill. 4, bibl. 6 (in English; summaries in English, Russian and Lithuanian)..

Ю. Артюх, В. Беспалько, Е. Буль. Возможности метода скоростного высокоточного таймирования событий, основанного на цифровой обработке сигналов // Электроника и электротехника. – Каунас: Технология, 2009. – № 4(92). – С. 19–22.

Рассмотрены общие принципы высокоточного таймирования событий, основанного на цифровой обработке сигналов, и, в частности, скоростной метод такого таймирования. Более детально рассмотрены пример реализации этого метода и его основные характеристики (основные компоненты ошибок, достижимая точность и быстродействие). На этом примере показано, что метод может обеспечивать пикосекундную точность таймирования с частотой повторения измерений до десятков МГц. Ил. 4, библ. 6 (на английском языке; рефераты на английском, русском и литовском яз.).

Yu. Artyukh, V. Bespal'ko, E. Boole. Labai tikslus įvykių tyrimas apdorojant signalą skaitmeniniu būdu // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 4(92). – P. 19–22.

Išnagrinėti labai tikslaus skaitmeninio signalo apdorojimo (SSA) metodo bendrieji principai ir greičio įtaka. Plačiau ištirtos metodo realizavimo galimybės ir charakteristikos (pagrindinės klaidos komponentai, pasiekiamas tikslumas ir greitaveika). Iš pateikto pavyzdžio matyti, kad šiuo metodu galima pasiekti pikosekundės tikslumą, kai matavimų sparta yra iki dešimčių megahercų. Il. 4, bibl. 6 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).