ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2008. No. 4(84)
ELEKTRONIKA IR ELEKTROTECHNIKA

SIGNAL TECHNOLOGY
T121
SIGNALŲ TECHNOLOGIJA

Constructing of Unlimited Single-valued Time Scale for TDC-based Event Timers

Yu. Artyukh, V. Vedin
Institute of Electronics and Computer Science
Dzerbenes st. 14, LV-1006 Riga, Latvia; phone: +371 7554500; e-mail: vedinv@edi.lv

Introduction

There is quite a wide range of applications in science and technology where data is represented by event streams. Examples of such applications are: Satellite Laser Ranging, LIDAR, Time-of-Flight (TOF) spectrometry, single photon/molecule/ion counting, phosphorescence lifetime studies, etc. One may say that in these applications various physical processes practically directly generate the events (like a photon coming into a photo-multiplier tube) although certain signal conversion circuitry always exist. Beside such processes there are cases when primary "slow" signals (such as temperature, pressure, etc.) from sensors or transducers feed inputs of specialized converters that produce events at their outputs. This is often done to simplify electronic equipment and make it easer to transmit measurement data. Typical examples are the wide use of Voltage-to-Frequency Converters and Pulse Width Modulation.

In most cases (although not always) the results that have to be obtained by measuring event-represented signals are time intervals. It could be either time intervals associated with some initial stimulus (triggering event) and some response events (as, for example, in LIDAR or TOF spectrometry) or time interval between adjacent events (for example, for restoration of Voltage-to-Frequency converted or Pulse-Width-Modulated signals). Traditionally, specific time interval measurement devices have been used to perform such measurements and they still are.

In recent years a new approach to time measurements based on event timing has been introduced. Generally the term “event timing” can have various meanings. We keep in mind one of them where event timing is a measuring of time at instants when some events occur. Detecting of specific events usually is performed by a dedicated conditioner that presents events at the output by the leading edges of uniform pulses (e.g., of NIM 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. Conventionally the devices of such kind are called Event Timers.

The measured value of time (called “time-tag” or “time-stamp”) is expressed relative to a time scale of the event timer. This scale is repeated with some predetermined periodicity (Fig.1). Mostly the time scale is device-specific (in terms of the reference time, period *Ts* of the scale repetition, etc).

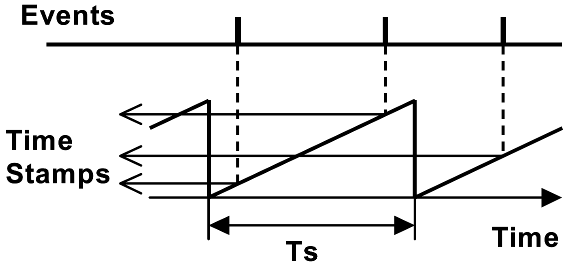

Fig. 1. Definition of the Event Timing

Event Timers are regarded as instruments that provide much more universality that traditional time interval measurement devices. For example, as most simple case, time intervals are not necessarily to be measured directly [1]. Often, it is more convenient to measure the instants {*t*0, *t*1, *t*2, ...*tN*} of arrival of the input pulses (timing events corresponding, for example, to the leading edges of the input pulses). Then, if necessary, one can calculate the time intervals as the differences between the results for adjacent events. Of course, depending on a particular application, more complicated processing could be employed, e.g. calculation of Allan variance, Poisson distribution, etc. Obviously the time scale period T_S is a very important parameter - the longer it is the longer time interval can be measured. As a rule, wide-range Event Timers are characterized by long duration (up to hours in some cases) of their time scale. It is required in Satellite/Asteroid/Moon Laser Ranging applications, in many physical tasks.

There are two basic parameters that specify in general terms the applied potential of a wide-range event timer: its resolution (absolute precision) and the highest measurement rate. Consequently, the goal usually pursued at development of a new type of event timers is increased resolution and higher maximum measurement rate (or so-called "dead" time) achieved in a cost-effective way.

Typically, the time scale of precision Event Timers is composed of two basic components - coarse time scale (as a rule, implemented by a counter that counts pulses coming from a time base generator) and an interpolator. The interpolator is a device that is able to measure a time interval between the time instance of an input event and the following pulse of the time base generator. So, after arrival of an event there are two readings - the first one is from the coarse counter and the second one is from the interpolator. The composition of these two gives the final Event Timer reading. In most cases, especially when very high precision is required, the interpolators are responsible for slowing down a Timer.

Long time scale duration, in combination with very high precision (typical RMS resolution ranges from dozens of ps down to several ps) and low "dead" time, makes Event Timers quite expensive instruments. The interpolators built on discrete components or low-integration chips are responsible for the instrument cost to a large extend. It would be quite attractive to employ high-integration time interval measurement chips with built-in interpolation circuitry so as to reduce the cost of the Event Timers and expand their application field. During last years such chips called Time-to-Digital Converters (TDC) became available on the market. There are two leading companies in this field - MSC Vertriebs and Acam-messelectronic (both from Germany). The best TDC chip from MSC (TDC10000) features 60 ps resolution but only 2 channels (all TDCs from MSC have two channels). ACAM offers the chip TDC-GPX featuring different channel number versus resolution. In particular, in its multi-channel mode the chip provides 8 channels at 80 ps resolution with up to 180 MHz event rate for each channel. The main drawback of TDC chips is that they are implemented according to the traditional time interval measurement technique and have a limited time interval measurement range. It means that they cannot be used directly to build Event Timers.

In this paper we consider a method for solving this problem and adapt multi-channel TDC chips for Event Timers so that they could support even the unlimited single-valued time scale.

The Principle of the Method

A typical simplified block diagram of a TDC is depicted in Fig. 2. The Measurement Block provides raw timing data that are further processed by ALU to obtain Start-Stop time intervals. The latter are written in the buffer FIFO and can be read by an external controller (CPLD, FPGA, μC).

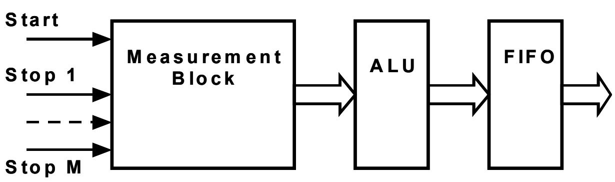

Fig. 2. Simplified block diagram of a TDC chip

A TDC used as it is simply performs time interval measurements between the Start and Stop signals within its specified time range T_R. So as to adapt a TDC for the event timing it is proposed to employ the mechanism of restarting in combination with an additional binary restart counter with the modulus $M_C=2^N$ (see Fig. 3).

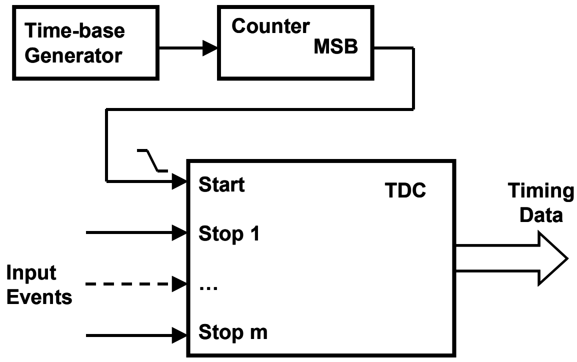

Fig. 3. A TDC with additional restarting circuitry

The main condition for the restart counter is:

$$M_C \times T_{CLK} \geq T_R, \quad (1)$$

where T_{CLK} is the period of the time-base generator. If falling edge of the MSB (Most Significant Bit) is connected to the Start input of the TDC the device becomes an Event Timer with the limited time scale duration of $M_C{\times}T_{CLK}$ which needs to be extended to achieve true Event Timer functionality. There is always a unique correspondence between the states of the counter and those of the internal time scale of the TDC. Let us assume, for better understanding the principle, that $M_C{\times}T_{CLK}=T_R$ and the MSB of the TDC time scale fully corresponds to that of the restart counter.

To extend the time scale by traditional methods [2], an additional time scale extension synchronous counter that counts restart counter MSB pulses has to be added (see Fig. 4).

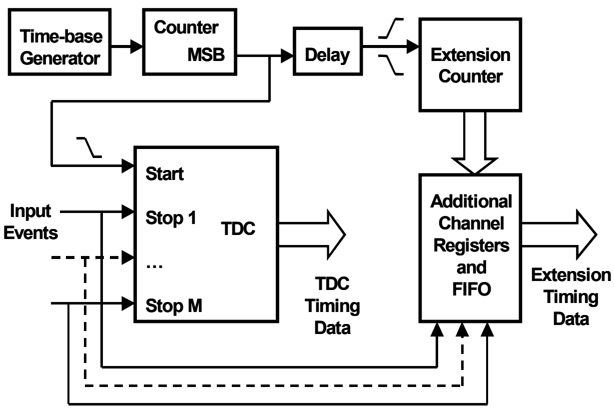

Fig. 4. Traditional Approach to Event Timer Time Scale Extension

Input events have to properly perform readings of the state of this counter into additional registers dedicated for every channel. The proper reading is important because if the synchronous counter is read at the time of the counter transition it may lead to irreducible errors. One of the methods to avoid such errors is to employ additional synchronization circuits for the input events. The extension counter must count both rising and falling edges of the restart counter MSB. It has to be done so that the restart counter MSB and the extension counter LSB (Least Significant Bit) had the same weight. Only under this condition it is possible to eliminate timing uncertainty that may occur when different time scales are used independently. The other requirement - the extension time scale has to either run ahead of restart counter or behind of it (but not both) and this must be known a priori to perform correct timing uncertainty removal calculations. In our particular case it is much easier to make it run behind. The algorithm of uncertainty elimination is based on the comparison of the MSB of the TDC output code TDC_C and the LSB of extension counter. If the MSB of TDC code and LSB of extension counter have the same value, no correction required - the composed result (time stamp - TS) consists of the TDC code without its MSB and extension counter code (EXT_C) as follows:

$$TS = TDC_C \times W + 0.5T_R \times EXT_C, \tag{2}$$

where W is the weight of the LSB of the TDC.

If the extension counter runs behind the restart counter and the restart counter MSB and extension counter LSB are of different value then we know for certain that an event arrived at some time slot between transition of the restart counter MSB and transition of the extension counter LSB. Because the extension counter lags behind the resulting time stamp (TS) is composed of the interpolation code, restart counter code without its MSB, and full extension counter code plus one weight of its LSB as follows:

$$TS = TDC_C \times W + 0.5T_R(EXT_C + 1). \tag{3}$$

Each additional channel register should have a channel number indication bits and be connected to a FIFO with the same depth as the FIFO of the TDC. In this way the correct measurement result composition can be achieved.

Such or similar solution looks clumsy and may degrade the accuracy performance of a timer. Besides, the amount of data to be transferred increases according to the required time scale extension length. And finally, the timeless measurement range cannot be obtained at all.

To solve this problem we have come to a different solution. One measurement input of the TDC was assigned as a specific marker input (see Fig. 5). The MSB of the restart counter is delayed and then is fed into this input. The marker input is configured for accepting both positive and negative edges. In this way we insert specific marker events, corresponding to transitions of the MSB of the restart counter, into the output digital data stream that is transmitted further (into some controller block based on µC, CPLD or FPGA).

The constructing of single-valued time scale could be done either by the controller block firmware or by PC software where the data finally come in most of applications. The firmware or software detects the marker measurement data blocks and constructs the extension time scale simply as a variable to use for composing resultant time stamps. The algorithm of the composition is as in formulas given above. When it is done on a PC, the proposed solution not only allows constructing practically limitless single-valued time scale by means of software but also substantially reduces the amount of transferred data for high rate event streams.

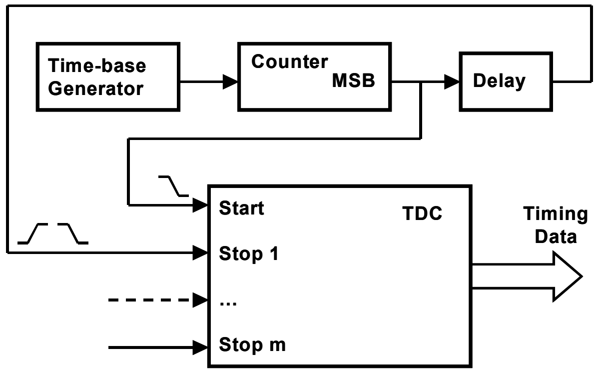

Fig. 5. A TDC with Restarting and Marker Event Insertion Circuitry

For example, if the required duration of the time scale with 100 ps resolution is 1 sec (which is not much in many cases) then 32 bits of the timing data need to be transferred for each event. With typical for TDCs time range T_R of 100 µsec each event requires not more than 10 bits (for the same resolution). Although two marker events have to be additionally inserted during every interval T_R (100 µsec in our example, one marker event every 50 µsec), it is a negligibly small overhead if the event rate ranges from hundreds KHz up.

Implementation and Experimental Results

The described method was realized in 6-channel High Speed Event Timer (HSET, see Fig. 6) designed in Institute of Electronics and Computer Science (Riga, Latvia).

Fig. 6. Photograph of the High Speed Event Timer

The Timer employs the IC TDC-GPX as its main measurement core. The controller block is implemented on a Cyclone II Altera FPGA. The HSET is a PC based instrument and communicating with the PC is done via USB port (2.0 high-speed) by using the IC CY7C68013A from CYPRESS.

The HSET features relatively high RMS resolution (90 ps) in combination with very high event burst rate (up to 150 MHz for each channel). The HSET supports average event rate up to 3 MHz, which was limited by the

USB throughput and USB drivers of the development software (National Instruments LabWindows/CVI and VISA Drivers).

The measurement data are transferred from the HSET as 4-byte elementary data blocks - each block corresponds to one input event (including time scale extension marker events). One such data block contains the data from the TDC-GPX (28 bits - timing data and channel number) and additional 4 bits inserted by the FPGA for messaging purposes. The application SW performs parsing the obtained data and when the data blocks corresponding to the marker events are detected the program increments a coarse time scale variable.

To carry out experiments, an equidistant sequence of events was applied to one or several inputs of the HSET. A stable pulse generator served for this purpose. Any failure during data transfer and the process of constructing the SW time scale would lead to easily detected time interval error between adjacent events. Multiple experimental tests taken at different input event rates and used numbers of input channels showed no failures of the constructed time scale when the input average event rate did not exceed the specified maximum rate.

Conclusions

The proposed method of constructing the unlimited single-valued time scale for TDC-based Event Timers proved to be very effective for significant hardware optimization and cost reduction. In addition, the method substantially reduces the amount of transferred timing data for relatively high (hundreds of KHz and higher) event rates.

References

1. **Artyukh Yu. N.** A method for continuous extreme precise time-interval measurement // Automatic Control and Computer Science. - 2001. - vol.35, No.5. - P. 11-18.
2. **Беспалько В. А., Ведин В. Ю.** Устранение неоднозначности в комбинированных время-цифровых преобразователях. // Метрология. - 1985.- № 9. - С. 9-15.

Submitted for publication 2008 01 22

Yu. Artyukh, V. Vedin. Constructing of Unlimited Single-valued Time Scale for TDC-based Event Timers // Electronics and Electrical Engineering. – Kaunas: Technologija, 2008. – No. 4(84). – P. 17–20.

A method of time scale extension, that allows achieving practically limitless measurement range for event timing applications and substantially reducing unwanted excessive data transfer, has been proposed. The method is based on generating specific marker events, arrival times of which, relative to some "short" time scale of the primary measurement electronic hardware (Time-to-Digital Converter IC), are transferred along with measured event arrival times (time stamps) into remote hardware or into software application. The correct mechanisms of generating and using the marker events for constructing the unlimited single-valued time scale, free of uncertainty errors, has been developed and tested. Ill. 6, bibl. 2 (in English; summaries in English, Russian and Lithuanian).

Ю. Н.Артюх, В. Ю. Ведин. Построение неограниченной однозначной временной шкалы для таймеров событий основанных на интегральных время-цифровоых преобразователях // Электроника и электротехника. – Каунас: Технология, 2008. – № 4(84). – С. 17–20.

Предложен метод "удлинения" временной шкалы позволяющий достичь практически неограниченного диапазона таймирования событий и существенно сократить нежелательную избыточность передаваемых данных. Метод основан на формировании особых реперных событий, времена наступления которых по отношению к некоторой "короткой" временной шкале первичного измерителя (интегрального время-цифрового преобразователя) передаются вместе с временами наступления измеряемых событий в удаленное аппаратное или программное обеспечение. Были разработаны и проверены корректные механизмы формирования и использования реперных событий для построения однозначной и неограниченной временной шкалы, свободной от ошибок неоднозначности считывания. Ил. 6, библ. 2 (на английском языке; рефераты на английском, русском и литовском яз.).

Yu. Artyukh, V. Vedin. Neribotos vienareikšmės laiko skalės, skirtos įvykių laikmačiams, sukurtiems integralinių laikinių kodo keitiklių pagrindu, sudarymas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2008. – Nr. 4(84). – P. 17–20.

Pasiūlytas laiko skalės ištęsimo metodas, kuris leidžia pasiekti beveik beribį matavimo diapazoną. Metodas yra pagrįstas nustatymu specifinių žymėjimo įvykių nustatymu, kurių įvykimo laikas, palyginti su kai kuriomis „trumpomis“ laiko ribomis pirminio matavimo elektronine aparatine įranga (keitiklis laikas-kodas), kartu su įvykimo laikais yra perduodamas į tolimą aparatinę ar programinę įrangą. Sukurti ir išbandyti tikslūs žymėjimo įvykių formavimo ir naudojimo mechanizmai, siekiant sudaryti vienareikšmę ir neribotą laiko skalę, kurioje būtų galima išvengti skaitymo daugiareikšmiškumo klaidų. Il. 6, bibl. 2 (anglų k.; santraukos anglų, rusų ir lietuvių k.).

DOI: 10.5755/j02.eie.11107