A seamless acquisition digital storage oscilloscope with three-dimensional waveform display

Yang, Kuojun; Tian, Shulin; Zeng, Hao; Qiu, Lei; Guo, Lianping

2014

Yang, K., Tian, S., Zeng, H., Qiu, L., & Guo, L. (2014). A seamless acquisition digital storage oscilloscope with three-dimensional waveform display. *Review of Scientific Instruments*, 85(4), 045102-.

<https://hdl.handle.net/10356/104124>

<https://doi.org/10.1063/1.4869871>

© 2014 AIP Publishing LLC. This paper was published in *Review of Scientific Instruments* and is made available as an electronic reprint (preprint) with permission of AIP Publishing LLC. The paper can be found at the following official DOI:

<http://dx.doi.org/10.1063/1.4869871>. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 14:31:51 SGT

A seamless acquisition digital storage oscilloscope with three-dimensional waveform display

Kuojun Yang, Shulin Tian, Hao Zeng, Lei Qiu, and Lianping Guo

Citation: [Review of Scientific Instruments](#) **85**, 045102 (2014); doi: 10.1063/1.4869871

View online: <http://dx.doi.org/10.1063/1.4869871>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/rsi/85/4?ver=pdfcov>

Published by the [AIP Publishing](#)

Articles you may be interested in

[A digital hysteresis loop experiment](#)

Am. J. Phys. **81**, 745 (2013); 10.1119/1.4819169

[Submicron three-dimensional trenched electrodes and capacitors for DRAMs and FRAMs: Fabrication and electrical testing](#)

J. Appl. Phys. **104**, 064112 (2008); 10.1063/1.2981197

[Rapid multiplexed data acquisition: Application to three-dimensional magnetic field measurements in a turbulent laboratory plasma](#)

Rev. Sci. Instrum. **74**, 2361 (2003); 10.1063/1.1544417

[Effect of display luminance on the feature detection rates of masses in mammograms](#)

Med. Phys. **26**, 2266 (1999); 10.1118/1.598740

[Time-to-digital converter of very high pulse stretching ratio for digital storage oscilloscopes](#)

Rev. Sci. Instrum. **70**, 1568 (1999); 10.1063/1.1149626

Re-register for Table of Content Alerts

Create a profile.

Sign up today!

A seamless acquisition digital storage oscilloscope with three-dimensional waveform display

Kuojun Yang,^{1,2,a)} Shulin Tian,¹ Hao Zeng,¹ Lei Qiu,² and Lianping Guo^{1,2}

¹*School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China*

²*School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore*

(Received 26 December 2013; accepted 17 March 2014; published online 3 April 2014)

In traditional digital storage oscilloscope (DSO), sampled data need to be processed after each acquisition. During data processing, the acquisition is stopped and oscilloscope is blind to the input signal. Thus, this duration is called dead time. With the rapid development of modern electronic systems, the effect of infrequent events becomes significant. To capture these occasional events in shorter time, dead time in traditional DSO that causes the loss of measured signal needs to be reduced or even eliminated. In this paper, a seamless acquisition oscilloscope without dead time is proposed. In this oscilloscope, three-dimensional waveform mapping (TWM) technique, which converts sampled data to displayed waveform, is proposed. With this technique, not only the process speed is improved, but also the probability information of waveform is displayed with different brightness. Thus, a three-dimensional waveform is shown to the user. To reduce processing time further, parallel TWM which processes several sampled points simultaneously, and dual-port random access memory based pipelining technique which can process one sampling point in one clock period are proposed. Furthermore, two DDR3 (Double-Data-Rate Three Synchronous Dynamic Random Access Memory) are used for storing sampled data alternately, thus the acquisition can continue during data processing. Therefore, the dead time of DSO is eliminated. In addition, a double-pulse test method is adopted to test the waveform capturing rate (WCR) of the oscilloscope and a combined pulse test method is employed to evaluate the oscilloscope's capture ability comprehensively. The experiment results show that the WCR of the designed oscilloscope is 6 250 000 wfms/s (waveforms per second), the highest value in all existing oscilloscopes. The testing results also prove that there is no dead time in our oscilloscope, thus realizing the seamless acquisition. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4869871>]

I. INTRODUCTION

Oscilloscope is an important time domain testing instrument.^{1,2} Digital storage oscilloscope (DSO) has replaced analog oscilloscope owing to its advantages in mathematical operations of waveform, LCD (Liquid Crystal Display) display, advanced trigger function, etc.³⁻⁶ However, it needs to process the sampled data after each acquisition. During data processing, the oscilloscope is blind to the measured signal and the phenomena during this period remain hidden to the user.⁷ This period is called bind time or dead time, which is longer in DSO than that of analog oscilloscope.

In Ref. 8, the loss waveform interval of microcomputer-based oscilloscope system is analyzed. It proves that the loss waveform interval will increase as the sampling rate increases. It also gives an explicit formula to calculate data loss probability. However, no solution is proposed to reduce the loss interval. Actually, as same as microcomputer-based oscilloscope system, normal DSO needs to process the sampled data after acquisition. In Ref. 8, the oscilloscope is used to measure repetitive "periodic" waveforms, so the loss waveform intervals due to state transition will not cause any serious problem from a steady-state point of view. However, with the rapid development of modern electronic systems, the

signals are becoming more and more complicated and their frequencies are getting higher and higher. Such increase of signal frequency reduces the time margin of signal. Moreover, jitter is more common in high speed electronic systems now. Therefore, not only repetitive periodic waveforms, but also random and infrequent events need to be tested with oscilloscopes, whose capability in capturing infrequent events are gaining more importance in modern electronic measurement.⁹

In oscilloscopes, a specification to evaluate the capability in capturing infrequent and elusive events is waveform capturing rate (WCR). Some manufactures call it waveform update rate. All the oscilloscope manufactures are trying their best to increase WCR. For example, Tektronix proposes DPX (Digital Phosphor technology (Tektronix)) to increase WCR. This technology is used in Digital Phosphor Oscilloscope (DPO).¹⁰ Agilent uses Mega Zoom technology in their InfiniiVision and Infinium series oscilloscopes to enhance WCR.¹¹ With the use of DPX and Mega Zoom technology, the WCR of Tektronix DPO70000 series oscilloscopes can reach 300 000 wfms/s (waveforms per second),¹² and the maximal WCR of Agilent oscilloscopes can reach 1 090 000 wfms/s.¹¹ The WCR of R&S RTO1000 series oscilloscopes is 1 000 000 wfms/s.¹³ Although the WCR of aforementioned oscilloscopes can reach 1 000 000 wfms/s, the dead time persists. Therefore, a seamless acquisition

^{a)}Author to whom correspondence should be addressed. Electronic mail: kuojunyang@gmail.com.

oscilloscope without dead time is urgently needed to meet the demand of modern measurement.

In this paper, a seamless acquisition digital storage oscilloscope with three-dimensional waveform display is proposed. Such an oscilloscope shows not only the signal's amplitude versus time, but also the signal's probability of occurrence in each point with variable brightness, and it is named digital three-dimensional oscilloscope (DTO). This paper is organized as follows. Section II introduces the definition of WCR and the relationship between dead time and WCR. The mathematic model and implementation method of three-dimensional waveform mapping (TWM) are presented in Sec. III. The techniques which help to eliminate the dead time of DTO are described in Sec. IV. Section V is devoted to the experimental and testing results, and Sec. VI is dedicated to the conclusion.

II. WAVEFORM CAPTURING RATE

In this section, the definition of WCR and ratio of dead time (RDT) are introduced first. Then, the relationship between WCR and RDT is explained. Subsequently, the definition of a seamless acquisition oscilloscope and the desired WCR for implementing a seamless acquisition oscilloscope are presented.

A. WCR and RDT

WCR is defined as the acquired and displayed waveform numbers in unit time. The calculation formula is given in (1), where t_{acq} is the acquisition time and t_{pro} is the process time. When the time-base is faster, t_{acq} is smaller, so WCR will get the maximum value in the fastest time-base with no interpolation (interpolation will take more time, and t_{pro} will be greater):

$$WCR = \frac{1}{t_{acq} + t_{pro}}. \quad (1)$$

Another concept related to WCR is RDT. RDT is defined as the ratio between dead time and acquisition period (the sum of acquisition time and dead time), and it is calculated as

$$RDT = \frac{t_{pro}}{t_{acq} + t_{pro}} \times 100\%. \quad (2)$$

As can be noted in Fig. 1, the acquisition time is $K \times T_s$ (K refers to the number of sampling points for a waveform in each acquisition, T_s refers to the sampling period of oscilloscope, which is the reciprocal of sampling rate), and the summation of the acquisition time and dead time is $1/WCR$. What is more, the dead time is

$$t_{pro} = 1/WCR - K \times T_s. \quad (3)$$

So, the relationship between RDT and WCR can be obtained by substituting (1) and (3) into (2):

$$RDT = \left(1 - \frac{K \times T_s}{1/WCR}\right) \times 100\%. \quad (4)$$

FIG. 1. Diagram of the dead time of oscilloscope.

The sampling rate of RTO1000 oscilloscope mentioned above is 10 GS/s, WCR is 1 000 000 wfms/s, and the waveform consists of 1000 sampling points in 10 ns/div. Thus, with the use of (4), we can obtain that the RDT of this oscilloscope is 90%. This result proves that although the WCR is as high as 1 000 000 wfms/s, RDT is still 90%.

B. WCR of seamless acquisition oscilloscope

The seamless acquisition oscilloscope can be defined as an oscilloscope that acquires waveform with no interval between two acquisitions in the real-time time-base (no interpolation is needed in those time-bases). Because the interpolation will take a long time, the definition of the seamless acquisition oscilloscope is constrained in the real-time time-base. As shown in Fig. 1, if dead time is zero, it can be called the seamless acquisition oscilloscope. If a seamless acquisition oscilloscope is to be realized, t_{pro} in (1) should be zero, and the WCR should be

$$WCR = \frac{1}{t_{acq}} = \frac{1}{K \times T_s}. \quad (5)$$

If the sampling rate of an oscilloscope is 10 GS/s, the displayed waveform consists of 1000 points, noting that the full waveform is displayed in the fastest real-time time-base. To realize a seamless acquisition oscilloscope, the maximum WCR should be 10 000 000 wfms/s. In addition, this result indicates that RTO1000 series oscilloscopes of R&S are not seamless acquisition oscilloscopes.

III. WAVEFORM MAPPING TECHNOLOGY FOR DTO

The conventional DSO processes sampled data with a serial architecture. In this architecture, the waveform is sampled and stored first, and then processed by MCU (Micro Controller Unit). When MCU is processing and displaying, new acquisition cannot start, so this time interval waiting for new acquisition is the dead time. In order to enhance the WCR of oscilloscope, a parallel structure is employed. In this architecture, a parallel coprocessor designed in field programmable gate array (FPGA) is added to process sampled data, and the MCU is utilized to respond to the user operation, control the oscilloscope, and display the operation interface. Accordingly, the waveform processing and displaying are not done by MCU anymore. In this way, the loop time of software

execution in MCU is reduced greatly. What is more, because the process speed of coprocessor implemented in FPGA is much faster than that of MCU, and sampled data can be processed parallelly in FPGA, the waveform process time of coprocessor will be much less than that of MCU. Thus, this architecture can reduce the dead time significantly.

As mentioned above, the coprocessor is used to process sampled data and convert them to the displayed waveform. TWM technique, which converts sampled data to displayed waveform, is proposed here to design a parallel coprocessor whose process speed is fast enough to realize the seamless acquisition oscilloscope. Therefore, in this section, the mathematic model of TWM is depicted first. Then, the realization of TWM is described, and the third part explains the waveform brightness adjustment method.

A. Mathematic model of TWM

After trigger and acquisition, K sampling points are got, which are denoted as $D_1, D_2, \dots, D_K$. Supposing the resolution of the analog to digital converter (ADC) in the oscilloscope is N , then

$$D_i \in (0, 2^N - 1) \quad i = 0, 1, \dots, K. \quad (6)$$

Modern oscilloscopes use LCD to display waveform. The display principle is that the whole screen is divided into some discrete dots, and each dot is assigned with a different color value. Therefore, a Graphic Digital Matrix (GDM) is constructed, in which each element corresponds to one dot in the LCD. Supposing K sample points are displayed in the LCD, then the GDM is depicted as (7), where the elements denote the signal's times of occurrence at each position:

$$A = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1K} \\ a_{21} & a_{22} & \dots & a_{2K} \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & a_{mK} \end{pmatrix}_{2^N \times K}. \quad (7)$$

Oscilloscope is a time domain instrument which displays the waveform in the form of time-amplitude. Therefore, a group of amplitude vectors with 2^N dimension is defined, and the expression is shown as

$$\alpha_1 = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 1_{D_1} \\ 0 \\ \vdots \\ 0 \end{pmatrix}, \alpha_2 = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 1_{D_2} \\ 0 \\ \vdots \\ 0 \end{pmatrix}, \dots, \alpha_K = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 1_{D_K} \\ 0 \\ \vdots \\ 0 \end{pmatrix}. \quad (8)$$

In (8), every vector has 2^N elements, and the value of each element is 0 or 1. The D_i th element of the vector α_i is 1, others are 0.

Furthermore, a matrix A_m which represents the TWM result of one waveform is defined in (9). It has 2^N rows which correspond to the voltage level of the sample. The i th column of A_m corresponds to the i th sample in the waveform. As can be noted, A_m is composed of the amplitude vectors

0	2^N	$\dots$	$(K-1)2^N$	a_{11}	a_{12}	$\dots$	a_{1K}
1	$2^N + 1$	$\dots$	$(K-1)2^N + 1$	a_{21}	a_{22}	$\dots$	a_{2K}
$\dots$	$\dots$	$\dots$	$\dots$	$\dots$	$\dots$	$\dots$	$\dots$
$2^N - 1$	$2 \cdot 2^N - 1$	$\dots$	$K \cdot 2^N - 1$	a_{m1}	a_{m2}	$\dots$	a_{mK}
Address				Data			

FIG. 2. The corresponding relationship between address and data of GDM.

defined in (8):

$$A_m = \begin{pmatrix} 0 & 0 & \vdots & 0 \\ 0 & 0 & \vdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 1_{D_1} & 1_{D_2} & \vdots & 1_{D_K} \\ 0 & 0 & \vdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \vdots & 0 \end{pmatrix} = (\alpha_1, \alpha_2, \dots, \alpha_K). \quad (9)$$

After M acquisitions, the result of TWM is

$$A = \sum_{m=1}^M A_m. \quad (10)$$

In the GDM A obtained by (10), the summation of all the elements in each column will be M , and there is at least one non-zero element in each column.

B. Realization of TWM

The TWM is a matrix solving process and the whole process consists of decoding operation and accumulation, both of which can be easily realized in FPGA. Block RAM (random access memory) in FPGA is used to store GDM, and the address and data of this block RAM are organized as Fig. 2.

Actually, as shown in (9), the TWM result of one acquisition is a sparse matrix with finite nonzero elements in it. Supposing that in one acquisition, the value of the j th sampling point is i , then the address of the nonzero element can be calculated by (11):

$$Addr = 2^N \times (j - 1) + i. \quad (11)$$

After the address of this nonzero element is calculated, the previous TWM result is read from this address, added by one, and then written back to the block RAM in the same address. This process is repeated until all sampling points are mapped. The flow chart is shown in Fig. 3.

C. The waveform brightness adjustment method

After a period of time, the GDM is ready. Before converting the GDM to displayed waveform, it needs to be converted to color information, which is called waveform brightness adjustment.

FIG. 3. Flow chart of three-dimensional waveform mapping.

If the maximum value in GDM shown in (7) is $a_{\max}$, the probability of a_{ij} is

$$p_{ij} = a_{ij}/a_{\max}. \quad (12)$$

FIG. 5. Principle of ping-pong operation.

FIG. 4. The curve of P^γ with different values of γ .

Based on (12), the GDM can be converted to probability information matrix (PIM):

$$P = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1K} \\ p_{21} & p_{22} & \cdots & p_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mK} \end{pmatrix}_{2^N \times K}. \quad (13)$$

Subsequently, Eq. (14) is used to convert the PIM to color information. In (14), C and γ are constants. C is the color value of the waveform display. For example, supposing a LCD with 24-bit color information is used, the high 8 bits, middle 8 bits, and low 8 bits of the color information refer to the red color, green color, and blue color, respectively. When waveform color is red, the high 8 bits of C are all one and other 16 bits of C are all zero. That means C can be represented by hexadecimal notation, i.e., $C = FF0000$:

$$B_{ij} = C P_{ij}^\gamma. \quad (14)$$

The curves of P^γ with different values of γ are shown in Fig. 4. Different function relationships between probability and brightness can be obtained by adjusting γ . If $\gamma = 1$, the relationship between B_{ij} and P_{ij} is linear, and the brightness grade will be changed evenly with P_{ij} . If $\gamma < 1$, more brightness grades are used to display small probability event and the resolution of small probability event is higher. If $\gamma > 1$, more brightness grades are used to display high probability event and the resolution of high probability event is higher. User can select the value of γ according to measured waveform.

FIG. 6. Block diagram of parallel TWM.

IV. TECHNIQUES FOR SEAMLESS ACQUISITION DTO

TWM described in Sec. III can reduce the dead time in oscilloscopes, however, it does not eliminate the dead time. In this section, the techniques that eliminate the dead time entirely are discussed.

A. Ping-pong operation

As shown in (5), to realize a seamless acquisition oscilloscope, t_{pro} should be zero. However, no matter how fast the process speed is, t_{pro} will not be zero. Therefore, ping-pong operation is utilized to acquire and process the waveform. The work process is illustrated in Fig. 5. There are two memories named M1 and M2 in the system. During t_1 , sampled data are stored into M1 until it is full. During t_2 , sampled data are stored into M2, and meanwhile, the sampled data stored in M1 during t_1 are processed. Then, during t_3 , sampled data are stored to M1 again, and sampled data stored in M2 during t_2 are processed at the same time, and so forth.

To realize seamless acquisition, the process time and the acquisition time must meet the inequality shown in (15):

$$t_{map} + t_{display} \leq t_{acquisition}. \quad (15)$$

B. Parallel TWM technique

In order to reduce t_{map} , a parallel TWM technique is proposed. Amplitude vectors in (8) are divided into N_D groups and then regrouped, as shown in (16), where the subscript i

refers to the i th sample and $K \bmod N_D = 0$ (mod is the modular operator):

$$\begin{aligned} \mathbf{S}_{1i} &= (\alpha_1, \alpha_{N_D+1}, \dots, \alpha_{k-N_D+1}), \\ \mathbf{S}_{2i} &= (\alpha_2, \alpha_{N_D+2}, \dots, \alpha_{k-N_D+2}), \\ &\vdots \\ \mathbf{S}_{N_D i} &= (\alpha_{N_D}, \alpha_{2N_D}, \dots, \alpha_k). \end{aligned} \quad (16)$$

The N_D groups are processed simultaneously. After M acquisitions, the TWM result of the p th group is

$$\mathbf{A}_p = \sum_{i=1}^M \mathbf{S}_{pi}, \quad (17)$$

where $1 \leq p \leq N_D$.

Then, the final result of M acquisitions can be obtained by regrouping all the N_D matrixes shown in (17), and it is represented as (18). In (18), $K_e = K/N_D$, and $\mathbf{A}_{ij}$ represents the j th column of the matrix $\mathbf{A}_i$ calculated by (17):

$$\begin{aligned} \mathbf{A} &= (\mathbf{A}_{11}, \mathbf{A}_{21}, \dots, \mathbf{A}_{N_D 1}, \mathbf{A}_{12}, \mathbf{A}_{22}, \dots, \mathbf{A}_{N_D 2}, \dots \\ &\times \mathbf{A}_{1K_e}, \mathbf{A}_{2K_e}, \dots, \mathbf{A}_{N_D K_e}). \end{aligned} \quad (18)$$

It can be noted that every mapping module processes only K_e sampling points. Therefore, the total TWM time for one waveform is $K_e \times T_{map}$, that is shorter than $K \times T_{map}$ (T_{map} refers to process time of one point). With greater N_D , time used for mapping one waveform will be shorter. The block diagram of parallel TWM is shown in Fig. 6. In Fig. 6, DGP is digital graphic processor where TWM is executed.

C. Pipelining technique reducing mapping time

With the use of ping-pong operation and parallel TWM technique, inequality (15) can be rewritten as

$$\frac{L}{N_D} \times T_{map} + R_x \times R_y \times T_{disp} \leq L \times T_s. \quad (19)$$

In (19), L represents the number of sampling points stored in each memory, R_x and R_y denote the horizontal and vertical resolution of waveform display, respectively, and T_{disp} represents the period of display clock.

FIG. 7. Pipelining technique for TWM based on dual-port RAM.

FIG. 8. Diagram of segmented storage based on DDR3.

Increasing N_D or decreasing T_{map} will facilitate to meet (19). Because increasing N_D needs more resources, minimizing T_{map} is preferred.

According to Fig. 3, GDM should be read and written in the process of TWM. If the process is done in sequence as the flow chart shows, T_{map} will be three clock periods. To reduce T_{map} , pipelining technique is employed and it is shown in Fig. 7. The GDM is built in the form of dual-port RAM, so that it can be read and written simultaneously. During t_1 , the first sampling point D1 is ready to be processed. During t_2 , D2 is ready, and A1, the mapping address of D1, is obtained. During t_3 , D3 and A2 are obtained, meanwhile, previous result PR1 in A1 is read out from GDM. In clock period t_4 , D4, A3, and PR2 are obtained, and the updated result UR1 obtained by adding one to PR1 is written back to GDM in A1 at the same time. With the use of pipelining technique and dual-port RAM, each sampling point can be processed in one clock period.

D. Segmented storage and compressive mapping

TWM is based on the accumulation of large number of waveforms. Hence, if there is only one waveform stored, after the TWM is finished, there will be no more waveform to be processed, and the efficiency of the total system decreases. Consequently, DDR3 (Double-Data-Rate Three Synchronous Dynamic Random Access Memory) is adopted to store more waveforms.

DDR3 is divided into several regions based on time-base. In each region, the waveforms with the same trigger condi-

tion are stored. When DDR3 is full, the sampled data are processed with TWM technique. This is named segmented storage and it is shown in Fig. 8. L_d refers to the number of sampling points in each region, and it varies with the time span of displayed waveform (all the acquisition waveforms are displayed). The relation between L_d and the time span T_{span} is shown in (20):

$$L_d = \frac{T_{span}}{T_s}. \quad (20)$$

There are two benefits to realize segmented storage by using DDR3. One is that a great number of waveforms are stored in memory, hence, when an abnormal waveform is found in the screen, the acquisition of oscilloscope can be paused to analyze the stored waveform. If only one waveform is stored, after it is displayed on screen, the memory may be rewritten and the original data are covered, consequently, the waveform cannot be analyzed again. The other is that it can increase storage length, which is an important specification of oscilloscope. If the storage length is short, when oscilloscope is in slow time-base, sampling rate has to be reduced to meet sampling time requirement, causing loss of some waveform information.

When oscilloscope is in slow time-base, storage length L_d is larger than the columns of waveform display area in screen. In order to display all the sampling points on screen, compressive mapping is used. Setting R_d as the columns of waveform display area on screen, and R_c is the ratio between L_d and R_x :

$$R_c = \frac{L_d}{R_d}. \quad (21)$$

FIG. 9. Block diagram of the proposed seamless acquisition DTO.

TABLE I. FIFO construction and occupied RAM.

	Width	Depth	Occupied RAM
FIFO1	64 bit	16K	1 048 576 bits
FIFO2	64 bit	16K	1 048 576 bits
FIFO3	64 bit	4K	262 144 bits
FIFO4	256 bit	4K	1 048 576 bits

In TWM process, R_c sampling points are mapped into the same column. This is called compressive mapping.

V. EXPERIMENTS

A. Implementation of seamless acquisition DTO

A seamless acquisition DTO whose circuit is mainly composed of ADC, FPGA, DDR3, static random access memories (SRAM), and digital signal processor (DSP) is implemented, and its block diagram is shown in Fig. 9.

The sampling rate of proposed DTO is 5 GS/s, and as most of the other oscilloscopes, the vertical resolution of proposed DTO is 8-bit. As we know, two main specifications of ADC are sampling rate and resolution. Accordingly, an ADC whose part number is EV8AQ160 is chosen. Its sampling rate is 5 GS/s, with 8-bit resolution. This ADC owns the highest sampling rate in all the mature ADC products, and it is the only one which can satisfy the design demand of proposed DTO.

A FPGA of Xilinx, part number of which is XC6VLX240T, is chosen to implement the proposed method for seamless acquisition. The selection of FPGA is decided by the block RAM resources of FPGA, the I/O (input/output) number, and I/O speed. First, the block RAM resource is considered. As depicted in (7), the GDM have $2^N \times K$ elements (noting that this big GDM is divided into 32 small GDMs in Fig. 9 because of parallel TWM). Therefore, the total block RAM resource used for constructing one GDM can be calculated as

$$RAM_t = 2^N \times K \times N_{BG} \text{ bits}, \quad (22)$$

where N_{BG} refers to the RAM resources occupied by each element in GDM. There are 256 brightness grades (0–255) in proposed DTO, and 255 can be represented by an 8-bit binary code, thus, N_{BG} is 8. In our oscilloscope, K is equal to 800 and N is equal to 8. What is more, when oscilloscope is working in “zoom mode,” the original waveform and its zoomed waveform are displayed simultaneously, so, two GDMs are needed for one analog channel. There are two analog channels in our oscilloscope. Thus, 4 GDMs are needed and 6 553 600 bits RAM is needed for GDMs.

Besides GDM, FIFO (first in first out) is also constructed by block RAM. As noted in Fig. 9, there are four FIFOs in proposed DTO. The depth of each FIFO is determined by the sampling point number for further process after FIFO, and the width of FIFO is determined by the data stored in FIFO. The width, depth, and occupied RAM of each FIFO are listed in Table I, from which we can obtain the total block RAM

TABLE II. The needed resources and usable resources in XC6VLX240T.

	Needed resource	Usable resource
I/O number	41 8	600
I/O speed	625 Mb/s	1.2 Gb/s
DDR3 interface speed	800 Mb/s	800 Mb/s
RAM	9 941 472 bits	14 976 000 bits

for FIFO is 3 407 872 bits. Thus, 9 961 472 bits block RAM resource is needed in the design.

Second, I/O number and I/O speed are considered. As can be noted in Fig. 9, ADC, two DDR3s, two SRAMs, DSP, and LCD are connected to the FPGA. The pin numbers of all the devices connected to FPGA is 418. The transmission speed of sampled data from ADC is 625 Mb/s, and the data speed of DDR3 is 800 MHz.

In summary, the needed resources and usable resources in XC6VLX240T are listed in Table II. As can be seen in Table II, XC6VLX240T can meet the design requirement. Accordingly, after considering I/O number, I/O speed, block RAM resources, and the convenience of purchase and use, XC6VLX240T is selected.

Two DDR3 are used to store sampled data with ping-pong operation. Thirty-two sampling points will be obtained from DDR3 in one clock period. For simplicity, N_D is chosen as 32. The read clock period of DDR3 is 5 ns. Since the DDR3 read clock is used to process the sampled data, T_{map} is also 5 ns. The sampling rate of the oscilloscope is 5 GS/s, with T_s is 200 ps. R_x is 800, R_y is 200, and T_{disp} is 10 ns. The storage length L is set to 128 Mpts, which is proper for display. In this way, the value of left part in (19) is 21.6 ms, and the value of right part in (19) is 25.6 ms, which meets the inequality shown in (19).

B. Double-pulse test method

To prove that the oscilloscope is a seamless acquisition DTO, the double-pulse test method and the combined pulse test method are employed. First, the double-pulse test method is adopted to test the maximum WCR of the system. The double-pulse shown in Fig. 10 is input signal. The width of the first pulse is T_1 , and the width of the second pulse is T_2 . The time interval between the rising edges of two pulses is ΔT .

FIG. 10. Diagram of double-pulse waveform.

FIG. 11. An acquisition system has dead time but cannot be tested by the double pulse method.

To test the WCR of oscilloscope, double-pulse shown in Fig. 10 is generated by arbitrary waveform generator. T_1 and T_2 are kept shorter than the time span of displayed waveform. The trigger mode of oscilloscope is set to normal, and the trigger level is adjusted to a proper position in which the input signal can be triggered. Then, the double-pulse is output only once. If two pulses are captured, reduce ΔT until the second pulse cannot be captured. Thus, the minimum time interval for capturing two pulses, $\Delta T_{\min}$, is obtained. Actually, $\Delta T_{\min}$ is the summation of acquisition time and dead time of oscilloscope, therefore, the maximal WCR can be calculated by

$$WCR = \frac{1}{\Delta T_{\min}}. \quad (23)$$

C. Combined pulse test method

The maximal WCR can be measured by the double-pulse test method, but the double-pulse test method cannot evaluate the oscilloscope comprehensively. For example, as shown in Fig. 11, n waveforms are acquired without dead time, and then the sampled data are processed and displayed. For such an acquisition system, when the double-pulse mentioned above is input, both pulses will be captured. Therefore, the dead time in such an oscilloscope cannot be tested by the double-pulse test method.

The combined pulse test method is used to evaluate the oscilloscope comprehensively. The test waveform is shown in Fig. 12, where the pulses are comprised of many groups, and the pulse interval is taken by the double-pulse test method. In the first group, the pulse width is $W_{\min}$ and the amplitude of the first pulse is $A_{\min}$. The amplitudes of other pulses increase linearly with increment of ΔA . When the amplitude reaches $A_{\max}$, one group of pulses is finished. The pulse width of each

group increases linearly too, and the increment is ΔW . Let the pulse width of last group is $W_{\max}$, then the total time length of the pulses is

$$T_{all} = \Delta T_{\min} \times \left(\frac{A_{\max} - A_{\min}}{\Delta A} + 1 \right) \times \left(\frac{W_{\max} - W_{\min}}{\Delta W} + 1 \right). \quad (24)$$

If there is no dead time in the time range of T_{all} , all the pulses can be captured and displayed. Conversely, if dead time exists in the time range of T_{all} , some pulses cannot be captured.

In some cases, the testing time range will be longer than T_{all} , but pulses number is limited. In order to conduct testing at a wide time range, the regularity of each acquisition process under the normal trigger mode can be utilized. Several sections of pulse waveforms on interleaved time shown in Fig. 13 can be generated to meet the requirements for testing of acquisition process at a wide time range. Input these sections of pulse waveforms to oscilloscope for the test, respectively. If some pulses are not captured when measuring the n th section of pulse, we can judge that the dead time exists in the time range $[(n-1) \times T_{all}, n \times T_{all}]$. Conversely, if all the pulses in each section are captured, we can conclude that it is seamless in the tested time range.

D. Testing results

The double-pulse test method is used to test the proposed DTO. The obtained $\Delta T_{\min}$ is $0.16 \mu s$. Therefore, the maximal WCR of proposed DTO is 6 250 000 wfms/s. The WCR of DPO can reach 400 000 wfms/s,¹⁴ and the WCR of RTO1000 is 1 000 000 wfms/s. Therefore, the WCR of proposed DTO is much higher than that of DPO and RTO1000.

In this design, T_s is 200 ps, and the fastest real-time time-base is 10 ns/div. In 10 ns/div, the displayed waveform consists of 800 points, and the full waveform is displayed. Thus,

FIG. 12. Diagram of combined pulse.

FIG. 13. Multiple sections of combined pulse suitable for the test of different time ranges.

the maximal WCR of a seamless acquisition oscilloscope calculated by (5) is 6 250 000 wfms/s. The measured WCR is also 6 250 000 wfms/s, satisfying the demand of a seamless acquisition oscilloscope.

After the maximal WCR of each oscilloscope is obtained, the combined pulse test method is employed to evaluate the oscilloscopes' WCR in a long time. As mentioned above, the storage length is 128 Mpts, and the sampling period of proposed DTO is 200 ps. Two DDR3 are used to store the sampling points. Therefore, the test time range is

$$T_{\text{test}} = 2 \times 200 \text{ ps} \times 128\text{M} = 51.2 \text{ ms}. \quad (25)$$

The test time range is so long that a lot of combined pulses as shown in Fig. 13 have to be generated. Each section of combined pulse consists of 135 pulses with 15 different widths and 9 different voltages, and the time interval between two adjacent pulses is 160 ns. Thus, the time length of each section of combined pulse is

$$T_{\text{all}} = 160 \text{ ns} \times 15 \times 9 = 21.6 \mu\text{s}. \quad (26)$$

To prove the seamless acquisition property in the time range of 51.2 ms, 2000 sections of combined pulse must be generated to test the DTO. This test is very complicated, and takes a long time. However, due to the similarity of the combined pulse, the pulses can be generated automatically by combined pulse waveform generation software written by us. This reduces the test time greatly. Due to the principle of TWM, the similarity of the combined pulse and the seamless acquisition property of our system, displayed waveforms of 2000 tests are the same. If dead time exists in the system, some pulses will be lost, and the displayed waveforms will not be the same. Fig. 14 shows the displayed waveform. It is formed by TWM, which adds up the 135 pulses with different widths and voltages to generate one displayed waveform. Because the time interval between two adjacent pulses is 160 ns, and the time span of displayed waveform is 160 ns too, if dead time exists in oscilloscope, after 160 ns acquisition time, the acquisition will stop until the sampled data are processed, then when the next pulse is generated, it will be missed. It can be noted that in Fig. 14, all the 135 pulses are captured and displayed, which proves that the deigned oscilloscope is seamless.

FIG. 14. Combined pulse captured by the proposed seamless acquisition oscilloscope.

FIG. 15. Captured combined pulse by RTO1012.

FIG. 16. The display effect of the proposed seamless acquisition DTO when FM wave is input.

Conversely, when dead time exists in oscilloscope, some pulses cannot be captured and displayed, such as Fig. 15, which shows the combined pulse captured by RTO1012. The combined pulse consists of 81 pulses with 9 different amplitudes and 9 different widths. The pulse widths are 10 ns, 20 ns, ..., 90 ns, respectively, and the pulse amplitudes are 50 mV, 100 mV, ..., 450 mV, respectively. The time interval between two adjacent pulses is 1 μ s (the reciprocal of the maximal WCR of RTO1012). It can be noted that 9 pulses whose width is 20 ns are all missed, and the pulses whose width is 10 ns are also missed except for the first pulse whose amplitude is 50 mV.

Fig. 16 shows the waveform of seamless acquisition DTO with a frequency modulated (FM) wave input. The waveform is shown with three-dimensional effect. The brightness of the waveform at each point is proportional to the probability of signal's occurrence at that position.

Table III shows the comparison of proposed DTO and other oscilloscopes proposed in Refs. 8 and 15–18. Two main aspects are compared. One is whether the oscilloscope has three-dimensional display effect, and the other is whether dead time exists in that oscilloscope. Table III shows

TABLE III. Comparison of different oscilloscopes.

Type of oscilloscope	Three-dimensional display effect	Dead time
Microcomputer-based oscilloscope ⁸	No	Exist
PC-based virtual oscilloscope ¹⁵	No	Exist
Virtual oscilloscope ¹⁶	No	Exist
DAQ card base virtual oscilloscope ¹⁷	No	Exist
Digital storage oscilloscope card ¹⁸	No	Exist
Proposed DTO	Yes	Do not exist

that the proposed DTO is the only oscilloscope with three-dimensional display effect, and dead time exists in all oscilloscopes except the proposed DTO.

VI. CONCLUSIONS

A seamless acquisition oscilloscope is proposed and implemented in this paper. This oscilloscope is implemented simply, with a lower cost. The proposed design demonstrates that digital oscilloscope can capture infrequent signals as quick as analog oscilloscopes, eliminating the only disadvantage of digital oscilloscope. It can be widely used in signal integrity testing and other testing occasion in which infrequent signal measurements are needed.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (No. 61301263), the Specialized Research Fund for the Doctoral Program of Higher Education of China (No. 20120185130002), and the Fundamental Research Fund for the Central University of China (Nos. A03007023801217 and A03008023801080). The research result has won the second prize of National Technological Invention Award of China in 2013. The authors would like to thank Dr. Libing Bai and Dr. Yijiu Zhao for informative discussion.

¹J. M. D. Pereira, *IEEE Instrum. Meas. Mag.* **9**(6), 27 (2006).
²M. R. Lombardi, *IEEE Aerosp. Electron. Syst. Mag.* **25**(7), 20 (2010).
³S. A. Khan, A. K. Agarwala, D. T. Shahani, and M. M. Alam, *IEEE Trans. Instrum. Meas.* **56**(3), 944 (2007).
⁴K. P. S. Rana, R. Singh, and K. S. Sayann, *Measurement* **43**(3), 299 (2010).
⁵S. A. Khan, A. Nigam, A. K. Agarwala, and M. S. Thomas, *Sens. Transducers J.* **112**(1), 95 (2010).
⁶K. P. S. Rana, R. Singh, and K. S. Sayann, *IEEE Trans. Instrum. Meas.* **59**(6), 1652 (2010).
⁷M. D'Arco, M. Genovese, E. Napoli, and M. Vadursi, *IEEE Trans. Instrum. Meas.* **63**(2), 287 (2014).
⁸Y.-W. Bai and H.-G. Wei, *IEEE Trans. Instrum. Meas.* **54**(1), 45 (2005).
⁹X. Cheng, X. Tian, M. Zeng, and X. Han, *IEEE Trans. Nucl. Sci.* **57**(2), 539 (2010).
¹⁰See http://www.tek.com/dl/55W_13757_0.pdf for Tektronix, technical brief, "Third-Generation Digital Phosphor Oscilloscopes Deliver Unprecedented Waveform Visualization."
¹¹See <http://cp.literature.agilent.com/litweb/pdf/5991-1024EN.pdf> for Agilent, application note, "Oscilloscope Memory Architectures—Why All Acquisition Memory is Not Created Equal."
¹²See <http://www.tek.com> for Tektronix, DPO70000, data-sheet.
¹³See <http://www.rohde-schwarz.com> for Rohde-Schwarz, RTO1012, data-sheet.
¹⁴G. Lizhong, H. Binjie, and Y. Jixiang, in *Proceedings of the ICEMI 2007* (IEEE, 2007), p. 1-644.
¹⁵C. Bhunia, S. Giri, S. Kar, S. Haldar, and P. Purkait, *IEEE Trans. Edu.* **47**(2), 295 (2004).
¹⁶P. Gong and W. Zhou, *Procedia Eng.* **29**, 3245 (2012).
¹⁷K. P. S. Rana and S. H. Khan, *Measurement* **41**(9), 1032 (2008).
¹⁸H. Zhiqiang, F. Guonan, and Z. Jingzhi, in *Proceedings of the ICEMI 2011* (IEEE, 2011), p. 346.