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[Continued on nextpage]

(54) Title: SYSTEM AND METHODS FOR PRODUCING AN IMAGE FROM A ROTATIONAL INTRAVASCULAR ULTRASOUND DEVICE

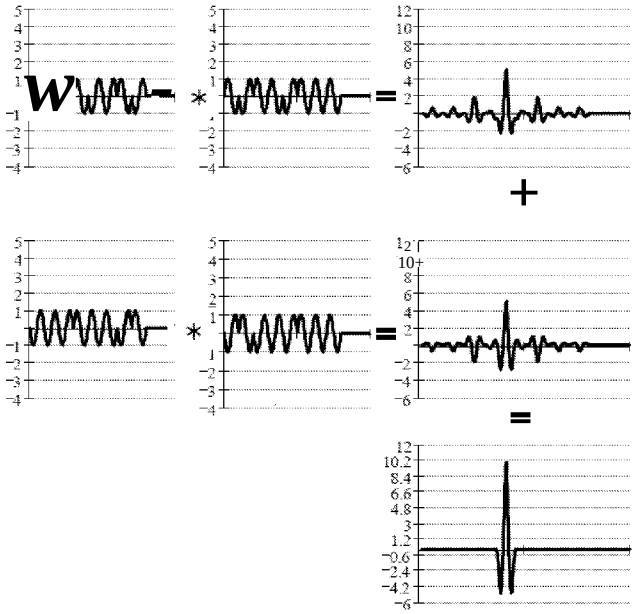

FIG. 1

(57) Abstract: The invention generally relates systems and methods to for producing an image from a rotational intravascular ultrasound device. In ultrasound imaging, spatial resolution and depth penetration are important parameters to quantitatively assess image quality. Generally, the wavelength at the ultrasound center frequency determines spatial resolution, with revolution improving as the frequency increases. However, tissue attenuation typically increases as a linear function of frequency, even becoming nonlinear at higher frequencies (e.g., greater than 40 MHz) commonly employed in intravascular ultrasound imaging applications.

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SYSTEMS AND METHODS FOR PRODUCING AN IMAGE FROM A ROTATIONAL INTRAVASCULAR ULTRASOUND DEVICE

Related Application

The present application claims the benefit of and priority to U.S. provisional patent application serial number 61/778,757, filed March 13, 2013, the content of which is incorporated by reference herein in its entirety.

Field of the Invention

The invention generally relates to systems and methods to for producing an image from a rotational intravascular ultrasound device.

Background

In ultrasound imaging, spatial resolution and depth penetration are important parameters to quantitatively assess image quality. Generally, the wavelength at the ultrasound center frequency determines spatial resolution, with revolution improving as the frequency increases. However, tissue attenuation typically increases as a linear function of frequency, even becoming nonlinear at higher frequencies (e.g., greater than 40 MHz) commonly employed in intravascular ultrasound imaging applications. Although high frequency ultrasound facilitates high resolution imaging in the near field, the depth penetration may be compromised, rendering the deep tissue structures difficult to identify.

To enhance the depth penetration without the loss of spatial resolution, transmit voltage levels are typically increased to deliver more transmit energy to the imaging target. However, this approach is limited both by regulations of diagnostic medical ultrasound and by the nature of the intravascular ultrasound imaging environment, such as the long cable length between ultrasound transducer elements and imaging system electronics and the small size of electronics integrated with the catheter mounted transducer.

Rather than increasing the transmit voltage levels, coded excitation methods using elongated modulated transmit bursts have been employed to address the dilemma of maintaining depth of penetration while increasing operating frequency for improved spatial resolution. This method is called pulse compression. An ultrasound imaging apparatus using pulse compression

employs a coded long pulse instead of the conventional short pulse. One type of coded excitation methods uses Golay codes. A Golay code is a binary code modulated with a short burst. Two different binary code (of particular sequence) constitute a Golay pair. When two codes are separately decoded and summed, range sidelobes are completely eliminated with only the main lobe remaining. Due to that characteristic of Golay codes, there have been great endeavors to take advantage of Golay codes in ultrasound imaging apparatuses.

In practice, the range sidelobes are not completely removed, due to nonlinear propagation of ultrasound within tissue structures, motion artifacts, and other non-idealities. Particularly for rotational intravascular ultrasound, the continuous rotation causes a slight angular misalignment for adjacent A-scans used to produce a Golay pair, resulting in increased range sidelobe levels.

Summary

The invention uses short burst modulated Golay codes with a multi-beam approach to suppress the motion artifact in Golay code rotational intravascular ultrasound (IVUS). The multi-beam strategy for use with Golay codes involves alternately transmitting complementary Golay codes and then summing an odd number (greater than one) of weighted, decoded A-scans.

In certain aspects, the invention provides methods for producing an image from a rotational intravascular ultrasound device. The methods involve alternately transmitting complementary Golay codes to a plurality of transducers in an intravascular ultrasound device. Additionally, the methods involve receiving echoes of the complementary codes from the transducers and performing pulse compression of the echoes. The pulse compression involves weighting the received echoes and summing an odd number of weighted echoes, in which a center echo is given a weighted value of 1.0 and weighted sums of its neighbors constitute complementary echoes of a Golay pair. An image is produced from the compressed echoes, and that image may be displayed. Methods of the invention may additionally involve computing convolution of the received echoes of the complementary codes.

Any technique known in the art may be used to produce the Golay codes. In certain embodiments, the Golay codes are produced by applying a bi-phase window over the Golay codes. The bi-phase window may be one of a bi-phase rectangular window, a bi-phase Hamming window, a bi-phase Hanning window and bi-phase Bartlett window.

Another aspect of the invention provides a system for producing an ultrasound image from a rotational intravascular ultrasound device. The system includes a processor, and a plurality of beam modules coupled to the processor. Each module includes a receiver for receiving a trigger signal from the processor, a complex programmable logic device programmed with a Golay code, a high voltage switching transmitter, and an ultrasound transducer.

The processor alternately transmits trigger signals to the beam modules, thereby causing the beam modules to alternately transmit complementary Golay codes. The processor receives echoes of the complementary codes. The processor performs pulse compression of the echoes that includes weighting the received echoes and summing an odd number of weighted echoes, in which a center echo is given a weighted value of 1.0 and weighted sums of its neighbors constitute complementary echoes of a Golay pair. The processor produces an image from the compressed echoes. The processor is coupled to a display device and causes the image to be displayed.

Brief Description of the Drawings

FIG. 1 is a set of graphs showing the principle of side lobe cancellation using pair of Golay complementary sequences of length 8.

FIG. 2 illustrate a system of the invention.

FIG. 3 is a diagraph showing how methods of the invention are performed.

Detailed Description

The invention generally relates systems and methods to for producing an image from a rotational intravascular ultrasound (IVUS) device. Systems and methods of then invention are particularly useful for rotational IVUS. In a rotational IVUS catheter, a single transducer having a piezoelectric crystal is rapidly rotated (e.g., at approximately 1800 revolutions per minute) while the transducer is intermittently excited with an electrical pulse. The excitation pulse causes the transducer to vibrate, sending out a series of transmit pulses. The transmit pulses are sent at a frequency that allows time for receipt of echo signals. The sequence of transmit pulses interspersed with receipt signals provides the ultrasound data required to reconstruct a complete cross-sectional image of a vessel.

The general design and construction of rotational IVUS catheters is shown, for example in Yock, U.S. Pat. Nos. 4,794,931, 5,000,185, and 5,313,949; Sieben et al., U.S. Pat. Nos. 5,243,988, and 5,353,798; Crowley et al., U.S. Pat. No. 4,951,677; Pomeranz, U.S. Pat. No. 5,095,911, Griffith et al., U.S. Pat. No. 4,841,977, Maroney et al., U.S. Pat. No. 5,373,849, Born et al., U.S. Pat. No. 5,176,141, Lancee et al., U.S. Pat. No. 5,240,003, Lancee et al., U.S. Pat. No. 5,375,602, Gardineer et at., U.S. Pat. No. 5,373,845, Seward et al., Mayo Clinic Proceedings 71(7):629-635 (1996), Packer et al., Cardiostim Conference 833 (1994), "Ultrasound Cardioscopy," Eur. J.C.P.E. 4(2): 193 (June 1994), Eberle et al., U.S. Pat. No. 5,453,575, Eberle et al., U.S. Pat. No. 5,368,037, Eberle et at., U.S. Pat. No. 5,183,048, Eberle et al., U.S. Pat. No. 5,167,233, Eberle et at., U.S. Pat. No. 4,917,097, Eberle et at., U.S. Pat. No. 5,135,486, and other references well known in the art relating to intraluminal ultrasound devices and modalities. The catheter will typically have proximal and distal regions, and will include an imaging tip located in the distal region. Such catheters have an ability to obtain echographic images of the area surrounding the imaging tip when located in a region of interest inside the body of a patient. The catheter, and its associated electronic circuitry, will also be capable of defining the position of the catheter axis with respect to each echographic data set obtained in the region of interest.

Systems and methods of the invention use Golay codes. Use of Golay codes in ultrasound is described for example in U.S. patent numbers 7,535,797; 6,958,042; 6,663,565; 6,638,227; 6,491,631; 6,375,618; 6,350,240; 6,312,384; 6,210,332; 6,186,949; and 6,146,328, the content of each of which is incorporated by reference herein in its entirety.

Golay complementary sequences are pairs of binary codes, belonging to a bigger family of signals called complementary pairs, which consist of two codes of the same length N whose auto-correlation functions have side-lobes equal in magnitude but opposite in sign. Summing them up results in a composite auto-correlation function with a peak of 2N and zero side-lobes. Fig. 1 illustrates the principle of the side-lobe-canceling for a pair of signed of length equal to 8 bits each.

There are essentially several algorithms for generating Golay pairs.

Let the variables a_i and b_i (i=l,2,. ..n) are the elements of two n-long complementary series equal either '+l'or '-1', [3],

$$A = a_1, a_2, \ldots, a_n;$$
$$5 = ¾ b_2, \text{-}\ldots, \boldsymbol{b}_n. \qquad (1)$$

The ordered pair (A;B) are Golay sequences of length n if and only if their associated polynomials

$$A(x) = a_1 + a_2 x + \ldots + a_n x^{n-1},$$
$$B(x) = b_1 + b_2 x + \ldots + b_n x^{n-1}, \qquad (2)$$

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satisfy the identity

$$\boldsymbol{A(x)A(x^{-1}) + B(x)B(x^{-1}) = 2n} \qquad (3)$$

in the Laurent polynomial ring Z[x, x^{-1}].

Let their respectable auto-correlation functions NA and NB of the sequences A and B

10 respectively be defined by

$$N_A(j) = \sum_{i \in Z} a_i a_{i+j}$$
$$N_B(j) = \sum_{i \in Z} b_i b_{i+j} \qquad (4)$$

where we set $a_{¾} = 0$ if $k \notin$ (!...«). Now condition (3) can be expressed by the sum $N_A + N_B$, and

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$$N_A(j) + N_B(j) = \begin{cases} 2N, & j = 0 \\ 0, & j \neq 0 \end{cases} \qquad (5)$$

The sum of both autocorrelation function is at j=0 and zeroing otherwise.

The second, recursive method for constructing the Golay's sequences is presented below.

Let the variables a(i) and £>(i) be the elements (7=0,1,2,. . .2^n-l) of two complementary sequences with elements + 1 and - 1 of length 2^n

$$a_0(i) = \delta(i)$$
$$b_0(i) = \delta(i) \qquad (6)$$

$$a_n(?) = a_{n-1}(?) + b_{n-1}(i - 2^{n-1})$$
$$h_n(?) = a_{n-1}(?) - b_{n-1}(? - 2^{n-1}) \qquad (7)$$

where $\delta(i)$ is the Kronecker delta function.

Equation (7) shows that in each step the new elements of the sequences are produced by concatenation of elements $a_n(i)$ and $b_n(i)$ of the length n.

Example:

Let $n=l$, then i takes values 0 and 1.

$$a_1(0) = a_0(0) + b_0(-1) = 1;$$
$$b_1(0) = a_Q(0) - \&_0(-1) = I;$$
$$a_1(l) = a_0(l) + ¾(0) = 1;$$
$$b_1(l) = a_0(l) - ¾_0(0) = -1.$$

As final results we obtain two complementary sequences of the length 2^n:

$$a_1 = \{1, 1\};$$
$$b_1 = \{1, -1\}.$$

Once these operations are performed recursively for «=2,3,4. .. the following complementary sequences are obtained:

$$a_2 = \{1, 1, L -1\};$$

$$b_2 = \{1, 1, \sim 1, 1\}.$$

$$a_3 = \{1, L\ 1, -1, 1, L -L\ 1\};$$

$$b_3 = \{1, 1, 1, -1, -L -L\ 1, -1\}.$$

$$a_4 = \{1, 1, L -L\ L\ 1, -1, L\ 1, 1, 1, -1, -1, -1, 1, -1\};$$

$$b_4 = \{L\ L\ 1, -1, 1, L -L\ 1, -1, -1, -1, 1, L\ L -L\ 1\}.$$

Similar method of generating the complementary code pairs, differing only in the applied mathematical formalism has been described by Mendieta and al. (Complementary sequence correlations with applications to reflectometry studies, Instrumentation and Development, 3, 6, 1996), the content of which is incorporated by reference herein in its entirety.

FIGs. 2-3 illustrate systems and methods of the invention. The system includes a processor, and a plurality of beam modules coupled to the processor. Each module includes a receiver for receiving a trigger signal from the processor, a complex programmable logic device programmed with a Golay code, a high voltage switching transmitter, and an ultrasound transducer.

The processor alternately transmits trigger signals to the beam modules, thereby causing the beam modules to alternately transmit complementary Golay codes. In the first instance of ultrasound transmission, odd transducers of the transducer array transmit ultrasound pulse signals corresponding to first code sequence (Golay code 1 (Gl)). Even transducers the transducer array transmit ultrasound pulse signals corresponding to the second code sequence (Golay code 2 (G2)). Transmission of ultrasound pulse signals to a target object, such as a human body, and reception of reflected signals from the target object occur simultaneously. Switching between

even transducers and odd transducers of the transducer array with respect to corresponding Golay codes in the first and second ultrasound transmissions reduces the grating lobes. The grating lobe is the peak of a beam pattern generated when the ultrasound signals is supplemented in an unwanted way.

The processor receives echoes of the complementary codes. The processor performs pulse compression of the echoes that includes weighting the received echoes and summing an odd number of weighted echoes, in which a center echo is given a weighted value of 1.0 and weighted sums of its neighbors constitute complementary echoes of a Golay pair. For example, FIG. 3 shows that three beams are used for generating one composite Golay coded excitation scan line. The figure shows that each transmit signal is paired with a member of a Golay code. The system is set-up such that the pairs alternate (Gl, G2, Gl, G2, Gl, G2 etc). Looking at the top three beams as an example. The first scan line is produced by summing one member of the pair from Golay code 2 and both members of the pair of Golay code 1. A member of the pair of Golay code 2 is the center line with the pairs of Golay code 1 adjacent to the member of the pair of Golay code 2. The weighting for the center beam (Golay code 2) is 1.0, while the weights for the neighboring beams (Goley code pair Gl and Gl) are each 0.5. In this manner, the pair from Goley code 1 cancel each other, leaving only center line beam of the member of Goley code 2, thereby removing sidelobes for scanline 1 and eliminating motion artifacts for that scan line.

The process is then repeated for each scan line and image is assembled from the scan lines. The processor is coupled to a display device and causes the image to be displayed.

Incorporation by Reference

References and citations to other documents, such as patents, patent applications, patent publications, journals, books, papers, web contents, have been made throughout this disclosure. All such documents are hereby incorporated herein by reference in their entirety for all purposes.

Equivalents

Various modifications of the invention and many further embodiments thereof, in addition to those shown and described herein, will become apparent to those skilled in the art from the full contents of this document, including references to the scientific and patent literature cited herein. The subject matter herein contains important information, exemplification and

guidance that can be adapted to the practice of this invention in its various embodiments and equivalents thereof.

What is claimed is:

1. A method for producing an image from a rotational intravascular ultrasound device, the method comprising:

alternately transmitting complementary Golay codes to a plurality of transducers in a intravascular ultrasound device;

receiving echoes of the complementary codes from the transducers;

performing pulse compression of the echoes that comprises weighting the received echoes and summing an odd number of weighted echoes, wherein a center echo is given a weighted value of 1.0 and weighted sums of its neighbors constitute complementary echoes of a Golay pair; and

producing an image from the compressed echoes.

2. The method according to claim 1, further comprising displaying the image.

3. The method according to claim 1, wherein the Golay codes are produced by applying a bi-phase window over the Golay codes.

4. The method according to claim 3, wherein the bi-phase window is one of a bi-phase rectangular window, a bi-phase Hamming window, a bi-phase Hanning window and bi-phase Bartlett window.

5. The method according to claim 1, wherein the method further comprises computing convolution of the received echoes of the complementary codes.

6. A system for producing an ultrasound image from a rotational intravascular ultrasound device, the system comprising:

a processor; and

a plurality of beam modules coupled to the processor, each module comprising:

a receiver for receiving a trigger signal from the processor;

a complex programmable logic device programmed with a Golay code;

a high voltage switching transmitter; and

an ultrasound transducer.

7. The system according to claim 6, wherein the processor alternately transmits trigger signals to the beam modules, thereby causing the beam modules to alternately transmit complementary Golay codes.

8. The system according to claim 7, wherein the processor receives echoes of the complementary codes.

9. The system according to claim 8, wherein the processor performs pulse compression of the echoes that comprises weighting the received echoes and summing an odd number of weighted echoes, wherein a center echo is given a weighted value of 1.0 and weighted sums of its neighbors constitute complementary echoes of a Golay pair.

10. The system according to claim 9, wherein the processor produces an image from the compressed echoes.

11. The system according to claim 9, wherein the processor is coupled to a display device and causes the image to be displayed.

12. The system according to claim 11, wherein the Golay codes are produced by applying a bi-phase window over the Golay codes.

13. The system according to claim 12, wherein the bi-phase window is one of a bi-phase rectangular window, a bi-phase Hamming window, a bi-phase Hanning window and bi-phase Bartlett window.

14. The system according to claim 11, wherein the processor causes convolution of the received echoes of the complementary codes.

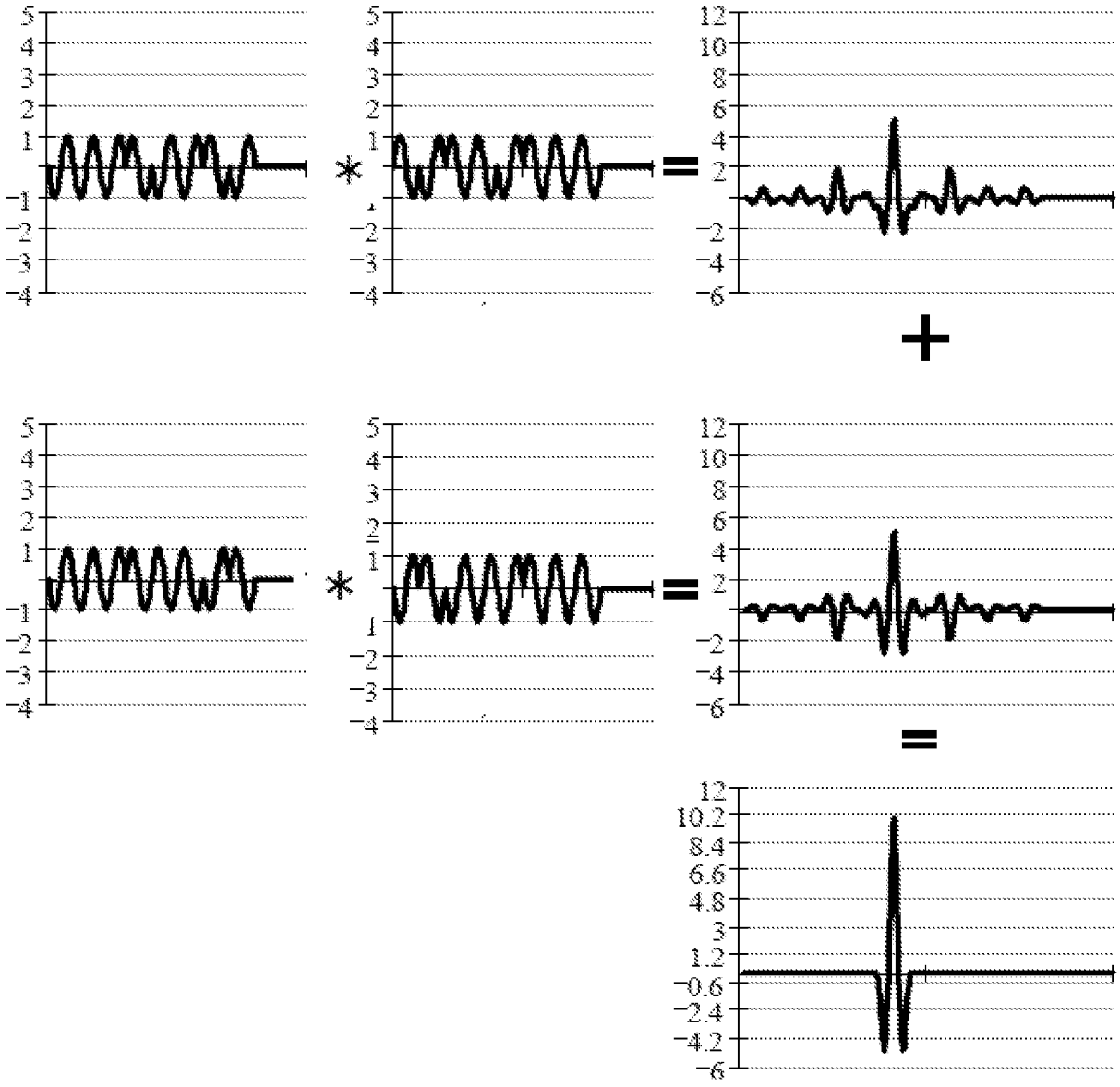

FIG. 1

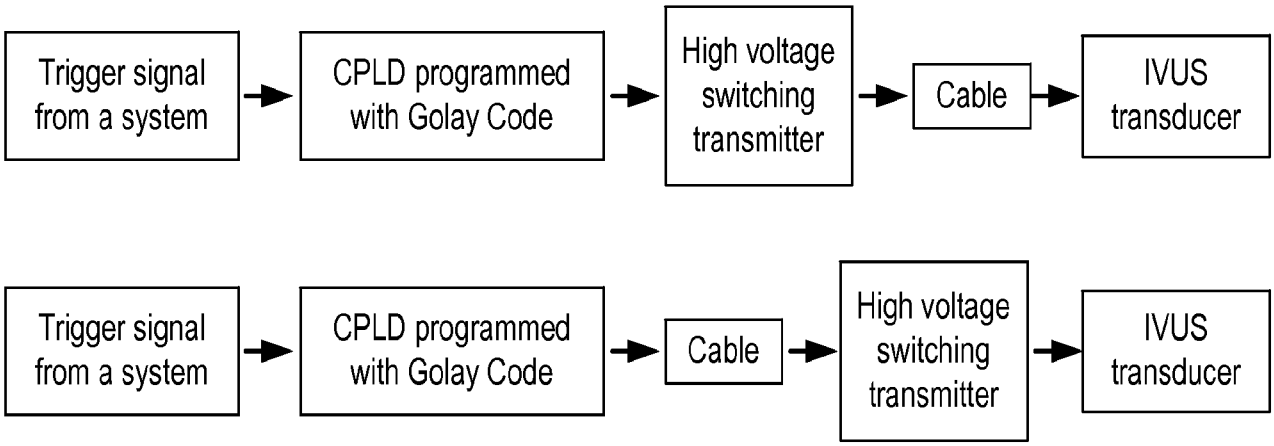
Trigger signal from a system
CPLD programmed with Golay Code
High voltage switching transmitter
Cable
IVUS transducer
Trigger signal from a system
CPLD programmed with Golay Code
Cable
High voltage switching transmitter
IVUS transducer

FIG. 2

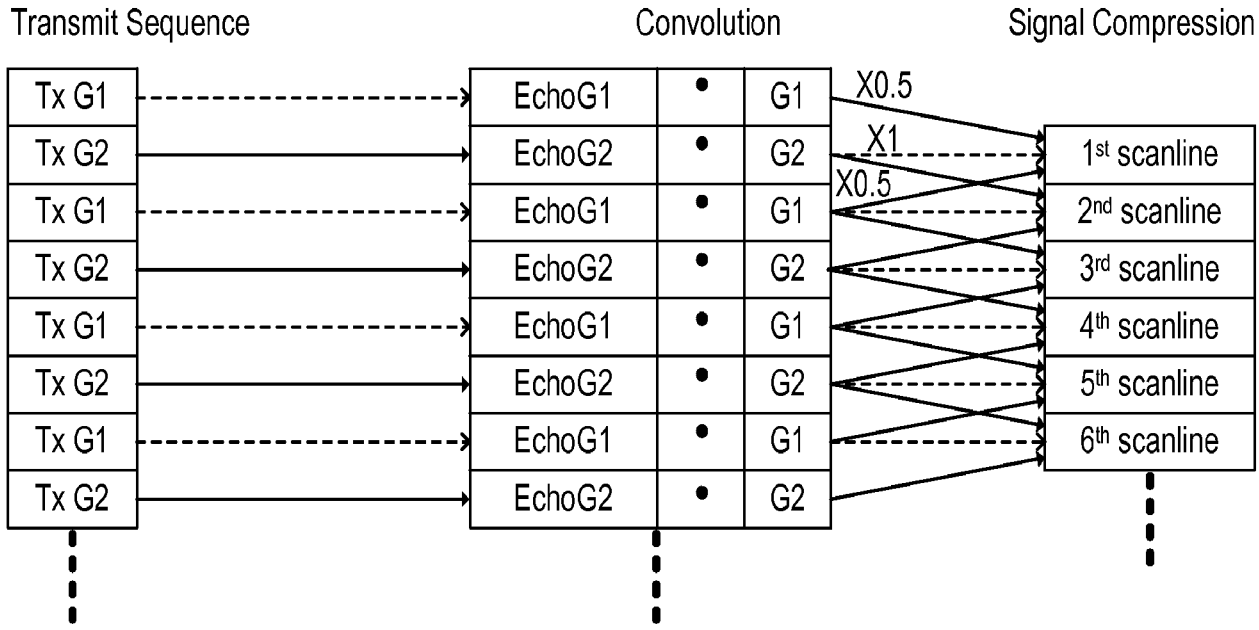
Transmit Sequence
Convolution
Signal Compression
Tx G1
Tx G2
Tx G1
Tx G2
Tx G1
Tx G2
Tx G1
Tx G2
EchoG1
EchoG2
EchoG1
EchoG2
EchoG1
EchoG2
EchoG1
EchoG2
G1
G2
G1
G2
G1
G2
G1
G2
X0.5
X1
X0.5
1st scanline
2nd scanline
3rd scanline
4th scanline
5th scanline
6th scanline

FIG. 3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/025253

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - A61B 8/00 (2014.01)
USPC - 600/443
According to International Patent Classification (IPC) or to both national classification and IPC

~B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - A61B 8/00, 8/06, 8/12; A61N 3/02; G01S 3/80 (2014.01)
USPC - 73/625, 627, 628; 128/916; 367/1; 600/437, 443, 444, 445, 447, 449

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
CPC - A61B 8/06, 8/0891, 8/12; A61N 7/00, 2007/0052 (2014.06)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatBase, Google Scholar, PubMed

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X -- Y	US 6,210,332 B1 (CHIAO et al) 03 April 2001 (03.04.2001) entire document	1-3, 5-12, 14 --- 4, 13
Y	US 6,350,240 B1 (SONG et al) 26 February 2002 (26.02.2002) entire document	4, 13
A	TROTS et al. 'Coded Transmission in Synthetic Transmit Aperture Ultrasound Imaging Method' World Academy of Science, Engineering and Technology; 24 March 2012; Vol. 6, pgs. 1-6	1-14
A	US 6,638,227 B2 (BAE) 28 October 2003 (28.10.2003) entire document	1-14

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29 June 2014	18 JUL 2014

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

专利名称(译)	用于从旋转血管内超声装置产生图像的系统和方法		
公开(公告)号	EP2967488A1	公开(公告)日	2016-01-20
申请号	EP2014774418	申请日	2014-03-13
[标]申请(专利权)人(译)	PARK JINHYOUNG CORL PAUL DOUGLAS		
申请(专利权)人(译)	PARK，JINHYOUNG CORL，PAUL DOUGLAS		
当前申请(专利权)人(译)	PARK，JINHYOUNG CORL，PAUL DOUGLAS		
[标]发明人	PARK JINHYOUNG CORL PAUL DOUGLAS		
发明人	PARK, JINHYOUNG CORL, PAUL DOUGLAS		
IPC分类号	A61B8/00 A61B8/08 A61B8/12 G01S7/52 G01S15/89		
CPC分类号	A61B8/4461 A61B8/0891 A61B8/12 A61B8/5207 A61B8/5276 G01S15/8956 G01S15/8961		
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摘要(译)

本发明一般涉及用于从旋转血管内超声装置产生图像的系统和方法。在超声成像中，空间分辨率和深度穿透是定量评估图像质量的重要参数。通常，超声中心频率处的波长确定空间分辨率，随着频率增加，旋转得到改善。然而，组织衰减通常作为频率的线性函数而增加，甚至在血管内超声成像应用中通常采用的较高频率（例如，大于40MHz）变为非线性。