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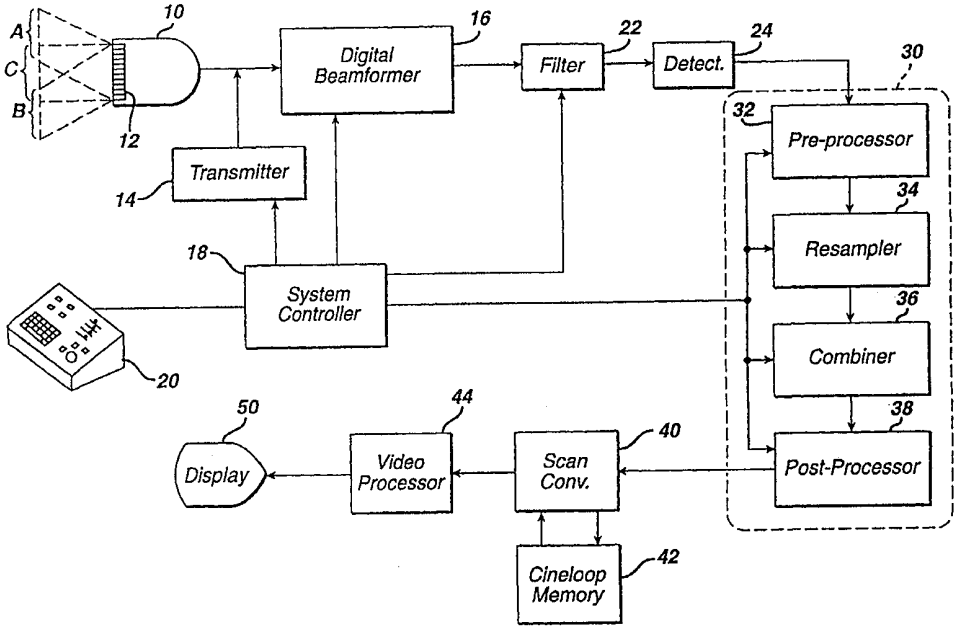
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(54) Title: ULTRASONIC DIAGNOSTIC IMAGING SYSTEM WITH VARIABLE SPATIAL COMPOUNDING



(57) Abstract

An ultrasonic diagnostic imaging system and method are described in which the number of acquired ultrasonic images which are compounded to form a spatially compounded image is variable. The number of acquired images which is compounded is varied in response to changes in system operating parameters initiated directly or indirectly by the system user.

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Ultrasonic diagnostic imaging system with variable spatial compounding.

Description

This application claims the benefit of Provisional U.S. Patent Application serial number 60/102,923, filed October 1, 1998.

This invention relates to ultrasonic diagnostic imaging systems and, in particular, to ultrasonic diagnostic imaging systems which produce spatially compounded images by combining a variable number of received images.

Spatial compounding is an imaging technique in which a number of ultrasound images of a given target that have been obtained from multiple vantage points or angles (look directions) are combined into a single compounded image by combining the data received from each point in the compound image target which has been received from each angle. Examples of spatial compounding may be found in US Patents 4649927; 4319489; and 4159462. Real time spatial compound imaging is performed by rapidly acquiring a series of partially overlapping component image frames from substantially independent spatial directions, utilizing an array transducer to implement electronic beam steering and/or electronic translation of the component frames. The component frames are combined into a compound image by summation, averaging, peak detection, or other combinational means. The acquisition sequence and formation of compound images are repeated continuously at a rate limited by the acquisition frame rate, that is, the time required to acquire the full complement of scanlines over the selected width and depth of imaging.

The compounded image typically shows lower speckle and better specular reflector delineation than conventional ultrasound images from a single viewpoint. Speckle is reduced (i.e. speckle signal to noise ratio is improved) by the square root of N in a compound image with N component frames, provided that the component frames used to create the compound image are substantially independent and are averaged. Several criteria can be used to determine the degree of independence of the component frames (see, e.g., O'Donnell et al. in IEEE Trans. UFFC v.35, no.4, pp 470-76 (1988)). In practice, for spatial compound imaging with a steered linear array, this implies a minimum steering angle between component frames. This minimum angle is typically on the order of several degrees.

The second way that spatial compound scanning improves image quality is by improving the acquisition of specular interfaces. For example, a curved bone-soft tissue interface produces a strong echo when the ultrasound beam is exactly perpendicular to the interface, and a very weak echo when the beam is only a few degrees off perpendicular. These interfaces are often curved, and with conventional scanning only a small portion of the interface is visible. Spatial compound scanning acquires views of the interface from many different angles, making the curved interface visible and continuous over a larger field of view. Greater angular diversity generally improves the continuity of specular targets. However, the angular diversity available is limited by the acceptance angle of the transducer array elements. The acceptance angle depends on the transducer array element pitch, frequency, and construction methods.

One of the problems associated with real time spatial compound imaging is that several image acquisitions are needed to produce each new compound image frame. The time needed to acquire a spatial compound image consisting of N component frames is approximately N times longer than that of each individual component frame. It is generally desirable to acquire a large number of component frames to maximize the image quality of the compound image. However, it is also generally desirable to maintain high compound image frame rates of display to facilitate real time examination, leading to a tradeoff between compound image quality and compound image frame rate.

In accordance with the principles of the present invention, the number of different look directions of a target which are compounded is variable in accordance with changes in ultrasound system operating parameters, either singly or in combination, which improves the performance of the spatial compounding system. These parameters include image display depth, acquisition rate, number of scanlines or line density, number of transmit focal zones, amount of deadtime per pulse repetition interval (PRI), number of transmissions per image line, depth of region of greatest compounding, clinical application, number of simultaneous modes, size of region of interest, and mode of operation (e.g., survey or target mode). In accordance with a preferred embodiment of the present invention, the steering angle(s) of the look directions are varied in response to changes in the image depth. In a constructed embodiment an ultrasonic transducer scans a target from a number of different perspectives. For example, several sector images can be sequentially acquired by a phased array transducer, each with an apex located at a different point in relation to the array. As a second example a steered linear array can be used to image the target with a sequence of groups of beams, each group steered at a different angle with respect to the axis of the array.

Thirdly, beams having no particular relationship to a frame or image format can interrogate targets in a region of the body from multiple directions, by the transmission of individual beams or multiple beams simultaneously. In either case the received images are processed in the usual way by beamforming and detection and stored in a memory. To form the compound image the component frames or target echoes to be combined are spatially aligned (if not already aligned by a common beam steering reference) by scan conversion or resampling. The common spatial locations in the image field are then compounded by averaging or summing and the resultant compound image is displayed.

In the drawings:

FIGURE 1 illustrates in block diagram form an ultrasonic diagnostic imaging system constructed in accordance with the principles of the present invention;

FIGURE 2 illustrates in block diagram form a preferred implementation of the spatial compounding processor of FIGURE 1; and

FIGURES 3a-3b illustrate the effects of increasing and decreasing the number of acquired frames which are compounded to form a spatially compounded ultrasonic image.

Referring first to FIGURE 1, an ultrasonic diagnostic imaging system constructed in accordance with the principles of the present invention is shown. A scanhead 10 including an array transducer 12 transmits beams at different angles over an image field denoted by the dashed rectangle and parallelograms. Three groups of scanlines are indicated in the drawing, labeled A, B, and C with each group being steered at a different angle relative to the scanhead. The transmission of the beams is controlled by a transmitter 14 which controls the phasing and time of actuation of each of the elements of the array transducer so as to transmit each beam from a predetermined origin along the array and at a predetermined angle. The echoes returned from along each scanline are received by the elements of the array, digitized as by analog to digital conversion, and coupled to a digital beamformer 16. The digital beamformer delays and sums the echoes from the array elements to form a sequence of focused, coherent digital echo samples along each scanline. The transmitter 14 and beamformer 16 are operated under control of a system controller 18, which in turn is responsive to the settings of controls on a user interface 20 operated by the user of the ultrasound system. The system controller controls the transmitter to transmit the desired

number of scanline groups at the desired angles, transmit energies and frequencies. The system controller also controls the digital beamformer to properly delay and combine the received echo signals for the apertures and image depths used.

The scanline echo signals are filtered by a programmable digital filter 22, which defines the band of frequencies of interest. When imaging harmonic contrast agents or performing tissue harmonic imaging the passband of the filter 22 is set to pass harmonics of the transmit band. The filtered signals are then detected by a detector 24. In a preferred embodiment the filter and detector include multiple filters and detectors so that the received signals may be separated into multiple passbands, individually detected and recombined to reduce image speckle by frequency compounding. For B mode imaging the detector 24 will perform amplitude detection of the echo signal envelope. For Doppler imaging ensembles of echoes are assembled for each point in the image and are Doppler processed to estimate the Doppler shift or Doppler power intensity.

In accordance with the principles of the present invention the digital echo signals are processed by spatial compounding in a processor 30. The digital echo signals are initially pre-processed by a preprocessor 32. The pre-processor 32 can preweight the signal samples if desired with a weighting factor. The samples can be preweighted with a weighting factor that is a function of the number of component frames used to form a particular compound image. The pre-processor can also weight edge lines that are at the edge of one overlapping image so as to smooth the transitions where the number of samples or images which are compounded changes. The pre-processed signal samples may then undergo a resampling in a resampler 34. The resampler 34 can spatially realign the estimates of one component frame to those of another component frame or to the pixels of the display space.

After resampling the image frames are compounded by a combiner 36. Combining may comprise summation, averaging, peak detection, or other combinational means. The samples being combined may also be weighted prior to combining in this step of the process. Finally, post-processing is performed by a post-processor 38. The post-processor normalizes the combined values to a display range of values. Post-processing can be most easily implemented by look-up tables and can simultaneously perform compression and mapping of the range of compounded values to a range of values suitable for display of the compounded image.

The compounding process may be performed in estimate data space or in display pixel space. In a preferred embodiment scan conversion is done following the compounding process by a scan converter 40. The compound images may be stored in a

Cineloop memory 42 in either estimate or display pixel form. If stored in estimate form the images may be scan converted when replayed from the Cineloop memory for display. The scan converter and Cineloop memory may also be used to render three dimensional presentations of the spatially compounded images as described in U.S. Patents 5,485,842 and 5,860,924, or displays of an extended field of view by overlaying successively acquired, partially overlapping images in the lateral dimension. Following scan conversion the spatially compounded images are processed for display by a video processor 44 and displayed on an image display 50.

FIGURE 2 illustrates a preferred implementation of the spatial compounding processor 30 of FIGURE 1. The processor 30 is preferably implemented by one or more digital signal processors 60 which process the image data in various ways. The digital signal processors 60 can weight the received image data and can resample the image data to spatially align pixels from frame to frame, for instance. The digital signal processors 60 direct the processed image frames to a plurality of frame memories 62 which buffer the individual image frames. The number of image frames capable of being stored by the frame memories 62 is preferably at least equal to the maximum number of image frames to be compounded such as sixteen frames. In accordance with the principles of the present invention, the digital signal processors are responsive to changes in system control parameters including image display depth, number of scanlines or line density, number of transmit focal zones, amount of deadtime per pulse repetition interval (PRI), number of transmissions per image line, depth of region of greatest compounding, clinical application, number of simultaneous modes, size of region of interest, mode of operation, and acquisition rate for determining the number of component frames to compound at a given point in time. The digital signal processors select component frames stored in the frame memories 62 for assembly as a compound image in accumulator memory 64. The compounded image formed in the accumulator memory 64 is weighted or mapped by a normalization circuit 66, then compressed to the desired number of display bits and, if desired, remapped by a lookup table (LUT) 68. The fully processed compounded image is then transmitted to the scan converter for formatting and display.

The digital signal processors 60 determine the number of frames which are to be compounded to improve image quality while still providing an acceptable realtime compound image frame rate. Increasing the number of component frames does not lead to a proportional or unlimited increase in the image quality of the compound image. There is, therefore, a practical maximum number of frames, each steered by a minimum angle, that can be usefully employed to improve image quality in spatial compound scanning. This number

can vary widely depending on the transducer design and size of the active aperture, but can be as large as 16 component frames per compound image for an array with a large acceptance angle and small active apertures. The maximum useful number of frames will also depend on the mixture of speckle and anisotropic scatterers in the tissue of interest, and therefore on the clinical application.

The present invention has particular utility when the clinician is changing between "survey" and "target" modes of operation. During the survey mode of operation, the clinician is rapidly maneuvering the scanhead to quickly ascertain the presence of prominent physiological landmarks or features. The compounding of a large number of component frames when the scanhead is in motion will result in blurred images. Consequently the number component frames being compounded is reduced during the survey mode. As the clinical operator identifies potential abnormalities, the scanning motion is slowed down or stopped completely to image the features of interest ("targeted" or "study" mode). At this point, the image features within the component frames are more highly correlated, and motion blurring in the compound image is substantially reduced or completely eliminated as long as the scanhead is substantially stationary. During the target mode, the number of component frames being compounded is increased to produce high quality images without the consequence of blurring.

It is well known that the frame rate of an image with a given line density is dependent upon the maximum display depth of the image, because the speed of sound in tissue (~1.54 millimeters per microsecond) imposes a minimum round trip propagation delay of 13 microseconds for every centimeter of image depth. Typically, additional delay time is also added to prevent reverberation artifacts, that is the receipt of echoes at the beginning of one image line which are returning from deep depths of a previous image line. For an image consisting of 192 ray lines and a depth of 2 centimeters, the acquisition frame rate can be 100 frames per second or greater, but for an 8 centimeter image depth the frame rate can drop to 25 frames per second. While 25 frames per second is adequate for real time examination, a compound image frame rate for 7 component frames at this depth is less than 4 frames per second. A frame rate this slow would generally be considered inadequate for real time examination. Conversely, a compound image with 3 component frames with an image depth of 2 centimeters would have a compound frame rate of 33 frames per second, which is higher than necessary for real time examinations.

Compound scanning with a steered linear array results in a pattern of overlapping component frames such that the region of maximum image quality (RMIQ) where

all N frames overlap is a trapezoidal or an inverted triangular region with its base at the top of the compound image. For a small number of component frames steered at the minimum angle, this region of maximum image quality extends deep into the compound image. For a large number of component frames, the RMIQ is relatively shallow. This is illustrated by FIGURES 3a-3c, which show three different compound scan geometries, each consisting of several partially overlapping steered linear component frames scanned from a linear array scanhead 10. For visual clarity, the minimum steering angle was chosen as 15° between component frames. FIGURE 3a shows three component frames A, B, and C which are compounded, and the RMIQ extends the full 4.0 cm height of the image. FIGURE 3b shows an image which compounds five component frames A, B, C, D and E, and the RMIQ now extends only 2.3 cm from the top of the compound frame. Similarly, FIGURE 3c shows that for seven component frames A-G, the RMIQ of the compound image only extends 1.3 centimeters in depth. These drawings show that increasing the number of frames in the compound image decreases the size of the RMIQ. Thus, spatial compounding using component frames with large steering angles contributes very little additional image quality at depths deeper than the RMIQ.

It is apparent from the foregoing illustrations that at shallow depths the frame rate is relatively high, which allows the use of more component frames (larger value of N) for spatial compound imaging while still maintaining an adequate frame rate of display. This is also consistent with the decrease in the depth of the RMIQ associated with more component frames (larger value of N) for spatial compound imaging. Therefore, the relationships between image depth, frame rate, the number of component frames in a spatial compound image, the size and depth of the RMIQ, and image quality can be exploited to optimize overall performance. Table 1 below shows how these tradeoffs can advantageously be made for different depths, while always maintaining a compound frame rate of 10 Hz or greater.

Table 1.

Image display depth, cm	# of frames in compound image	Acquisition frame rate, Hz	Compound display rate, Hz	Max. steering angle, degrees	Depth of RMIQ, cm
2	7	100	14	45	1.3
4	5	50	10	30	2.3
6	3	37.5	12.5	15	4.0
8	2	25	12.5	9	8.0

Thus it is seen that as the image display depth increases, the system controller 18 responds by decreasing the number of frames which are acquired and compounded to form the displayed compound image. When the user selects a greater display depth for the scanhead 10, the ultrasound system responds by decreasing the number of frames of the compounded display. As the acquisition frame rate declines the number of frames compounded is also decreased. If the user reduces the frame rate as by increasing the number of lines of an image, for example, the ultrasound system will respond by decreasing the number of compounded frames in a displayed image. When the look directions of the acquired image frames is varied by steering the transmit beams in a number of different look directions the angle of the sides of the trapezoidal-shaped image decreases with increases in the number of images which are compounded. These adaptive changes in the number of frames being compounded maintain the display rate of the compound image at more than ten frames per second, or some other rate which is acceptable for the particular clinical application being performed.

As the number of frames compounded in the displayed compound image decreases, the depth of the region of greatest compounding increases, but is comprised of fewer compounded image frames. In accordance with another aspect of the present invention, as the image depth is decreased, the maximum steering angle of the steered transmit beams also increases. A comparison of FIGURES 3a-3c illustrates how a greater maximum steering angle will more effectively cover a shallow imaging depth, whereas a lesser maximum steering angle is more effective for greater imaging depths.

Thus it is seen that as the image depth is increased the number of look directions compounded in the compound image is decreased, as is the maximum steering angle. The number of look directions is also decreased when the number of lines or line density of the image is increased; when the number of transmit focal zones is increased; when the amount of deadtime per PRI is increased; when the number of transmissions per image line

is increased (e.g., for synthetic aperture, pulse inversion harmonic imaging), when the number of simultaneous modes is increased (e.g., spectral Doppler together with 2D imaging), the size of the region of interest is increased (e.g., image zoom is decreased or turned off), the clinical application (e.g., changing from abdominal or peripheral vascular imaging to cardiac imaging), or changing from target to survey mode. When the number of lines which are simultaneously acquired is increased by increasing multiline acquisition, the number of look directions can be increased. It will be apparent to one skilled in the art that other changes in imaging parameters by the user, or various changes in a combination of the above parameters, should also be responded to by a change in the number of look directions which are compounded.

CLAIMS:

1. An ultrasonic diagnostic imaging system, operable in response to the setting of a plurality of operating parameters, comprising :

an array transducer that is operated to acquire ultrasonic echoes from a target at a plurality of different look directions, and

an image processor, referred to as compound image processor, that is responsive to changes of one or more operating parameters and that combines echo information of different look directions to form a spatially compounded image, characterized in that the compound image processor forms said spatially compounded image by combining a number of different look directions, which number is variable in response to changes of said one or more operating parameters.

2. An ultrasonic diagnostic imaging system as claimed in Claim 1, characterized in that one of said operating parameters is chosen among the following operating parameters :

image depth,

the number of lines in an image,

the density of lines in an image,

the number of transmit focal zones,

the amount of deadtime per pulse repetition interval,

the number of lines acquired per transmission,

the number of transmissions per image line,

the number of simultaneous imaging modes,

the size of an image region of interest,

clinical application,

the selection of survey or target mode of operation.

3. An ultrasonic diagnostic imaging system as claimed in one of Claims 1 or 2, characterized in that one of said operating parameters is the number of transmissions per line and in that said array transducer transmits multiple times per image line during at least one synthetic aperture operation and pulse inversion harmonic imaging operation.

4. An ultrasonic diagnostic imaging system as claimed in one of Claims 1 or 2, characterized in that, one of said operating parameters is the number of transmissions per line and in that said array transducer produces multiple image lines in response to one pulse transmission.

5. An ultrasonic diagnostic imaging system as claimed in one of Claims 1 or 2, characterized in that one of said operating parameters is the size of an image region of interest and in that the size of the region of interest changes in response to changes in image zoom.

6. An ultrasonic diagnostic imaging system as claimed in one of Claims 1 or 2, characterized in that, one of said operating parameters is the image depth and in that the maximum steering angle of the different look directions is varied in response to a change of image depth.

7. An ultrasonic diagnostic imaging system as claimed in one of Claims 1 or 2, characterized in that :

the array transducer is operated to acquire images at one of a plurality of different acquisition frame rates, and

the compound image processor forms said spatially compounded image by combining a number of echo signals from different look directions, which number is related to the acquisition frame rate at which said array transducer is operated.

8. An ultrasonic diagnostic imaging system as claimed in one of Claims 1 or 2, characterized in that said compound image processor forms spatially compounded images for real time display while said array transducer is operated to acquire target ultrasonic echoes at a plurality of look directions.

9. A method of forming a spatially compounded ultrasonic image using an ultrasonic diagnostic imaging system as claimed in Claim 1, said method being characterized in that it comprises the steps of :

acquiring a plurality of ultrasonic echoes from a target from a plurality of different look directions,

and combining a number of said ultrasonic echoes, which number is chosen in relation to the setting of one or more operating parameters.

10. A method as claimed in Claim 9, characterized in that, one of said operating parameters is chosen among the following operating parameters :

image depth,
the number of lines in an image,
the density of lines in an image,
the number of transmit focal zones,
the amount of deadtime per pulse repetition interval,
the number of lines acquired per transmission,
the number of transmissions per image line,
the number of simultaneous imaging modes,
the size of an image region of interest,
clinical application,
the selection of survey or target mode of operation.

11. A method as claimed in one of Claims 9 or 10, characterized in that one of said operating parameters is image depth, and in that the maximum steering angle of the different look directions is varied in response to a change in image depth.

12. A method of forming a spatially compounded ultrasonic image using an ultrasonic diagnostic imaging system as claimed in Claim 1, said method being characterized in that it comprises the steps of :

acquiring a plurality of ultrasonic images of a region of the body from different look directions,

and compounding a number of said ultrasonic images, which number is chosen in relation to an acceptable display frame rate of said spatially compounded ultrasonic images.

13. A method of forming a spatially compounded ultrasonic image using an ultrasonic diagnostic imaging system as claimed in Claim 1, said method being characterized in that it comprises the steps of :

acquiring a plurality of ultrasonic images of a region of the body that exhibit different look directions by means of an array transducer,

compounding a number of said ultrasonic images to form a spatially compounded ultrasonic image,

and displaying said spatially compounded ultrasonic image at a display frame rate,

and in that the number of images which are compounded to form said spatially compounded image is varied in response to the setting of one or more of parameters chosen among the following parameters :

image display depth,
frame acquisition rate,
number of scanlines,
image line density,
number of transmit focal zones,
amount of deadtime per PRI,
number of transmissions per image line,
depth of region of greatest compounding,
clinical application,
number of simultaneous modes,
size of region of interest
and mode of operation.

14. A computer program product characterized in that it comprises a set of instructions for carrying out the method as claimed in one of Claims 9 to 13.

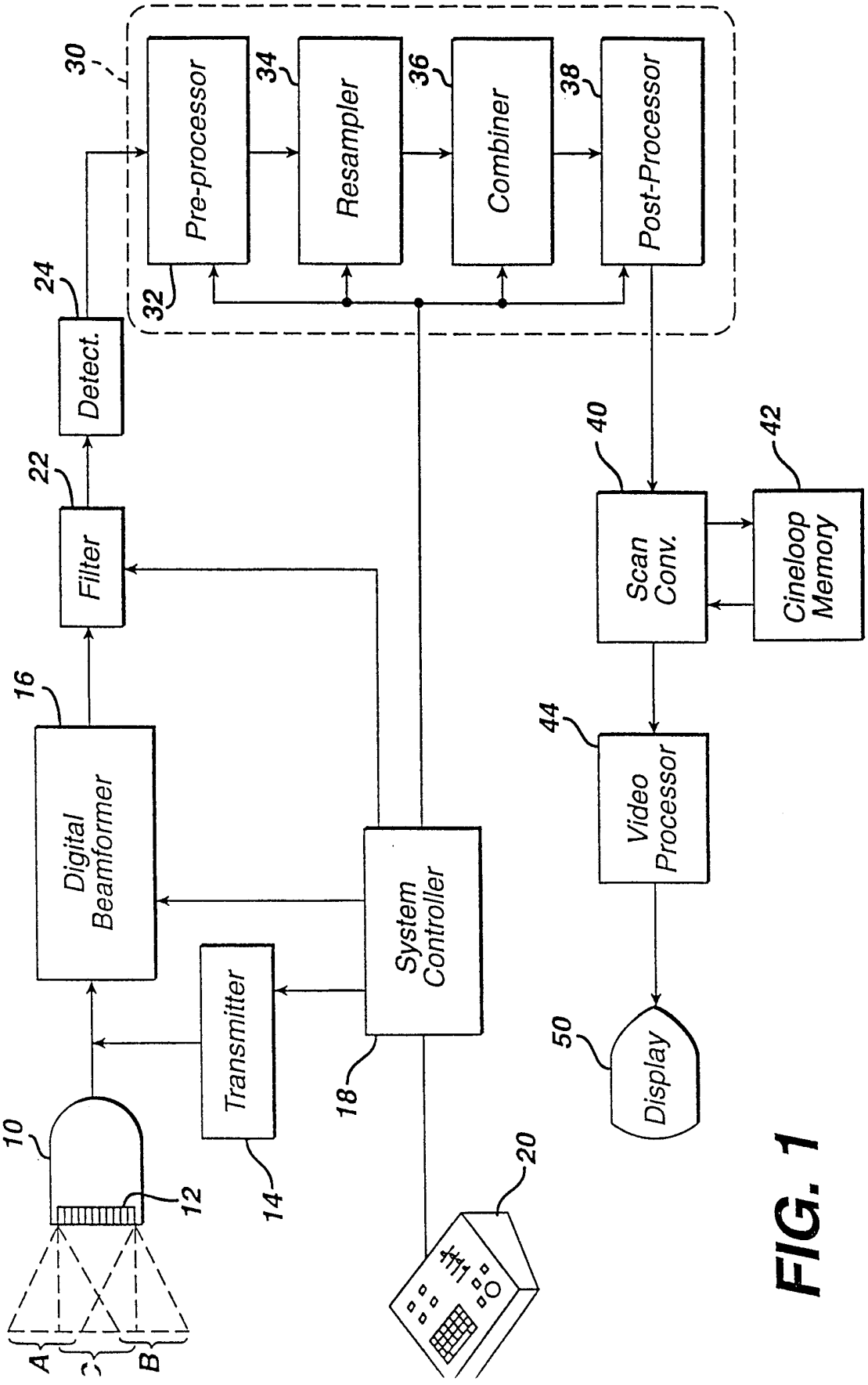

30
Pre-processor
34
Resampler
36
Combiner
38
Post-Processor
32
24
Detect.
22
Filter
16
Digital Beamformer
Transmitter
14
System Controller
18
20
10
12
A
B
40
Scan Conv.
42
Cineloop Memory
44
Video Processor
50
Display

FIG. 1

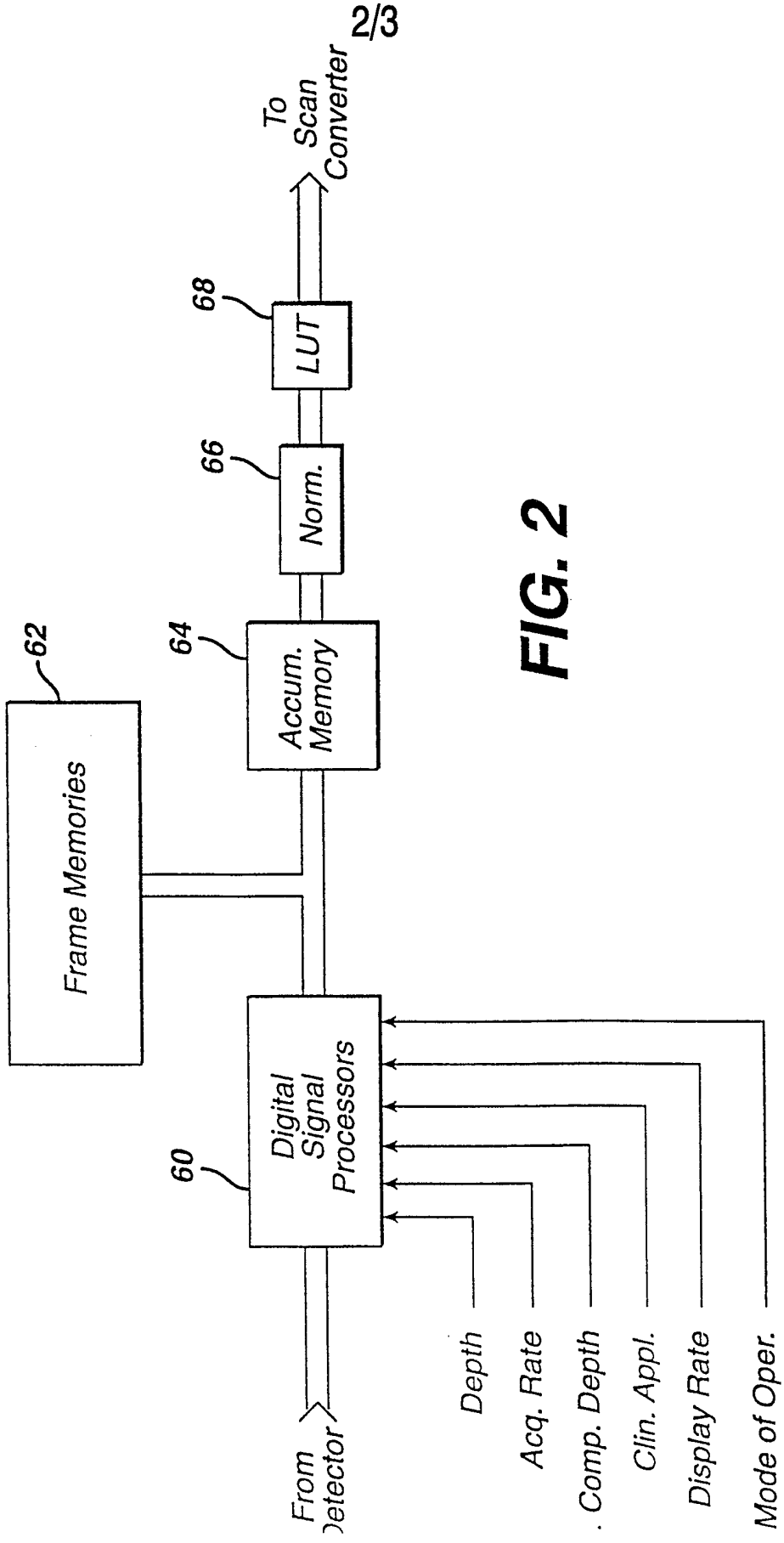

To Scan Converter
68
LUT
66
Norm.
64
Accum. Memory
62
Frame Memories
60
Digital Signal Processors
From Detector
Depth
Acq. Rate
Comp. Depth
Clin. Appl.
Display Rate
Mode of Oper.

FIG. 2

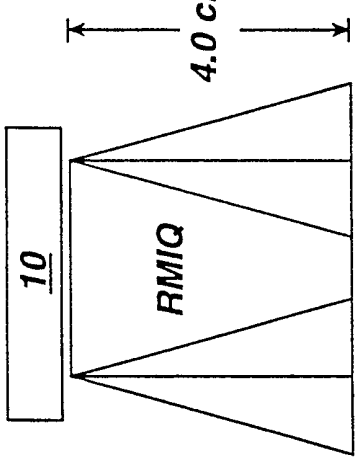


FIG. 3a

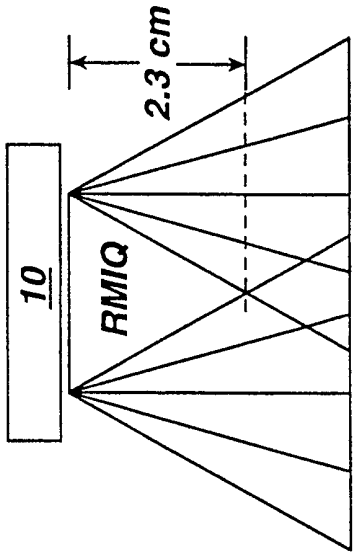


FIG. 3b

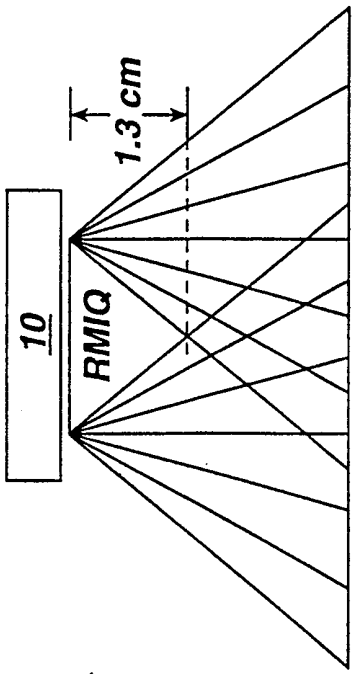


FIG. 3c

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 99/07473

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01S7/52 G01S15/89

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 7 G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5 655 535 A (TEO TAT-JIN ET AL) 12 August 1997 (1997-08-12) column 5 -column 6	1,9, 12-14
A	column 11; figures	2-8,10, 11

Y	US 5 782 766 A (NOCK LEVIN ET AL) 21 July 1998 (1998-07-21)	1,9, 12-14
A	column 5 -column 7 column 11 -column 14; figures	2-8,10, 11

A	US 5 623 928 A (FINGER DAVID J ET AL) 29 April 1997 (1997-04-29) the whole document	3

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[X] Further documents are listed in the continuation of box C.

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Date of the actual completion of the international search	Date of mailing of the international search report
14 January 2000	24/01/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Devine, J

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 99/07473

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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