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(54) Title: DIFFERENTIAL ENDFIRE ARRAY ULTRASONIC RANGEFINDER

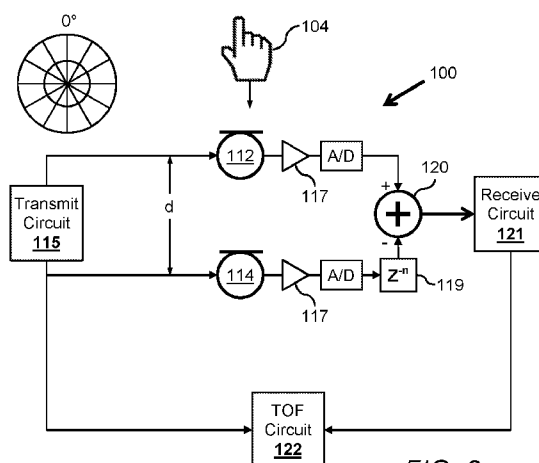


FIG. 3

(57) **Abstract:** An ultrasonic time of flight range sensor is based on an array of two or more ultrasound transducers that are arranged as an endfire phased array. The acoustic beam profile of the array can be shaped using two degrees of freedom: the distance between the transducers of the array and the electronic delay applied to the transducers' outputs. This allows the array to have a more directional response, so that objects in a desired direction can be detected while objects in other directions are ignored. Differential measurements are used to reduce or cancel the ring-down signal that follows transmission. This ring-down cancellation is important in micromachined ultrasonic transducers that typically have narrow bandwidth and therefore poor pulse response. The differential end-fire array can be used for ultrasonic rangefinding and object detection in consumer electronics devices such as smart phones, tablets, personal computers, monitors, and display devices.



DIFFERENTIAL ENDFIRE ARRAY ULTRASONIC RANGEFINDER**FIELD OF THE DISCLOSURE**

[0001] Aspects of the present disclosure relate to ultrasound and more particularly to rangefinding and object detection based on ultrasonic time-of-flight measurements.

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BACKGROUND

[0003] An example of a conventional system for rangefinding and object detection based on ultrasonic time-of-flight measurements is described in US 2014/0253435, to Boser et al. One limitation of such a system is that the minimum measurable range is limited by the finite bandwidth of the ultrasound transducer. When the same transducer is used to transmit and receive ultrasound, time is required after transmitting for the transducer's output to decay or "ring-down" to a level below which returning echo signals can be detected. It is desirable to develop methods to reduce or eliminate the amplitude of this ring-down signal.

[0004] A second feature that is desirable in rangefinders is the ability to create a more directional acoustic beam. Many ultrasonic transducers, especially micromachined ultrasonic transducers (MUTs) and micro-electromechanical systems (MEMS) microphones are omnidirectional, meaning that these transducers respond equally to sound coming in all directions. In many applications, it is desired to detect objects in a

specific location, such as in front of the rangefinder, and reject signals from objects in other locations, such as behind or to the sides of the rangefinder.

[0005] Array beamforming is well-known in microphone applications, as described for example in “Microphone array beamforming,” J. Lewis, Analog Devices Application Note AN1140. Array beamforming allows a directional acoustic response to be achieved using an array of omnidirectional microphones. However, the prior art does not teach how to use a differential endfire array to perform ultrasonic range measurement. Moreover, the prior art describes arrays of sound receivers (microphones) or, in the case of medical ultrasound transducers, broadband transducers where the ring-down signal has negligible impact on system performance.

BRIEF SUMMARY OF THE DISCLOSURE

[0006] This disclosure relates to an ultrasonic time of flight range sensor based on an array of two or more ultrasound transducers that are arranged as an endfire phased array. The acoustic beam profile of the array can be shaped using two degrees of freedom: the distance between the transducers of the array and the electronic delay applied to the transducers’ outputs. This allows the array to have a more directional response, so that objects in a desired direction, such as the front of the array, can be detected while objects in other directions, such as behind the array, are ignored.

[0007] The present disclosure describes the use of differential measurements to reduce or cancel the ring-down signal that follows transmission. This ring-down cancellation is important in micromachined ultrasonic transducers that typically have narrow bandwidth and therefore poor pulse response. The disclosure also describes embodiments of the differential endfire array for ultrasonic rangefinding and object detection in consumer electronics devices such as smart phones, tablets, personal computers, monitors, and display devices.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING(S)

[0008] The invention will be more fully understood by reference to the following

drawings which are for illustrative purposes only:

[0009] FIG. 1 illustrates the operation of an ultrasonic rangefinder, according to various embodiments of the present subject matter.

[0010] FIG. 2A shows the transmit, ring-down, and echo signals of a single-transducer rangefinder measuring a distant target, known from prior art.

[0011] FIG. 2B shows the transmit, ring-down, and echo signals of a single-transducer rangefinder measuring a close target, known from prior art.

[0012] FIG. 3 shows an embodiment of the invention using a differential endfire array for ultrasonic range measurement.

[0013] FIG. 4 shows the transmit, ring-down, and echo signals of the differential endfire array rangefinder according to an embodiment.

[0014] FIG. 5A shows a bi-directional beam-pattern according to an embodiment.

[0015] FIG. 5B shows a cardioid beam-pattern according to an embodiment.

[0016] FIG. 5C shows a super-cardioid beam-pattern according to an embodiment.

[0017] FIG. 6A shows a differential endfire transducer array mounted on the top edge of a smart phone or tablet device, according to an embodiment.

[0018] FIG. 6B shows two differential endfire transducer arrays mounted on the top edge of a monitor or display device, according to an embodiment.

[0019] FIG. 6C shows three differential endfire transducer arrays mounted on the bezel of a tablet, monitor or display device, according to an embodiment.

DETAILED DESCRIPTION OF THE INVENTION

[0020] Although the description herein contains many details, these should not be construed as limiting the scope of the invention but as merely providing illustrations of some of the presently preferred embodiments of this invention. Therefore, it will be appreciated that the scope of the present invention fully encompasses other embodiments which may become obvious to those skilled in the art.

[0021] In the following detailed description, reference is made to the accompanying drawings, which form a part hereof, and in which is shown by way of illustration specific embodiments in which the invention may be practiced. In this regard, directional terminology, such as "top," "bottom," "front," "back," "first," "second," etc., is used with reference to the orientation of the figure(s) being described. Because components of embodiments of the present invention can be positioned in a number of different orientations, the directional terminology is used for purposes of illustration and is in no way limiting. It is to be understood that other embodiments may be utilized and structural or logical changes may be made without departing from the scope of the present invention. The following detailed description, therefore, is not to be taken in a limiting sense, and the scope of the present invention is defined by the appended claims.

[0022] FIGs. 1A-1B illustrate the operation of an ultrasonic rangefinder 100 according to various aspects of the present disclosure. A rangefinder 100 transmits a pulse of ultrasound 102. A target 104 approaching rangefinder 100 is detected based on a reflected echo 106 when some portion of the original ultrasound pulse 102 is reflected from target 104. The time-of-flight (ToF), which is the time elapsed from transmitting the original pulse 102 to receiving the reflected echo 106, is used to detect the range d of target 104 from the rangefinder 100. Using the known value of the speed of sound, c , the estimate of range d is computed as $d = \text{ToF} * c / 2$. While FIGs 1A-1B show a single target 104, multiple targets having different ranges from the rangefinder 100 may also be detected.

[0023] FIGs. 2A-2B illustrate the signals from the ultrasound transducer in rangefinder 100 during a range measurement. The measurement begins with a transmit phase 108 in which the transducer is excited with an input voltage. Following the transmit phase 108, the excitation stops and the transducer's output begins to decay. This decay period is labelled the "ring-down" 110 in FIGS 2A-B. Assuming linear transducer operation, the rise and decay times have a time-constant (τ) that is inversely proportional to the transducer's bandwidth. By way of example, to allow the transducer output to reach a

level that is within 5% of the maximum steady-state amplitude, the minimum duration of the transmit phase 108 is equal to approximately three time-constants, $T_{TX} = 3 \cdot \tau$. As used herein, “approximately three time-constants” means between 2.0 and 4.0 time constants. Longer transmit durations may be desirable to increase the signal-to-noise ratio (SNR), for example when measuring small targets or measuring over long range. Shorter transmit durations are also possible, at the cost of reduced signal levels and possibly degraded SNR. The duration of the ring-down 110 is similarly equal to approximately three time-constants.

[0024] Also shown in FIGs 2A-2B is the echo signal 106 that is received from the target 104. In FIG 2A, the echo arrives following the end of the ring-down period 110. The time-of-flight (ToF) is determined from the time between the transmit phase 108 and the arrival time of the echo 106. Various algorithms may be used to determine the ToF. When target 104 is very close to rangefinder 100, the echo 106 arrives during the ring-down period 110, making it difficult to accurately measure the time-of-flight.

[0025] An endfire array is an array of acoustic transducers that are arranged in line with the desired direction of sound propagation. FIG. 3 shows an embodiment of a rangefinder 100 consisting of an endfire array with two ultrasonic transducers 112 and 114 spaced by a distance d . According to aspects of the present disclosure, the transducers may be narrow band transducers characterized by an acoustic bandwidth (full width at half maximum (FWHM) that is 1%-30% of the common operating frequency of the transducers. The operating frequency is natural resonant frequency of the transducers. An optional transmit circuit 115 may be coupled to the transducers 112, 114. The transmit circuit produces electronic signals that drive the transducers 112, 114 in a common mode, i.e., such that the transducers are driven in phase at the same operating frequency. In some implementations, the transmit circuit 115 may include an amplifier (not shown) that amplifies the driving signals coupled to the transducers.

[0026] The transducers 112, 114 produce first and second transducer output signals in response to an acoustic input signal. The way in which the transducers generate the output signals depends on the construction of the transducers. For example a

piezoelectric micromachined ultrasound transducer (PMUT)_generally includes a layer of piezoelectric material sandwiched between two electrodes. An acoustic signal causes a bending or other deformation of the piezoelectric material which generates a time varying voltage between the electrodes. Alternatively, a capacitive micromachined ultrasound transducer (CMUT)_generally includes a layer of dielectric material sandwiched between two electrodes. An acoustic signal causes a compression or other deformation of the dielectric material which generates a time varying capacitance between the electrodes, which can be detected, e.g., due to a corresponding a time varying voltage, current or charge.

[0027] A difference circuit 116 is coupled to the transducers 112, 114. The difference circuit is configured to receive the first and second output signals and to produce a difference output based on a difference between the first and second transducer output signals. By way of example, and not by way of limitation, the difference circuit 116 may include amplifiers 117 configured to amplify the output signals from the transducers to produce corresponding amplified signals, a delay element 118 that delays one amplified signal with respect to the other to produce a delayed amplified signal, and a difference element 119 that computes a difference between the non-delayed amplified signal and the delayed amplified signal. It is noted that the difference computed by subtracting the delayed signal from the non-delayed signal or vice versa. The difference circuit 118 may optionally include one or more analog-to-digital (A/D) converters that digitize the amplified signals and digital circuit elements that perform the delay and difference functions on the resulting digitized signals. Alternatively, the difference circuit 116 may include analog circuit elements that perform the amplification, delay and difference functions.

[0028] In some implementations, the difference element 119 may include a differential amplifier that performs the amplification and difference functions to produce a difference signal that is equal to the difference between the output of transducer 112 and the output of transducer 114. In some such cases, the separate amplifiers 117 may be omitted and the delay element 118 may be a delay line 119 that delays the output of

transducer 114 before it is input to the differential amplifier. As explained further below, the amount of delay and the transducer spacing d are two degrees of freedom that can be adjusted to achieve different acoustic beam-patterns such as cardioid, hypercardioid and supercardioid patterns. A receive circuit 120 may be coupled to the difference circuit 116. The receive circuit may be configured to detect return echoes in the signals from the differential amplifier. The transmit circuit 115 and receive circuit 120 may in turn be coupled to a time of flight (TOF) circuit 122. The TOF circuit may include a clock and logic and arithmetic circuits configured to start counting clock pulses when the transmit circuit triggers an acoustic pulse by the transducers and to stop counting clock pulses when the receive circuit registers a corresponding return echo from an object. The TOF circuit 122 may be further configured to compute a distance to the object from the elapsed time between the pulse and return echo and a known speed of sound.

[0029] In other implementations the signals from transducers 112 and 114 may be amplified separately and the delay operation may be performed after amplification and/or digitization, or the delay operation may be performed in the acoustic domain, e.g., using two acoustic transmission lines with different lengths. These acoustic transmission lines may consist of pipes filled with air which conducts sound.

[0030] FIG. 4 shows the signals from transducers 112 and 114 and the difference signal from the difference circuit 116 during a range measurement of a target 104 that is located along the line between the two transducers (i.e. having angle near zero degrees, as indicated in FIG. 3). For clarity, the waveforms in FIG. 4 have been shifted vertically so that they do not overlap. In the embodiment illustrated in FIG. 4, the amount of delay is equal to zero and the distance d between the transducers 112, 114 is approximately equal to one-half the acoustic wavelength, $\lambda = c/f$, where f is the frequency used to excite the transducers. As used herein, "approximately equal to one-half" means between 0.4 and 0.6. The foregoing is meant as an illustrative non-limiting example. For cardioid and supercardioid patterns the spacing is approximately equal to one-quarter wavelength. As used herein, "approximately equal to one-quarter" means between 0.2 and 0.3. Other values for the distance d are possible. Target 104

produces an echo 106 that is measured by both transducer 112 and 114. Both transducers 112 and 114 are excited using an identical transmit waveform 108 and their response during the ring-down period 110 is substantially identical, as evidenced by the fact that the peaks of the waveforms from transducer 112 and 114 are both aligned at the vertical marker M1 in FIG. 4. As a result, the output of amplifier 118, which is equal to the difference between the outputs of transducers 112 and 114, does not show the ring-down signal 110. Because the spacing between transducers 112 and 114 is approximately equal to $\lambda/2$, the echo 106 in the output of transducer 114 is delayed by one-half cycle relative to the echo 106 in the output of transducer 112, as indicated by vertical markers M2 and M3 in FIG. 4. As a consequence, the peaks in the output of transducer 112 align with the troughs in the output of transducer 114. Amplifier 118, which measures the difference between these two signals, produces an echo 106 that is twice the amplitude of the echo 106 present in the outputs of transducer 112 and transducer 114.

[0031] By way of example, beam-patterns that may be realized by varying the transducer spacing d and delay are shown in FIGs. 5A-5C. FIG. 5A shows a bidirectional beam-pattern produced by two transducers operating at a frequency of 200 kHz, having spacing d equal to 0.86 mm (approximately equal to one-half the wavelength at 200 kHz) and delay equal to zero. The bidirectional beam-pattern is symmetric, having equal amplitude in the forward (0 degree) and backward (180 degrees) directions. FIG. 5B shows a cardioid beam-pattern produced by two transducers operating at a frequency of 100 kHz, having spacing d equal to 0.81mm (approximately equal to one-quarter wavelength at 100 kHz) and delay equal to 3 samples at a sampling frequency of 1.25 MHz. The cardioid beam-pattern has zero sensitivity in the backward (180 degrees) direction. FIG 5C shows a super-cardioid beam-pattern produced by two transducers operating at a frequency of 100 kHz, having spacing 116 equal to 0.81mm (approximately equal to one-quarter wavelength at 100 kHz) and delay 120 equal to 2 samples at a sampling frequency of 1.25 MHz. The super-cardioid beam has narrower forward beam-width and 12 dB rejection in the backward (180 degrees) direction. Other beam-patterns are possible.

[0032] The delay time implemented by delay line 120 may be adjusted during a transmit/receive cycle. For example, after the transmit sequence the delay time may be initially set to substantially zero, resulting in cancellation of the ring-down signals from transducers 112 and 114. After the ringdown signal has substantially decayed, the delay time may be adjusted to achieve a desired beam pattern.

[0033] The differential endfire array may have many applications in consumer electronics devices such as tablets, smart phones, personal computers, displays, and computer monitors. Two example embodiments of the differential endfire array in consumer electronics devices are shown in FIGs. 6A-6B. FIG 6A shows a device 600A, e.g., smart-phone or tablet device, where the two transducers 112 and 114 are located on the top edge of the device. The cardioid beam-pattern is shown directed towards the front of the device. Other implementations, with the end-fire array on the sides, front, back, or bottom edges of the device are also possible. Additionally, multiple differential end-fire arrays may be used on the same device. FIG 6B shows a device 600B, e.g., a monitor, display, or all-in-one computing device, where two endfire arrays 202, 204 are located on the top edge of a case 601 of the device. Each endfire array may have a corresponding differential amplifier and delay line, as described above. The two cardioid beam-patterns are shown directed towards the front of the device. Endfire arrays may also be used on the bezel of a flat panel display device to project sound which travels substantially parallel to the plane of the device.

[0034] In the examples depicted in FIG. 6A and FIG. 6C, the top edge containing transducers 112, 114 is a minor face 602 of the case 601 and a display 604 is on a major face 606 of the case. As used herein the terms “major face” and “minor face” generally refer to the largest and smaller faces, respectively. However, aspects of the present disclosure are not limited to just such implementations.

[0035] One possible alternative implementation is illustrated in FIG. 6C, which shows a device 600C, a monitor, display, or all-in-one computing device 200 in which three endfire arrays, 202, 204, and 206 are placed around the bezel of the device and are used to triangulate the position of a target 208 such as a hand, stylus, or finger that is

located near the surface of device 200. The beam patterns of the endfire arrays 202, 204, 206 are substantially in the plane of device 200, so that target 208 is detected by all three arrays. However, a second target 210 located some distance from the surface of device 200 is not detected because it is not within the acoustic beam-pattern of the endfire arrays. The estimated position of target 208 may be used to emulate a capacitive or resistive touchscreen and allow user input to device 200. In the example shown in FIG. 6C, the endfire arrays 202, 204, and 206 and the display are on the same major face 606.

[0036] All cited references are incorporated herein by reference in their entirety. In addition to any other claims, the applicant(s) / inventor(s) claim each and every embodiment of the invention described herein, as well as any aspect, component, or element of any embodiment described herein, and any combination of aspects, components or elements of any embodiment described herein.

[0037] The particular implementations disclosed above are illustrative only, as the invention may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular embodiments disclosed above may be altered or modified and all such variations are considered within the scope and spirit of the invention. Although illustrative embodiments of the invention have been described in detail herein with reference to the accompanying drawings, it is to be understood that the invention is not limited to those precise embodiments, and that various changes and modifications can be effected therein by one skilled in the art without departing from the scope and spirit of the invention as defined by the appended claims.

[0038] The appended claims are not to be interpreted as including means-plus-function limitations, unless such a limitation is explicitly recited in a given claim using the phrase “means for.” Any element in a claim that does not explicitly state “means for” performing a specified function, is not to be interpreted as a “means” or “step” clause as

specified in 35 USC § 112, ¶ 6. In particular, the use of “step of” in the claims herein is not intended to invoke the provisions of 35 USC § 112, ¶ 6.

CLAIMS

What is claimed is:

1. An ultrasonic time of flight range sensor, comprising:
first and second narrow-band ultrasound transducers separated from each other by a finite distance and arranged in line with a desired direction of sound propagation, wherein each of the first and second narrow-band ultrasound transducers is characterized by an acoustic bandwidth that is between 1% and 30% of a common operating frequency, wherein the first and second narrow band ultrasound transducers are configured to produce first and second transducer output signals in response to an acoustic input signal; and
a difference circuit configured to receive the first and second output signals and to produce a difference output based on a difference between the first and second transducer output signals.
2. The ultrasonic time of flight range sensor of claim 1, wherein the difference circuit is configured to amplify the first and second transducer output signals to produce corresponding first and second amplified signals, delay the second amplified signal with respect to the first amplified signal to produce a delayed second amplified signal, and compute a difference between the first amplified signal and the delayed second amplified signal.
3. The ultrasonic time of flight range sensor of claim 2, wherein the difference circuit is an analog circuit.
4. The ultrasonic time of flight range sensor of claim 1, wherein the difference circuit is configured to amplify the first and second output signals to produce corresponding first and second amplified signals, digitize the first and second amplified signals to produce corresponding first and second digitized signals, delay the second digitized signal with respect to the second digitized signal to produce a delayed second digitized signal, and digitally compute a difference between the first digitized signal and the delayed second digitized signal.

5. The ultrasonic time of flight sensor of claim 4, wherein the difference circuit includes a digital delay line configured to delay the second digitized signal by an integer number of samples.
6. The ultrasonic time of flight range sensor of claim 1, wherein the difference circuit includes a differential amplifier.
7. The ultrasonic time of flight range sensor of claim 1, wherein a distance between the first ultrasound transducer and the second ultrasound transducer is approximately equal to one-half an acoustic wavelength of an acoustic pulse emitted by the transducers.
8. The ultrasonic time of flight range sensor of claim 1, wherein a distance between the first ultrasound transducer and the second ultrasound transducer is approximately equal to one-quarter of an acoustic wavelength of an acoustic pulse emitted by the transducers.
9. The ultrasonic time of flight range sensor of claim 1, further comprising an analog-to-digital converter configured to digitize the first and second transducer output signals.
10. The ultrasonic time of flight range sensor of claim 2, wherein the delay, a distance between the first narrow band ultrasound transducer and second narrow band ultrasound transducer, and the common operating frequency of the first and second narrow band ultrasound transducers are selected to generate a bidirectional acoustic beam-pattern.
11. The ultrasonic time of flight range sensor of claim 2, wherein the delay, a distance between the first narrow band ultrasound transducer and second narrow band ultrasound transducer, and the common operating frequency of the first and second narrow band ultrasound transducers are selected to generate a cardioid acoustic beam-pattern.

12. The ultrasonic time of flight range sensor of claim 2, wherein a distance between the first narrow band ultrasound transducer and second narrow band ultrasound transducer, and the common operating frequency of the first and second narrow band ultrasound transducers are selected to generate a super-cardioid acoustic beam-pattern.
13. The ultrasonic time of flight range sensor of claim 1, further comprising a transmit circuit coupled to the first and second narrowband ultrasound transducers, wherein the transmit circuit is configured to generate common mode electronic transmit signals that cause the first and second ultrasound transducers to emit one or more acoustic pulses in phase with each other.
14. The ultrasonic time of flight range sensor of claim 1, further comprising a receive circuit that coupled to the difference circuit, wherein the receive circuit is configured to detect return echoes in signals from the differential difference circuit.
15. The ultrasonic time of flight range sensor of claim 1, further comprising a transmit circuit coupled to the first and second ultrasound transducers and a receive circuit coupled to an output of the difference circuit, wherein the transmit circuit is configured to generate common mode electronic transmit signals that cause the first and second ultrasound transducers to emit one or more acoustic pulses in phase with each other and wherein the receive circuit is configured to detect return echoes in signals from the differential difference circuit..
16. The ultrasonic time of flight range sensor of claim 15, further comprising a time of flight (TOF) circuit coupled to the transmit circuit and the receive circuit, wherein the TOF circuit is configured to determine an elapsed time between triggering of an acoustic pulse by the first and second narrow band transducers and receiving a corresponding return echo from an object by the first and second narrow band transducers.

17. The ultrasonic time of flight range sensor of claim 16, wherein the TOF circuit is configured to compute a distance to the object from the elapsed time and a known speed of sound.
18. The ultrasonic time of flight range sensor of claim 1, further comprising one or more additional narrow band ultrasound transducers.
19. The ultrasonic time of flight range sensor of claim 18 wherein the one or more ultrasound transducers include third and fourth narrow band ultrasound transducers separated from each other by a finite distance and arranged in line with a different desired direction of sound propagation.
20. The ultrasonic time of flight sensor of claim 19, wherein the desired direction of sound propagation and the different desired direction of sound propagation are parallel to each other.
21. The ultrasonic time of flight sensor of claim 19, wherein the desired direction of sound propagation and the different desired direction of sound propagation are perpendicular to each other.
22. A device, comprising:
 - a display;
 - two or more ultrasound transducers proximate an edge of the display, the two or more ultrasound transducers including first and second ultrasound transducers separated from each other by a finite distance and arranged in line with a desired direction of sound propagation; and
 - a difference circuit coupled to an output of the first and second ultrasound transducers.
23. The device of claim 22, further comprising a case, wherein the display is located on a major face of the case and the two or more ultrasound transducers are located on a minor face of the case.

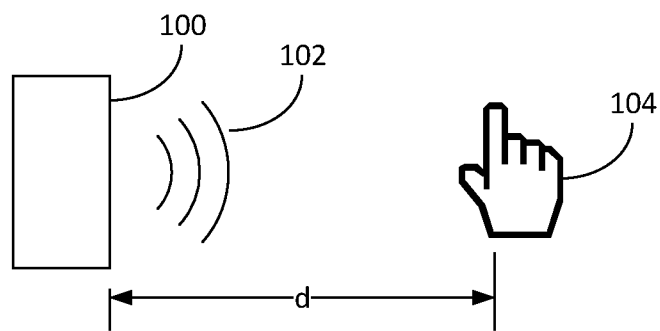
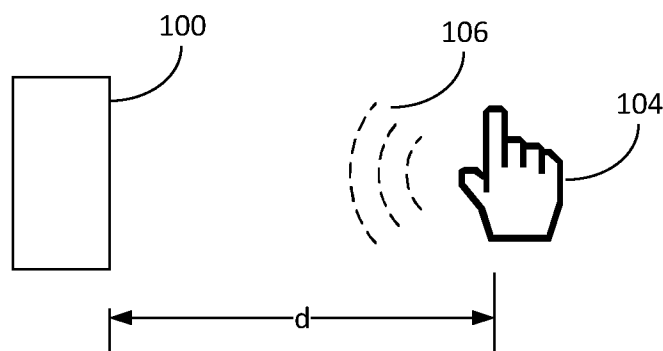
24. The device of claim 22, wherein the device is a tablet, smart phone, personal computer, display, or computer monitor.
25. The device of claim 22, wherein each of the first and second narrow band ultrasound transducers is characterized by an acoustic bandwidth that is between 1% and 30% of a common operating frequency.
26. The device of claim 25, wherein the first and second narrow band ultrasound transducers are configured to produce first and second transducer output signals in response to an acoustic input signal.
27. The device of claim 26, wherein the difference circuit is configured to receive the first and second output signals and to produce a difference output based on a difference between the first and second transducer output signals
28. The device of claim 27, wherein the difference circuit is configured to amplify the first and second transducer output signals to produce corresponding first and second amplified signals, delay the second amplified signal with respect to the first amplified signal to produce a delayed second amplified signal, and compute a difference between the first amplified signal and the delayed second amplified signal.
29. The device of claim 28, wherein the difference circuit is an analog circuit.
30. The device of claim 28, wherein the delay, a distance between the first narrow band ultrasound transducer and second narrow band ultrasound transducer, and the common operating frequency of the first and second narrow band ultrasound transducers are selected to generate a bidirectional acoustic beam-pattern.
31. The ultrasonic time of flight range sensor of claim 28, wherein the delay, a distance between the first narrow band ultrasound transducer and second narrow band ultrasound transducer, and the common operating frequency of the first and second narrow band ultrasound transducers are selected to generate a cardioid acoustic beam-pattern.

32. The ultrasonic time of flight range sensor of claim 28, wherein a distance between the first narrow band ultrasound transducer and second narrow band ultrasound transducer, and the common operating frequency of the first and second narrow band ultrasound transducers are selected to generate a super-cardioid acoustic beam-pattern.
33. The device of claim 27, wherein the difference circuit is configured to amplify the first and second output signals to produce corresponding first and second amplified signals, digitize the first and second amplified signals to produce corresponding first and second digitized signals, delay the second digitized signal with respect to the second digitized signal to produce a delayed second digitized signal, and digitally compute a difference between the first digitized signal and the delayed second digitized signal.
34. The device of claim 33, wherein the difference circuit includes a digital delay line configured to delay the second digitized signal by an integer number of samples.
35. The device of claim 27, wherein the difference circuit includes a differential amplifier.
36. The device of claim 27, wherein a distance between the first ultrasound transducer and the second ultrasound transducer is approximately equal to one-half an acoustic wavelength of an acoustic pulse emitted by the transducers.
37. The device of claim 27, wherein a distance between the first ultrasound transducer and the second ultrasound transducer is approximately equal to one-quarter of an acoustic wavelength of an acoustic pulse emitted by the transducers.
38. The device of claim 27, further comprising an analog-to-digital converter configured to digitize the first and second transducer output signals.
39. The device of claim 27, further comprising a transmit circuit coupled to the first and second narrowband ultrasound transducers, wherein the transmit circuit is configured to generate common mode electronic transmit signals that cause the

first and second ultrasound transducers to emit one or more acoustic pulses in phase with each other.

40. The device of claim 27, further comprising a receive circuit that is coupled to the difference circuit, wherein the receive circuit is configured to detect return echoes in signals from the difference circuit.
41. The device of claim 27, further comprising a transmit circuit coupled to the first and second ultrasound transducers and a receive circuit coupled to an output of the difference circuit, wherein the transmit circuit is configured to generate common mode electronic transmit signals that cause the first and second ultrasound transducers to emit one or more acoustic pulses in phase with each other and wherein the receive circuit is configured to detect return echoes in signals from the difference circuit..
42. The device of claim 41, further comprising a time of flight (TOF) circuit coupled to the transmit circuit and the receive circuit, wherein the TOF circuit is configured to determine an elapsed time between triggering of an acoustic pulse by the first and second narrow band transducers and receiving a corresponding return echo from an object by the first and second narrow band transducers.
43. The device of claim 42, wherein the TOF circuit is configured to compute a distance to the object from the elapsed time and a known speed of sound.
44. The device of claim 22, further comprising one or more additional narrow band ultrasound transducers.
45. The device of claim 44 wherein the one or more ultrasound transducers include third and fourth narrow band ultrasound transducers separated from each other by a finite distance and arranged in line with a different desired direction of sound propagation.
46. The device of claim 45, wherein the desired direction of sound propagation and the different desired direction of sound propagation are parallel to each other.

47. The device of claim 45, wherein the desired direction of sound propagation and the different desired direction of sound propagation are perpendicular to each other.

*FIG. 1A**FIG. 1B*

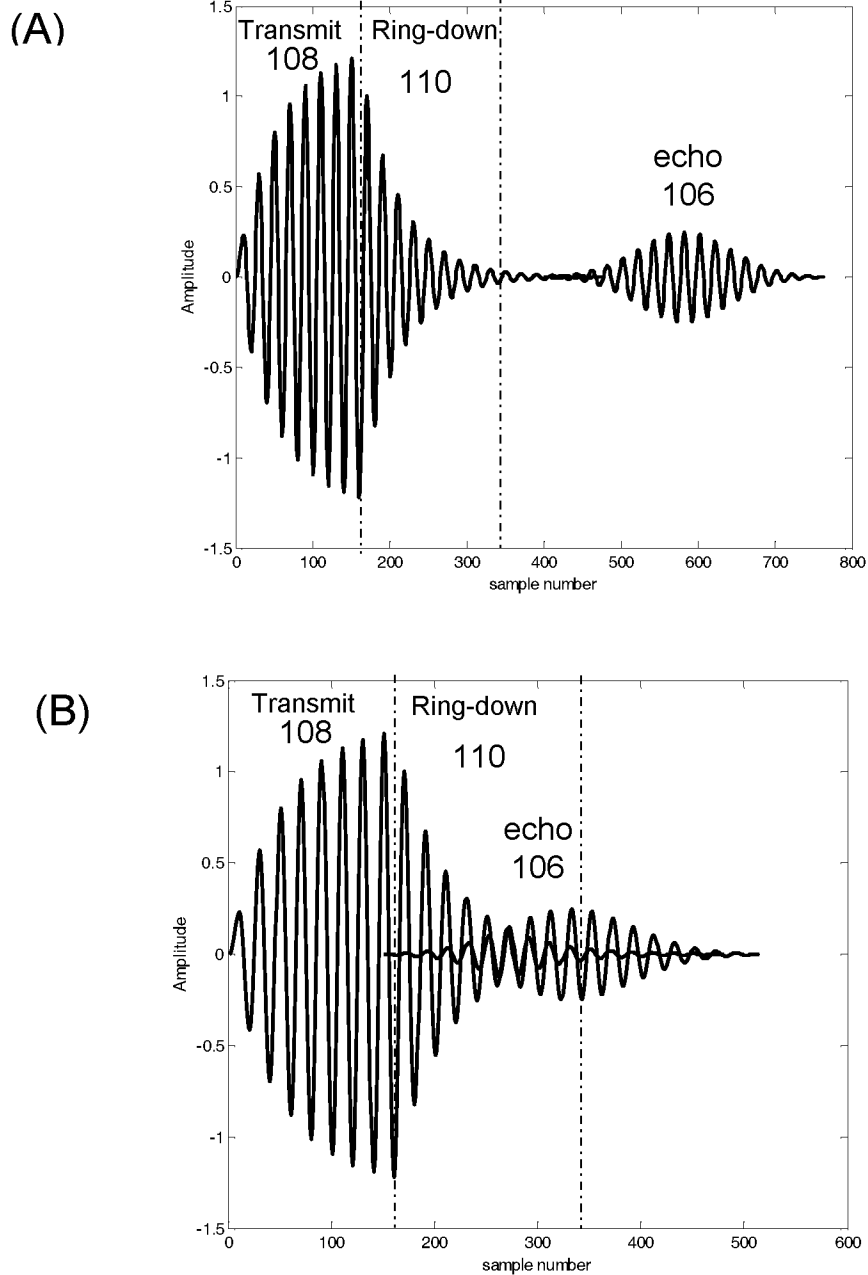


FIG. 2: PRIOR ART

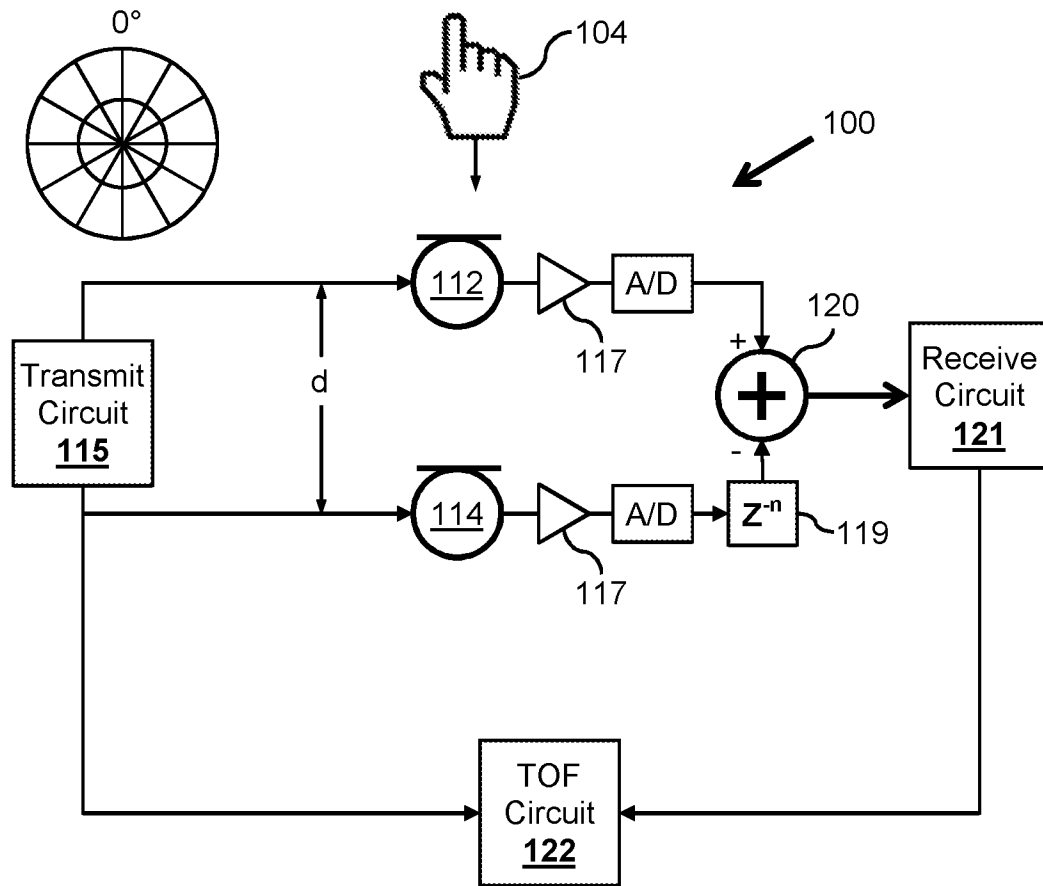


FIG. 3

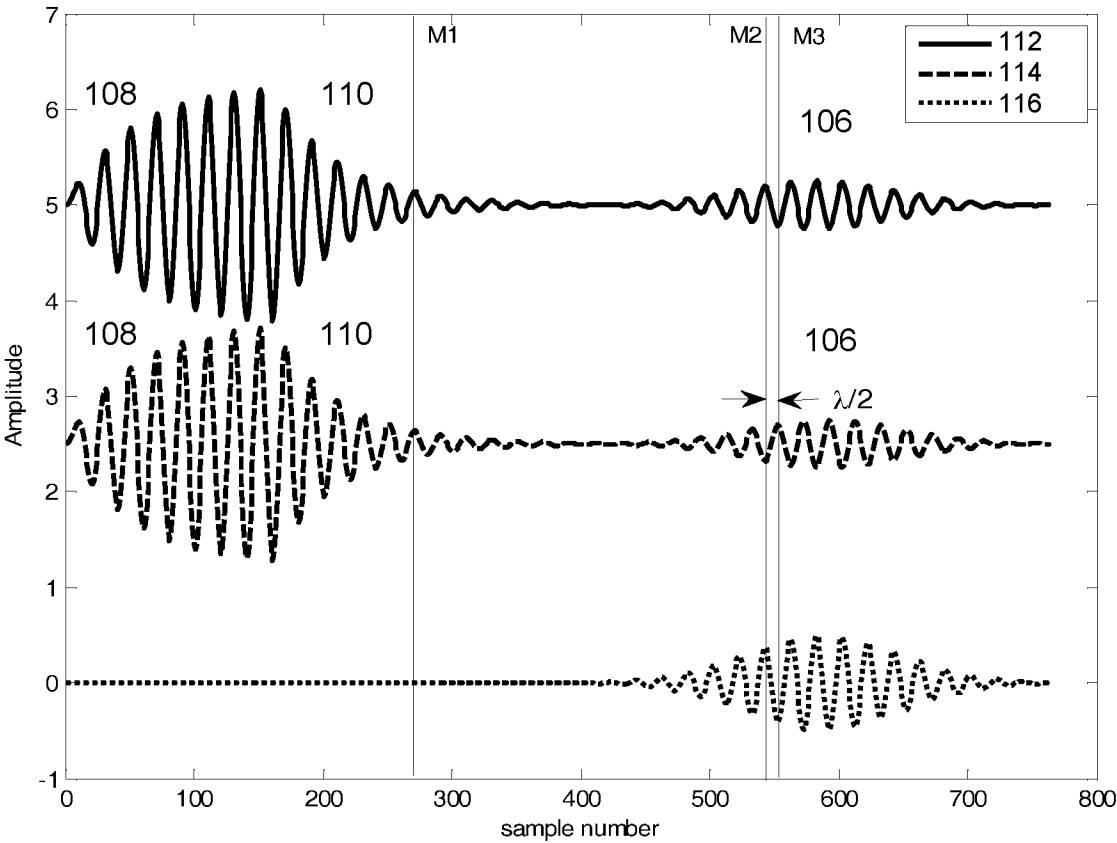


FIG. 4

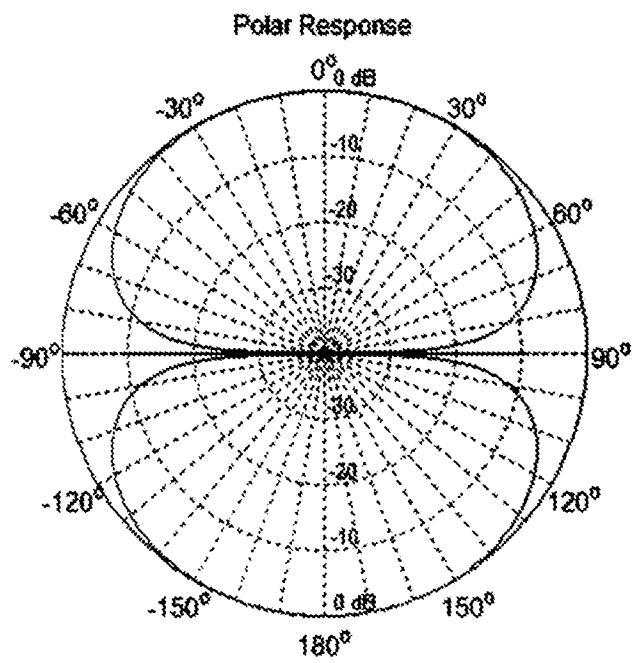


FIG. 5A

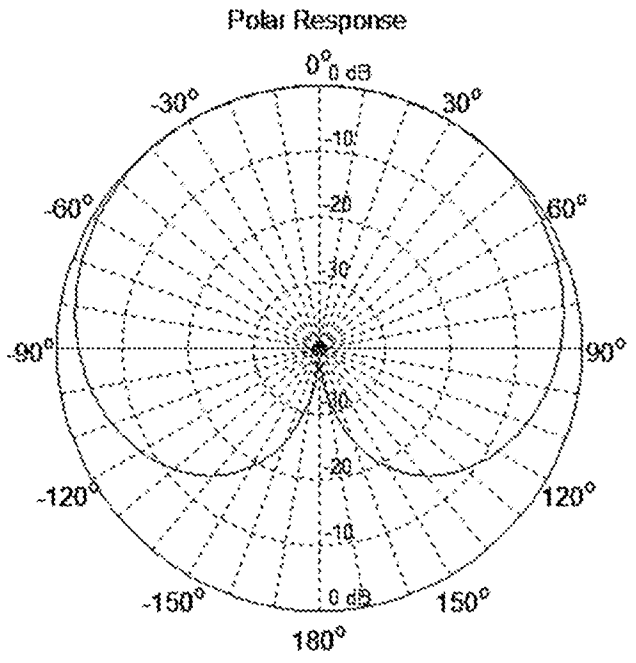


FIG. 5B

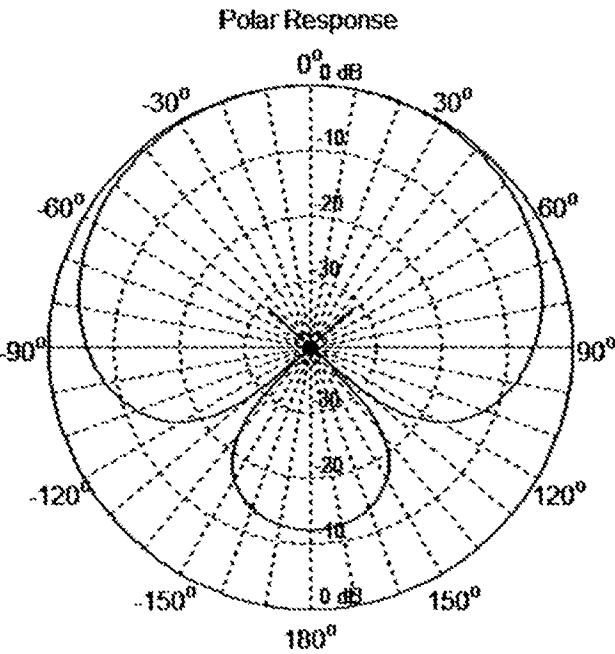


FIG. 5C

600A

604 606

112
114

602

FIG. 6A

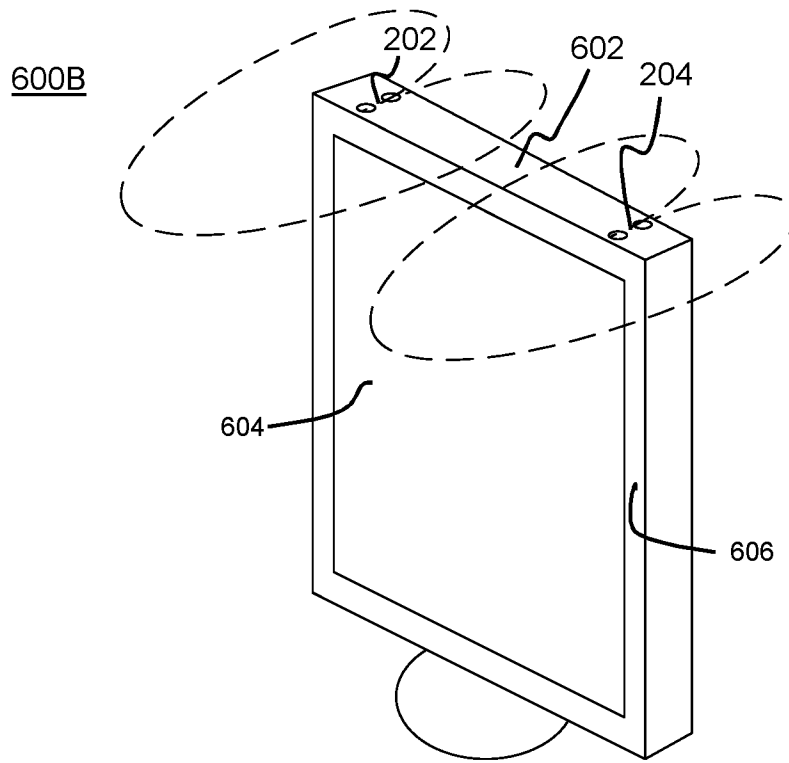


FIG. 6B

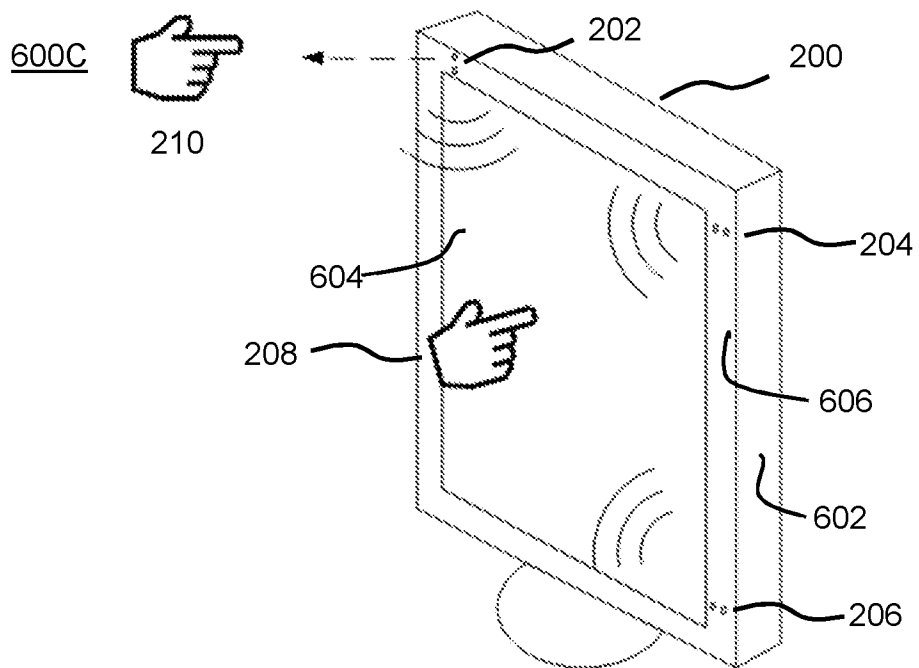


FIG. 6C

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 15/66910

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H04S 7/00 (2016.01)

CPC - H04S 7/302; H04R 1/40; H04R 2217/03; G10K 15/02; G01N 29/024

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): H04S 7/00 (2016.01)

CPC: H04S 7/302; H04R 1/40; H04R 2217/03; G10K 15/02; G01N 29/024

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
 IPC(8): H04S 7/00 (2016.01); CPC: H04S 7/302; H04R 1/40; H04R 2217/03; G10K 15/02; G01N 29/024; USPC: 381/303; 73/597
 (keyword limited, see terms below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
 PatBase, Google Patents, Google Scholar. Search terms used: ultrasound, ultrasonic, transducer, transceiver, object, range, distance, find, locate, detect, determine, measure, time, flight, difference, differential, signal, input, receive, bandwidth, frequency, range, delay, phase, shift, amplify, digitize, adc, analog, digital, acoustic, waveleng

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2014/0253435 A1 (BOSE et al.) 11 September 2014 (11.09.2014) entire document, especially: fig 2, para [0012], [0038], [0039], [0049],	1-21
Y	US 2004/0107779 A1 (KISHIMOTO et al.) 10 June 2004 (10.06.2004) entire document, especially: para [0010], [0045], [0051], [0051], [0098], [0118]	1-21
Y	US 4,719,605 A (EDER et al.) 12 January 1988 (12.01.1988) entire document, especially: col 4, ln 43-55	3, 6
Y	US 6,428,477 B1 (MASON) 06 August 2002 (06.08.2002) entire document, especially: col 3, ln 22-29	7, 8
Y	US 4,173,748 A (LEWANDOWSKI) 06 November 1979 (06.11.1979) entire document, especially: col 2, ln 17-24	10
Y	WO 2009/034524 A1 (KONINKL PHILIPS ELECTRONICS NV) 19 March 2009 (19.03.2009) entire document, especially: p 17, ln 3-6, p 23, ln 9-11	11, 12
Y	US 6,457,371 B1 (FELLER) 01 October 2002 (01.10.2002), entire document, especially: col 2, ln 28-35	13, 15-17
A	US 4,677,595 A (OBAYASHI et al.) 30 June 1987 (30.06.1987) entire document	1
A	US 5,462,058 A (YAMADA et al.) 31 October 1995 (31.10.1995) entire document	1

☐ 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

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"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

25 May 2016

Date of mailing of the international search report

06 JUN 2016

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-8300

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Lee W. Young

PCT Helpdesk: 571-272-4300

PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 15/66910

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I: claims 1-21: drawn to an ultrasonic time of flight range sensor.

Group II: claims 22-47: drawn to a display device.

The inventions listed as Groups I and II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

---See continuation sheet---

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-21

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 15/66910

---Continuation of Item Box III - Lack of Unity---

Special technical features:

Group I requires first and second narrow-band ultrasound transducers characterized by an acoustic bandwidth; and a difference circuit which produces a difference output based on a difference between the first and second transducer output signals, not found in the other groups.

Group II requires display with two or more ultrasound transducers proximate and edge of the display, not found in the other groups.

Shared Features:

The only technical features shared by Groups I and II that would otherwise unify the groups are two or more ultrasound transducers including first and second ultrasound transducers separated from each other by a finite distance and arranged in line with a desired direction of sound propagation; and a difference circuit coupled to an output of the first and second ultrasound transducers.

However, these shared technical features do not represent a contribution over prior art, because the shared technical features are disclosed by US 5,462,058 A to Yamada et al. (hereinafter 'Yamada') 31 October 1995 (31.10.1995), which discloses two or more ultrasound transducers including first and second ultrasound transducers separated from each other by a finite distance and arranged in line with a desired direction of sound propagation (col. 33, l n 55-67 -Pulse signals are transmitted from a transmission circuit 202 each in a predetermined timing toward ultrasonic transducers 201 arranged with a plurality of pieces, so that ultrasonic pulse beams are transmitted from the ultrasonic transducers 201 each in a predetermined direction inside the subject (not illustrated). The ultrasonic pulse beams irradiated within the subject are reflected within the subject, and the reflected ultrasounds are received by the ultrasonic transducers 201 and are applied to a receiving circuit 203.); and a difference circuit coupled to an output of the first and second ultrasound transducers (col 35, l n 5-23 -The space differentiation means 210 comprises a FIR filter, a difference circuit or the like in which the received signal is subjected to a space differentiation with respect to a predetermined direction toward which ultrasonic pulse beams are transmitted within the subject, thereby determining a rate of change of a movement velocity of the subject as to the predetermined direction.).

As the shared technical features were known in the art at the time of the invention, they cannot be considered special technical features that would otherwise unify the groups.

Groups I and II therefore lack unity under PCT Rule 13 because they do not share a same or corresponding special technical feature.