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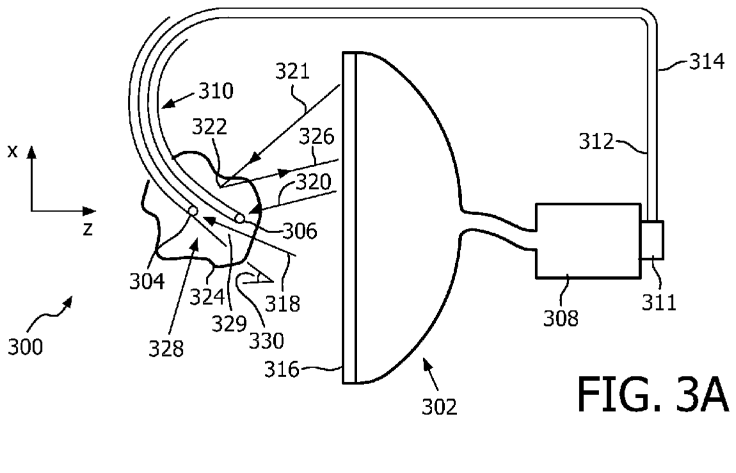

FIG. 3A

(57) Abstract: Beamforming to image an object (310), such as an interventional tool, is enhanced by initializing the beamformer (308) with the object's location, and optionally its orientation. The initializing uses an estimate of the location/orientation. The estimate is derived from the output of one or more sensors (304, 306). These are disposed external to the imaging array (316) that operates with the beamformer. The estimate is made without the need for a result of any imaging based on data arriving by reflected ultrasound. One or more of the sensors may be attached to the object, which may be elongated, as in the case of a needle or catheter used in medical diagnosis and treatment. In some implementations, one or more of the sensors are attached to the imaging probe (302). The sensors may be, for example, ultrasound, electromagnetic, optical, or shape sensors. Alternatively, ultrasound transmitting transducers may be substituted for the ultrasound sensors.

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OBJECT-POSE-BASED INITIALIZATION OF AN ULTRASOUND BEAMFORMER

FIELD OF THE INVENTION

The present invention is directed to using ultrasound in imaging an object and, more particularly, to initializing a beamformer for this purpose based on an estimate of the location and/or orientation of the object.

BACKGROUND OF THE INVENTION

Precise visualization of catheters and needles, and real-time knowledge of their localization with respect to the anatomy, are needed for minimally invasive interventions. Intra-operative ultrasound is often used for these purposes.

However, many surgical tools are difficult to image with conventional pulse-echo ultrasound. Also, visualization is often incomplete or artefact-prone.

For instance, the usability of 3D Transoesophagial Echocardiography (3D-TEE) for guidance of catheter cardiac interventions is still limited because it is challenging to image catheters reliably with ultrasound.

Catheters and needles are specular reflectors that reflect the sound away from the imaging probe if the insonifying angles are not favorable.

As a consequence, a catheter appears on and off on 3D-TEE images during its progression through the cardiac chambers. It also frequently happens that some parts of the catheter are visible and others not depending on the local angle between the catheter and the imaging beams. For instance the distal end of the catheter may be invisible and some point along its shaft may be mistaken as its tip. Also, due to weak reflection, signal from the catheter may be drowned in signal from the surrounding anatomy.

It is also difficult to image intravenous catheters.

Likewise, needles, often used for biopsy, nerve block, drug delivery, hyperthermic therapy, and radiofrequency (RF) ablation, etc., are hard to visualize, especially when thin and applied to deep tissue locations. Visibility greatly improves if the insonifying angle is perpendicular to the needle. However, achieving a favorable angle is usually limited to shallow needle insertions. In addition, due to tissue heterogeneities and asymmetric needle bevel, the needle often deviates from its planned trajectory, even when a needle guide is used. If the needle deviates from the imaged plane, it becomes invisible. Very often, the clinician jiggles the needle to see on the image display where it is located.

Electromagnetic (EM) sensors have been attached to the interventional tool and the ultrasound probe, to determine the tool pose, i.e., location and orientation, in the acquired image (SonixGPS Specifications Sheet, UltraSonix, http://www.ultrasonix.com/webfm_send/117).

In a technique proposed in a paper entitled "Enhancement of Needle Visibility in Ultrasound-Guided Percutaneous Procedures, by Cheung et al., Ultrasound in Medicine and Biology, Vol. 30, No. 5 (2004), the ultrasound probe is used to determine the tool pose. Beamforming parameters are created, based on the determination, to insonify the tool at a better angle.

SUMMARY OF THE INVENTION

The present invention is directed to addressing one or more of the above concerns.

In an aspect of the present invention, an estimate is derived of a location and/or orientation of an object. A beamformer is initialized with the estimate. The beamformer operates with an ultrasound transducer array in imaging the object. The estimate is based on output of at least one sensor external to the array and disposed with respect to the object for sensing the location/orientation.

According to another aspect, the estimate is made without the need for a result of any imaging based on data arriving by reflected ultrasound.

In one aspect, at least one of the sensors is attached to the object.

As a sub-aspect, at least two of the sensors, located mutually apart, are attached to the object.

In a different aspect, the object has an elongated body, and the at least one sensor conforms to at least a portion of the body for sensing a shape of the portion in determining the orientation.

In an alternative aspect, one or more of the sensors is an electronic device.

In a yet different aspect, one or more of the sensors is an ultrasound sensor.

In another aspect, a tool comprising the object is rigid and has a base. The at least one sensor is configured for optically detecting the base to afford the deriving of the estimate.

In a related aspect, the beamformer is configured for limiting an angle of incidence of a transmit beam, a receive beam, or both, to a nonzero value to avoid sidelobe and reverberation artefacts.

In one other related aspect, the beamformer is configured for using the estimate to optimize the beamforming.

In an additional aspect, the beamformer is configured for, based on the estimate, placing a transmit focus at the object.

In a sub-aspect of the above, the estimate is of the location and the orientation, the object is elongated, and the beamformer is further configured for, based on the estimate, placing a plurality of transmit foci along the object at different depths to conform to the object.

In one version, the object is elongated, and the beamformer is configured with steering capability in an elevation direction. The initializing is directed to forming an imaging plane in which at least a tip of the object longitudinally extends.

As a sub-aspect of the above version, at least the tip currently longitudinally extends within another imaging plane, the planes being mutually non-parallel. The beamformer is further configured for imaging both planes for concurrent display in real time.

In a different aspect, the object is elongated, and the beamformer is configured for beam spacing that is spatially fine enough to mitigate or eliminate imaging artefacts discernible as interruptions along the object.

As yet another aspect, the estimate includes an estimate of the location, the location being of a tip of the object.

In a complementary aspect, the estimate includes an estimate of the orientation.

In one additional aspect, the deriving, and beamforming by the beamformer, are performed in real time to track the object.

As a yet further aspect, the deriving includes calculating the estimate.

In yet another aspect, the object is a specular reflector of ultrasound.

In some embodiments, a device for performing the above-described functionality is configured as one or more integrated circuits.

In some versions, an estimate is derived of at least one of a location, and an orientation, of an object. A beamformer is initialized with the estimate. The beamformer operates with an ultrasound transducer array. The estimate is based on electromechanically-induced ultrasound that arrives at the array by transmission rather than by reflection.

Details of the novel, tool-pose-based ultrasound beamforming initialization technology are set forth further below, with the aid of the following drawings, which are not drawn to scale.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGs. 1A, 1B are conceptual diagrams for comparing between two-way beamforming and one-way only beamforming;

FIGs. 2A, 2B are conceptual diagrams that portray, correspondingly, a synthetic aperture acquisition scheme and the same scheme using virtual transducers;

FIGs. 3A-3C are schematic diagrams of exemplary ultrasound transducer and shape sensor embodiments;

FIG. 4 is a schematic and conceptual diagram of beamforming parameter considerations in mitigating or eliminating visual artefacts;

FIGs. 5A, 5B are schematic diagrams of electromagnetic- and optical-based sensor embodiments;

FIG. 6 is a conceptual diagram of imaging planes formed to contain an interventional tool in a longitudinal direction; and

FIG. 7 consists of three flow charts on beamformer initialization, imaging data acquisition, and imaging data display, respectively.

DETAILED DESCRIPTION OF EMBODIMENTS

According to one embodiment for imaging an interventional tool, ultrasound transducers attached to the tool are used in one-way only beamforming.

FIGs. 1A, 1B offer, by way of illustrative and non-limitative example, a comparison between two-way beamforming and one-way only beamforming. FIG. 1A, representative of two-way beamforming shows an imaging array 102 of N elements 104 issuing ultrasound that impinges on a reflector 106. Since the ultrasound waves go out and back (from the imaging array to the reflectors and back to the imaging array), this is describable as “two-way” or “round-trip” beamforming. On receive (of the ultrasound that has reflected back), beamforming determines the reflectivity of the reflector 106 and the position of the reflector relative to the array 102. Here, it is assumed that the reflector 106 is in the imaging plane of the array 102, but the same principles apply for three-dimensional beamforming with a two-dimensional array. The array 102 sends out a beam 108 that reflects off reflector 106 and returns to all elements 104 of the array 102. The flight of the pulse is over a distance r(P) + d(i,P) for element i. Each element 104 measures continually the amplitude of the return ultrasound. For each element 104, the time until a maximum of that measurement, i.e., the “round-trip time of flight,” is indicative of the total flight distance. From these measurements, the relative position of the reflector 106 is computed geometrically. As to the reflectivity of the reflector 106, it can be indicated by summing the received traces over all i (i.e., over all elements 104) after applying the adequate time delays corresponding to point P.

As seen from FIG. 1B, ultrasound generated by an ultrasound transducer in one-way only (receive) beamforming does not take account of an echo. Instead, as illustrated here, the ultrasound transducer acting as a transmitter 110 emits a pulse 112 which is incident on each element 104 of the array 102. Thus, the beamforming is based on ultrasound that arrives by transmission rather than by reflection. The flight here of the pulsed ultrasound upon which imaging is based is, in contrast to the two-way beamforming case, over the distance d(i,P). The time from emission of the pulse 112 until the maximum amplitude reading at an element 104 determines the value d(i,P) for that element i. Thus, the position of the transmitter 110 can be derived geometrically, and the reflectivity calculated by summing the received traces over all i after applying the adequate time delays.

Although one-way beamforming is implementable in the time domain via delay logic, as discussed hereinabove, it can also be implemented in the frequency domain by well-known Fourier beamforming algorithms.

FIGs. 2A, 2B portray, respectively, a synthetic aperture acquisition scheme and the same scheme using virtual array elements. Both schemes are utilizable in aspects of the invention.

Turning now to FIG. 2A, for an imaging array 202, each of the N elements 204 sequentially sends out an impulse, i.e., pulse, into the medium. Let $r_{i,P}(t)$ be the temporal signal received by the receiver P (on a catheter, needle, or other interventional tool) when element i fires an impulse. (The origin of time is taken each time an element is fired.) It is assumed that the receiver P is in the imaging plane of the array, but the same principles apply for three-dimensional beamforming with a two-dimensional array. The travel time from i to P is

$$t_{i,P} = d(i,P)/c \qquad \text{(equation 1)}$$

where d(i,P) is the distance between element i and receiver P, and c is the medium's speed of sound. Thus $r_{i,P}(t)$ has its maximum at $t_{i,P}$. An image of the receiver in space is formed by, for each point Q inside the field of view, taking the summation:

$$s(Q) = \Sigma\, r_{i,P}(t_{i,Q}) \qquad \text{(equation 2)}$$

over i = 1 to N. Apodization functions may optionally be used as is standard practice in the art.

The quantity s(Q) will be maximized for Q = P; that is, at the location of the receiver.

Referring now to FIG. 2B, the retrospective dynamic transmit (RDT) with virtual array elements scheme shown is similar to above-described synthetic aperture scheme – the imaging array is replaced by a "virtual array" made of "virtual elements." Each virtual element is the focal location of one focused beam emanating from the real (physical) imaging array. There are as many virtual elements as there are focused beams from the imaging array. The imaging array sends out N beams into the medium, sweeping the field of view. Let $r_{i,P}(t)$ be the temporal signal received by the receiver P in the medium when the beam number i is fired into the medium (i.e., the virtual element i emits an impulse). The origin in time is now taken when the beam is emitted. The travel time from virtual element i to P is

$$t_{i,P} = d(i,P)/c \qquad \text{(equation 3)}$$

The time it takes for the transmitted beam to focus at the location of the virtual array element is

$$t_i = d(i)/c \qquad \text{(equation 3)}$$

where d(i) is the distance between the center of the imaging array's active aperture and the focal point of transmit beam i (i.e., the virtual transducer i). In usual transmit schemes, all transmits are focused at the same depth, so d(i) does not depend on i; let us call it d_1 and

$$t_1 = d_1/c \qquad \text{(equation 4)}$$

It thus takes the time $t_1 + t_{i,P}$ between the emission of beam i and reception of the corresponding impulse at point P. The quantity $r_{i,P}(t)$ thus has its maximum at $t_1 + t_{i,P}$.

An image of the receiver in space is formed by, for each point Q inside the field of view, doing the summation:

$$s(Q) = \Sigma\, r_{i,P}(t_1 + t_{i,Q}) \qquad \text{(equation 2)}$$

over i = 1 to N.

The quantity s(Q) will be maximized for Q = P which is the location of the receiver. As in the synthetic aperture case described earlier, weights can be applied to the different terms of the sum of equation (2), giving more importance to some beams and less importance to others. The optimal weight design is well-known in the art.

In reality, since the virtual array elements are not punctual and have a certain directivity that is governed by the shape of the actually transmitted imaging beams, it is necessary, as well-known in the art, to perform some transmit beam simulations to compute the exact theoretical arrival times of each beam i at each point Q.

Use of retrospective dynamic transmit (RDT) with virtual array elements affords optimal (diffraction-limited) resolution of the tracked object at all depths.

FIG. 3A depicts, by way of illustrative and non-limitative example, an ultrasound imaging device 300. It includes an ultrasound imaging probe 302; ultrasound sensors (i.e., electronic devices that include transducers acting as receivers) 304, 306. The sensors 304, 306 are external to, i.e., separate and apart from, the probe. The device 300 also includes a beamformer 308; a catheter, needle or other tool 310 along which the sensors are attached or otherwise placed; an estimation and initialization module 311 for making or calculating a tool pose estimate and supplying it to the beamformer 308 to initialize the beamformer; and wire inputs 312, 314 from the sensors to the module 311. Alternatively, the sensors 304, 306 and the module 311 might be implemented for communicating wirelessly with each other. The probe 302 includes a transducer array 316 which operates with the beamformer 308 in imaging. The probe is two-dimensional (2D), or 1.75D, and is capable of three-dimensional (3D) imaging, although a one dimensional array can be used for 2D imaging. The lateral direction, denoted “x”, and the axial direction, denoted “z”, are in the plane of the drawing.

The beamformer 308, or a component thereof which may operate according to RDT discussed above, provides one-way-only beamforming of signals that arrive from the wire input 312, 314. The one-way beamforming is represented in FIG. 3 by the arrow 318 from the transducer array 316 to the ultrasound sensor 304 shown on the left, and by the arrow 320 from the array to the other sensor 306. The one-way beamforming is based for example on element-by-element emission in scanning the transducer array 316 and the arrival of the emitted ultrasound at the sensors 304, 306.

The beamformer 308 also performs two-way beamforming which is 2D here, but may be 3D. In the lateral direction, 2D imaging provides a “slice” referred to herein as the target plane. A transmit beam 321 is represented by the arrow from the array 316 to a point 322 in a region of interest 324. The corresponding receive beam 326 is represented by the arrow back to the array 316.

All points 322 in a 3D region of interest 324 are insonified and processed in the imaging.

Likewise, all sensors, here both sensors 304, 306, are utilized in respective one-way beamforming operations.

Within the region of interest 324 is a tip 328, of the catheter 310, which resides, at any given moment, at a respective location 329 and orientation 330 (only one angular component being shown in this drawing view), i.e., a point and a direction, respectively, in 3D space. The location 329 and orientation 330 (or "pose") are determined on-the-fly based on the known attachment points of sensors 304, 306 to the tool, and on the spatial positions of the sensors calculated by the beamformer 308 based on the one-way only beamforming. A separate one-way beamforming result is obtained for each of the sensors 304, 306. The beamforming localizes the sensor 304, 306 in the region of interest 324 in the same coordinate system as the regular pulse-echo image of the region of interest. By inclusion within the catheter 310, the sensors 304, 306 are disposed with respect to it for sensing its location and/or orientation. Optionally for instance, merely the location 329 of the catheter 310, for example of the tip 328, may be derived from the output of a given sensor 304, 306 onboard the catheter. Notably and in any event, the pose estimate is made without the need for a result of any imaging based on data arriving by reflected ultrasound.

In one embodiment, tissue-specific frames (with beamforming and other parameters (pulse length, frequency, filters…) optimized for viewing the anatomy are alternated, or otherwise interspersed, with tool-specific frames (with adaptively determined optimal beamforming parameters optimized, by the novel techniques herein, for the tool content of the frame). Both types of frames fall under the category of pulse-echo acquisition (or "imaging") frames.

An initialization frame, on the other hand, is acquired by scanning the transducer array 316 with the sensors 304, 306 switched into receive mode at the appropriate moments, as described in further detail below. These frames are used to make the tool pose estimate for initializing the beamformer 308 with respect to tool-specific frames.

Initialization and pulse-echo image acquisition are separated by means of frequency or by means of timing (e.g., alternating, or otherwise interspersing, imaging frames with initialization frames). The sensors 304, 306 are triggered active in receive (to, in other words, start the clock at time zero in measuring the one-way delay) by the line trigger of a scanner (not shown) that incorporates the probe 302 and the beamformer 308. A trigger signal is emitted each time the probe 302 emits a different transmit beam. The tissue-specific and tool-specific frames are combined, as discussed in more detail further below, in forming one or more display images. The dynamic range of the initialization frame can be made half that of the imaging frame to take into account one-way beamforming only that induces sidelobes roughly twice as high as conventional two-way imaging.

Although the ultrasound imaging device 300 is described herein above as implemented with ultrasound sensors 304, 306 as receivers, the transducers can alternatively be configured as ultrasound transmitters 110. They operate electromechanically, as in the case of a piezoelectric element, and are as omnidirectional as possible. The same separation, by time or frequency, of tool-pose-estimation (or "initialization") acquisition and imaging acquisition mentioned above in connection with receivers applies also in the case of transmitters. As to frequency separation, the transmitter (or "tracked source") 110 is able to emit short pulses (optionally, more complicated waveforms with transmit codes) which can (but do not necessarily) have a frequency band different from that of the imaging pulses of the intra-operative imaging ultrasound, in order to avoid interference between the initialization and imaging pulses. Reception of initialization and imaging pulses may be differentiated either simply with receive filters or more sophisticated pulse signature identification algorithms.

In addition, in the case of transmitters 304, 306, they are also separated, for initialization frame purposes, by time or frequency. The separation distinguishes the radiofrequency data of one transmitter from the other, for their separate localizations.

Propagation of sound occurs from the transmitter 110 to the individual elements 102 of the transducer array 316. Because of reciprocity, the transmitter 110 that sends signals toward individual elements 104 of the ultrasound scanner can, in an analogous sense, replace the ultrasound receiver, discussed in the previous embodiment, that receives signals from individual elements of the ultrasound scanner, without changing the signal processing for its localization. The transmitter 110, like the receiver 304, 306, can be precisely imaged by adjusting the ultrasound scanner's beamforming delays to account for the one-way only propagation of transmissive ultrasound between the tracked ultrasound transmitter(s) 110 and the transducer array 316. The device used to sense signals from the transmitter1 10 is the same ultrasonic probe 302 (e.g., a 2D probe for 3D tracking) and scanner that are used to make the intra-operative ultrasound anatomical images that are obtained from some combination of the tissue-specific and tool-specific frames.

The scanner triggers emission of sound from the transmitter(s) 110 with its line trigger (which is designed to be fired upon emission of each beam) or frame trigger (which is designed to be fired upon emission of each frame), propagation of sound then occurring from the transmitter(s) to the individual elements 104 of the transducer array 316.

Alternatively, the transmitter 110 can be the one that triggers image acquisition by the ultrasound scanner. This might be desirable in the case where the duty cycle and on/off times of the transmitter(s) on the surgical tool 310 have been optimized for best treatment safety and efficacy (in the case where the transmitter is actually used for treatment). In effect then, the ultrasound imaging device 300 is configured for an ultrasound scanner triggering, by a line trigger or by a frame trigger, emission of sound from the transmitter(s) 110 and/or for the transmitter(s) triggering the scanner active for image acquisition.

The ultrasound scanner can be modified for tracking the transmitter 110 by adjusting its receive beamforming delays, e.g., [r(P) + d(i,P)]/c as in FIG. 1, to account for the one-way only ultrasound propagation (from the transmitter(s) to the probe 302).

The ultrasound scanner alternates imaging frames (active ultrasound emission from the imaging probe 302, the transmitter(s) 110 on the interventional tool 310 are turned off, and conventional two-way beamforming is performed for pulse-echo imaging) with initialization frames (emission from the imaging probe is turned off, the transmitter(s) on the interventional tool are turned on, one-way only beamforming is performed). Optionally, if the transmitter(s) 110 are designed with a different frequency from the imaging frequencies, there is no need to turn on/off the transmitter/imaging probe during the imaging or initialization frames: for the initialization frames, the temporal receive filters are just modified to take into account the different nominal frequency of the transmitter(s) 110.

In an alternative, manual embodiment of the ultrasound imaging device 300, the pose estimate can be derived, instead of on-the-fly, responsive to selection by the user from among candidate poses. Each candidate is associated by software in the beamformer 308 with preset beamforming parameters. The user manually chooses the candidate that is thought to best match the current intervention geometry. The chosen candidate is supplied, and derived by the estimation and initialization module 331 for subsequent output to the beamformer 308.

The estimation and initialization module 311 may be implemented as one or more integrated circuits for deriving the estimate and using the derived estimate to initialize the beamformer.

For easier visualization, an imaging plane or slice 330 may be acquired, as seen in FIG. 3B which shows a side view of the x/z plane. In this example, the tip longitudinally extends within the imaging plane 330.

For display, the tissue-specific and tool-specific frames can be fused together. A weighted average of the two frames may be used. Or, the tool-specific frame may be overlaid in a different color. Alternatively, in a dual display, the left screen could show the tissue-specific frame, with the right screen showing the tool-specific frame.

If the tip 328 is oblique to the imaging plane 330, one or more planes that contain the tip can be imaged, as discussed in an example further below, to afford more accurate display of the anatomy immediately surrounding the distal end of the tip.

FIG. 3C illustrates an exemplary use of shape sensors 334, such as fiber Bragg gratings that are either stretched or compressed by an external stimulus, as an alternative or complement to the ultrasound sensors 304, 306. Here, the shape sensors 334 exist along optical fibers that run longitudinally along the catheter or other tool 310. The fibers, at a proximal end of the catheter 310, are connected to an optical frequency domain reflectometer (OFDR) (not shown) which is communicatively connected to the beamformer 308. Examples of shape sensors for medical instruments such as catheters are provided in U.S. Patent 7,772,541 to Froggatt et al. (hereinafter “Froggatt”), the entire disclosure of which is incorporated herein by reference. As in Froggatt, the shape sensors 334 conform to at least a portion of the catheter 310 for sensing a shape of the portion. They also allow detection of positions, i.e., locations, at the sensors. Based on these measurements, the location 329 and the orientation 330 of the catheter 310 in the imaging space of the probe 302 are calculated. The beamformer 308 uses the estimate of the location 329 and orientation 330 in forming transmit foci 338 along the catheter 310. If the orientation of the catheter 310 is such that its image depth varies along the catheter, the transmit foci 338 are at different depths to conform to catheter. The transmit beam 344, 346 has the richest angular spectrum content at its focal depth, thus maximizing the probability of ultrasound reflection toward the probe 302. Beamforming is accordingly being optimized based on the pose estimate. Although the foci 338 are shown in FIG. 3C as existing on the exterior of the catheter 310, they may be placed elsewhere, in the radial center for example.

The spacing 342 between two transmit beams 344, 346 is shown in FIG. 3C. Interruptions, i.e., interruption artefacts, are sometimes visible along the elongated tool 310, such as a catheter or needle, and can be caused by destructive interference due to echoes from neighboring parts of the tool. The artefacts can be mitigated or eliminated by making spatial sampling of the transmit and/or receive beams finer, as shown by example further below.

Steered beams that insonify an imaged tool 310 with an angle of 60 to 90 degrees with respect to the tool’s body, i.e., angle of incidence of 30 degrees or under, generate good reflections toward the probe 302. As seen in FIG. 3C, the angle of incidence 350 is within the 30 degree range. The good reflection toward the probe 302 provides an easily visible ultrasound image. The transmit and receive beam angles are optimized for tool reflectivity. The optimizing can include maximizing the coherence factor, i.e., ratio of coherently summed signals to incoherently summed signals, to thereby enhance visibility, reduce sidelobes and increase signal-to-noise ratio (SNR). Wiener filtering can be used in low SNR cases. Coherence factor and Weiner filtering techniques are discussed in U.S. Patent No. 7,744,532 to Ustuner et al. and “Weiner Beamforming and Coherence Factor in Ultrasound Imaging”, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 57, No. 6, June 2010.

The avoidance of a normal angle, i.e., exactly 90 degrees, between the tool body and the ultrasound beam can prevent or mitigate visual artefacts, as shown by example in FIG. 4. The beamformer 308 is accordingly configured for limiting an angle of incidence

408 of a transmit beam, a receive beam, or both, to a nonzero value to avoid sidelobe and reverberation artefacts. Thus, reverberation and sidelobe artefacts 410 are prevented or mitigated, this being represented by the circled “x.”

In addition, receive beams 402, 404 are spaced apart by a spatial interval 406. The beam spacing 406 is spatially fine enough to mitigate or eliminate imaging artefacts discernible as interruptions 412, 414, 416 along the interventional tool 310. This is represented in FIG. 4 by the replacement of the interruption 412 with the missing image 418.

FIG. 5A illustrates an (electromagnetic) EM sensing-based ultrasound imaging device 500. It includes an ultrasound probe 502, an EM sensor (or “transducer”) 504 attached to a needle 506 or other interventional medical tool, an EM sensor 508 attached to the probe, an EM field generator 510, a beamformer 512, and an estimation and initialization module 513 . The EM field generator 510 generates a field that induces a current in the EM sensors 504, 508. The EM sensors are configured for wirelessly communicating a measure of the induced current to the EM field generator 510, which, in turn, is designed for receiving the measure. Based on the induced current, the location and orientation of the sensors 504, 508 with respect to the EM field generator 510 are calculated. The estimation and initialization module 513 makes this calculation, registers electromagnetic tracking space with an imaging space of the probe 502, and supplies the results to the beamformer 512. Based on the results, the beamformer 512 performs imaging in conjunction with a transducer array 514. An example of using EM sensors in tracking a medical tool is provided in commonly-owned U.S. Patent No. 7,933,007 to Stanton et al. A similar system which also attaches to the tool an optical sensor is disclosed in commonly-owned U.S. Patent Publication No. 2010/0168556 to Shen et al. Both documents are incorporated herein by reference in their entirety. Although wireless communication of the induced current data is described herein above, the data may be conveyed by wires in the ultrasound probe 502 and wires running down the tool 506. Also, more than one EM sensor may be provided in the probe 502 and in the tool 506. By ultrasound imaging standards, the EM localization is a rough estimate. However, feedback with enhanced ultrasound beamforming according to what is proposed herein is used to fine tune the imaging of the object 506.

An image-based estimate approach, optionally enhanced by EM sensors, is shown in FIG. 5B. Two cameras 550, 552, serving as optical sensors, are aimed both at the base 553 of a needle 554 and at a probe 556, and are therefore disposed with respect to the needle for sensing its location/orientation. Indicia are provided around the periphery of the probe 556, near a transducer array 558, and optionally around the base 553 of the needle 554. The location and orientation of both cameras 550, 552, and images from the cameras, are supplied to an estimation and initialization module 563. From the imaged indicia, a location 329 of a rigid tool and the tool's orientation 330 may be estimated. Location and orientation data determined based on output of EM sensors 564, 566, as described in connection with FIG. 5A, is also supplied to the estimation and initialization module 563. The image based data may be used to update the EM-based data, and a pose estimate is registered with an image space of the beamformer 562. An example of this arrangement is found in commonly-owned U.S. Patent Publication No. 2010/0194879 to Pasveer et al., the entire disclosure of which is incorporated herein by reference.

FIG. 6 shows a cross-section 602 of an interventional tool at least a tip of which longitudinally extends in two separate imaging planes 604, 606. This imaging is particularly useful when the tool extends obliquely to the target plane.

The oblique planes 604, 606 are acquired by use of an ultrasound probe with elevation steering capability, e.g., with a 2D or 1.75D imaging array. Incrementally, in real time, the elevation is varied plane by plane, to create a "thick slice." Thick slice acquisition is alternated or otherwise interspersed, in real time, with acquisition of the target plane data. The thick slice is acquired in the tool-specific frame, and the target plane data is acquired in the tissue-specific frame. From the acquired thick slice, image data corresponding to the oblique plane(s) desired is extracted.

Tissue-specific content of the target plane can be displayed to the user, with one or more of the oblique imaging planes 604, 606, specifically the tool-specific content thereof, alongside. Or, a projection of the tool can be overlaid on the target plane. On the display, an indicator of the relative orientation of the planes can be included. The indicator could, for example, be a schematic of an imaging probe and, extending from it, the two oblique planes 604, 606, illustrating their relative positions to each other.

FIG. 7 consists of flow charts of exemplary processes of beamformer initialization 702, imaging data acquisition 704, and imaging data display 706, respectively.

According to the beamformer initialization process 702, pose data is acquired (step S708). From the acquired pose data, the pose, i.e., location 329 and orientation 330, is calculated (step S710). The beamformer is initialized with the calculated pose (step S712). If initialization is to be updated (step S714), as will typically occur in real time, processing returns to step S708.

In the concurrent data acquisition process 704, the estimated pose is used to acquire one or more tool-specific images (step S716). A tissue-specific image is then acquired (step S718). If imaging data acquisition is to be updated (step S720), as will typically occur in real time, processing returns to step S716.

In the also concurrent data display process 706, display is made of the current acquired imaging data (step S722). The display may include one tool-specific image, alongside a tissue-specific image. If the tool is oblique to the target plane, one or more tool-containing planes 604, 606, specifically the tool-specific content thereof, may instead be placed alongside the target plane, specifically the tissue-specific content thereof, along with an indication of the relative orientations of the planes. If the image display is to be updated (step S724), as will typically occur in real time, processing returns to step S722.

Beamforming to image an object, such as an interventional tool, is enhanced by initializing the beamformer with the object's location, and optionally its orientation. The initializing uses an estimate of the location/orientation. The estimate is derived from the output of one or more sensors. These are disposed external to the imaging array that operates with the beamformer. The estimate is made without the need for a result of any imaging based on data arriving by reflected ultrasound. One or more of the sensors may be attached to the object, which may be elongated, as in the case of a needle or catheter used in medical diagnosis and treatment. In some implementations, one or more of the sensors are attached to the imaging probe. The sensors may be, for example, ultrasound, electromagnetic, optical, or shape sensors. Alternatively, ultrasound transmitting transducers may be substituted for the ultrasound sensors.

The clinical applications of the novel technology discussed herein above include any procedure where determining the location and orientation of a surgical tool is desirable and cannot reliably be performed with standard ultrasound imaging alone.

Although the novel apparatus and methodology can advantageously be applied in providing medical diagnosis or treatment for a human or animal subject, the intended scope of claim coverage is not so limited. More broadly, enhanced imaging, in vivo, in vitro or ex vivo is envisioned.

While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive; the invention is not limited to the disclosed embodiments.

For example, the elongated tool may be an applicator for radioactive seed insertion in treating cancer. As another example, on a tool with multiple ultrasound tracking transducers, the type can be mixed, with some transmitters and others receivers. Also, mixing of sensor types in a single embodiment can involve ultrasound, shape, EM, optical or other types of sensors.

Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims. In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. Any reference signs in the claims should not be construed as limiting the scope.

A computer program can be stored momentarily, temporarily or for a longer period of time on a suitable computer-readable medium, such as an optical storage medium or a solid-state medium. Such a medium is non-transitory only in the sense of not being a transitory, propagating signal, but includes other forms of computer-readable media such as register memory, processor cache and RAM.

A single processor or other unit may fulfill the functions of several items recited in the claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

CLAIMS

What is claimed is:

1. A device (311) configured for deriving an estimate of at least one of a location, and an orientation, of an object (310) and for initializing, with said estimate, a beamformer for operating with an ultrasound transducer array in imaging said object, said estimate being based on output of at least one sensor (304, 306) external to said array and disposed with respect to said object for sensing said at least one of a location and an orientation.

2. The device of claim 1, said estimate being made without need for a result of any imaging based on data arriving by reflected ultrasound (326).

3. The device of claim 1, comprising said at least one sensor, one or more of the sensors being attached to said object.

4. The device of claim 3, said one or more amounting to at least two sensors located mutually apart.

5. The device of claim 1, said object having an elongated body, said at least one sensor (334) conforming to at least a portion of said body for sensing a shape of said portion in determining said orientation (330).

6. The device of claim 1, comprising said at least one sensor, one or more of which is an electronic device.

7. The device of claim 1, comprising said at least one sensor, one or more of which is an ultrasound sensor.

8. The device of claim 1, a tool (554) comprising said object being rigid and having a base (553), said device comprising said at least one sensor, one or more of the sensors being configured for optically detecting said base to afford said deriving.

9. The device of claim 1, comprising said beamformer (308), said beamformer configured for limiting angle of incidence (350) of a transmit beam, a receive beam, or both, to a nonzero value to avoid sidelobe and reverberation artefacts.

10. The device of claim 1, comprising said beamformer, said beamformer configured for using said estimate to optimize said beamforming.

11. The device of claim 1, said beamformer configured for, based on said estimate, placing a transmit focus (338) at said object.

12. The device of claim 11, said estimate being of said location (329) and said orientation (330), said object being elongated, said beamformer being further configured for, based on said estimate, placing a plurality of transmit foci along said object at different depths to conform to said object, said focus being among said plurality.

13. The device of claim 1, said object being elongated, said beamformer configured with steering capability in an elevation direction, said initializing being directed to forming an imaging plane (604) in which at least a tip (328) of said object longitudinally extends.

14. The device of claim 13, said at least a tip currently longitudinally extending within another imaging plane (606), the planes being mutually non-parallel, said beamformer being further configured for imaging both planes for concurrent display in real time.

15. The device of claim 1, said object being elongated, said beamformer configured for beam spacing that is spatially fine enough to mitigate or eliminate imaging artefacts discernible as interruptions (412-416) along said object.

16. The device of claim 1, said estimate comprising an estimate of said location, said location being of a tip of said object.

17. The device of claim 1, said estimate comprising an estimate of said orientation.

18. The device of claim 1, further configured for performing said deriving, and beamforming by said beamformer, in real time (S714, S720) to track said object.

19. The device of claim 1, said deriving comprising calculating said estimate (S710).

20. The device of claim 1, said object being a specular reflector of ultrasound.

21. The device of claim 1, configured as one or more integrated circuits.

22. A beamforming method for enhancing visualization (706) of an object, said method comprising:

to enhance said visualization, initializing, with an estimate of at least one of a location, and an orientation, of said object, a beamformer for operating with an ultrasound transducer array in imaging said object, said estimate being based on output of at least one sensor external to said array and disposed with respect to said object for sensing said at least one of a location and an orientation.

23. A computer software product for enhancing visualization of an object, said product comprising a computer-readable medium embodying a computer program that includes instructions executable by a processor for performing an act comprising:

to enhance said visualization, initializing, with an estimate of at least one of a location, and an orientation, of said object, a beamformer for operating with an ultrasound transducer array in imaging said object, said estimate being based on output of at least one sensor external to said array and disposed with respect to said object for sensing said at least one of a location and an orientation.

24. A device configured for deriving an estimate of at least one of a location, and an orientation, of an object and for initializing, with said estimate, a beamformer for operating with an ultrasound transducer array, said estimate being based on electromechanically-induced ultrasound that arrives at said array by transmission (112) rather than by reflection.

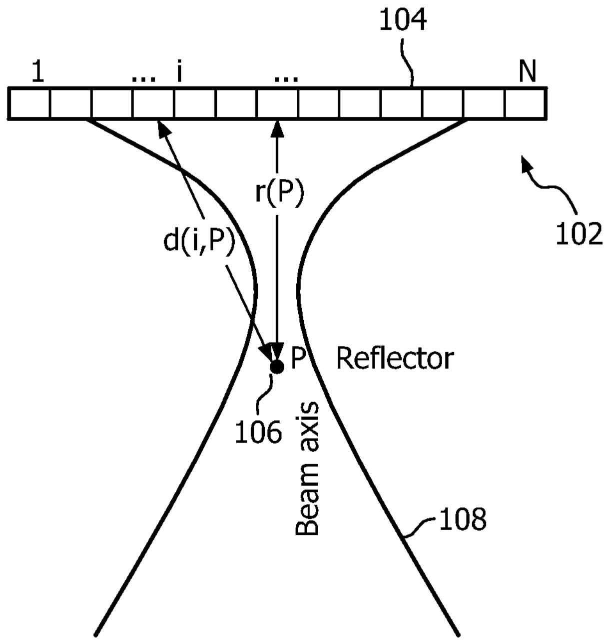

FIG. 1A
Prior Art

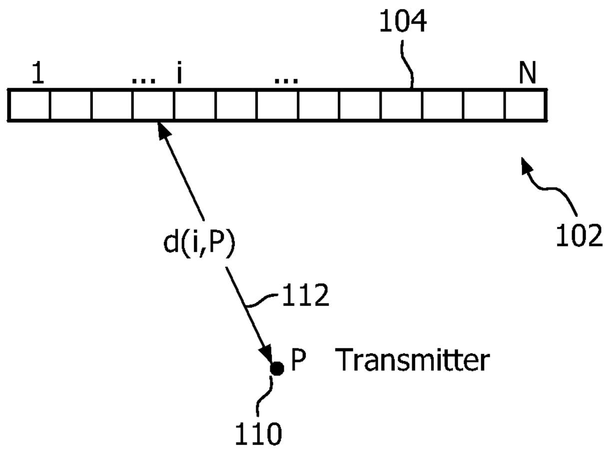

FIG. 1B

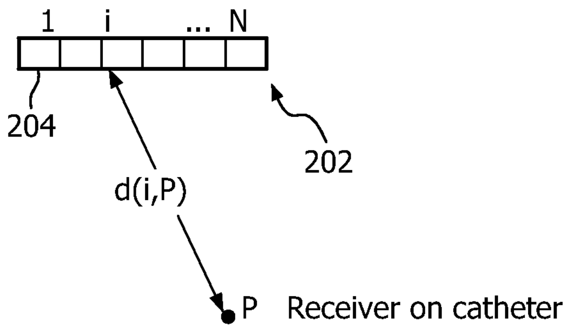
1
i
...
N
204
202
d(i,P)
P Receiver on catheter

FIG. 2A

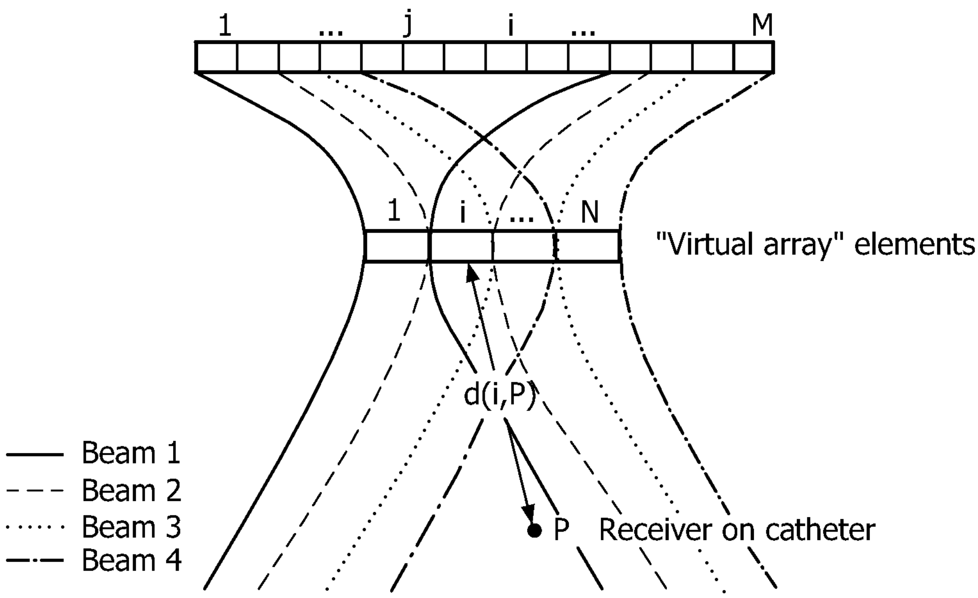
1
...
j
i
...
M
1
i
...
N
"Virtual array" elements
d(i,P)
P Receiver on catheter
Beam 1
Beam 2
Beam 3
Beam 4

FIG. 2B

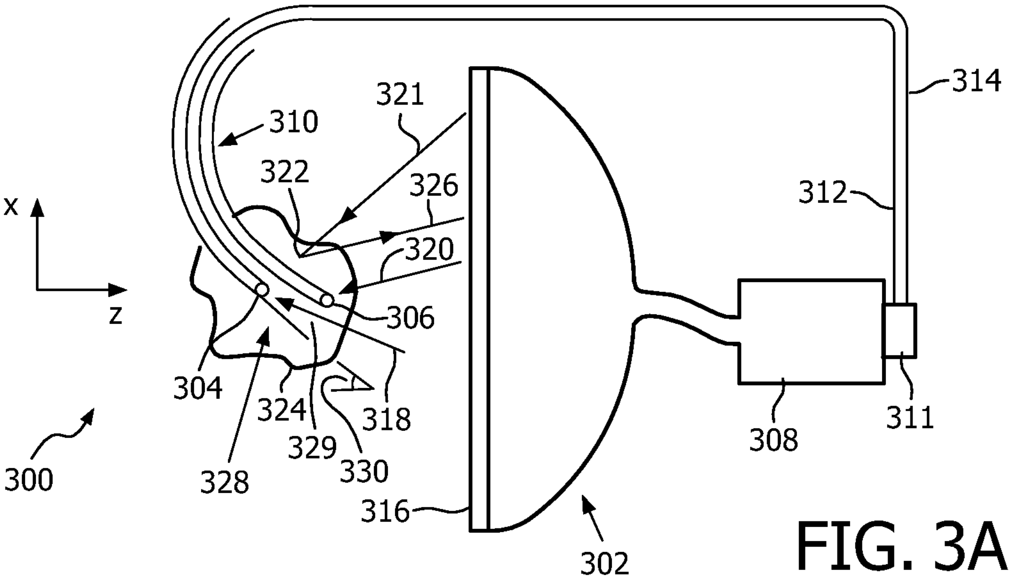

FIG. 3A

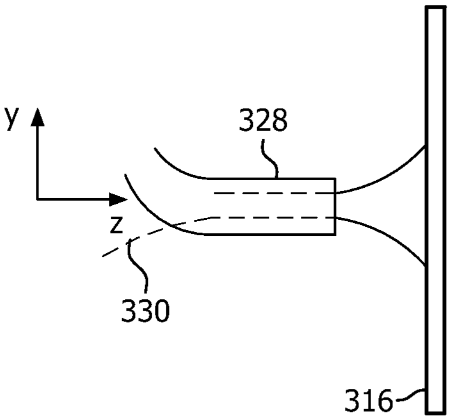

FIG. 3B

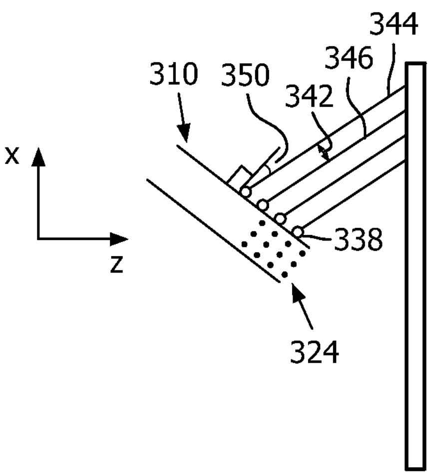

FIG. 3C

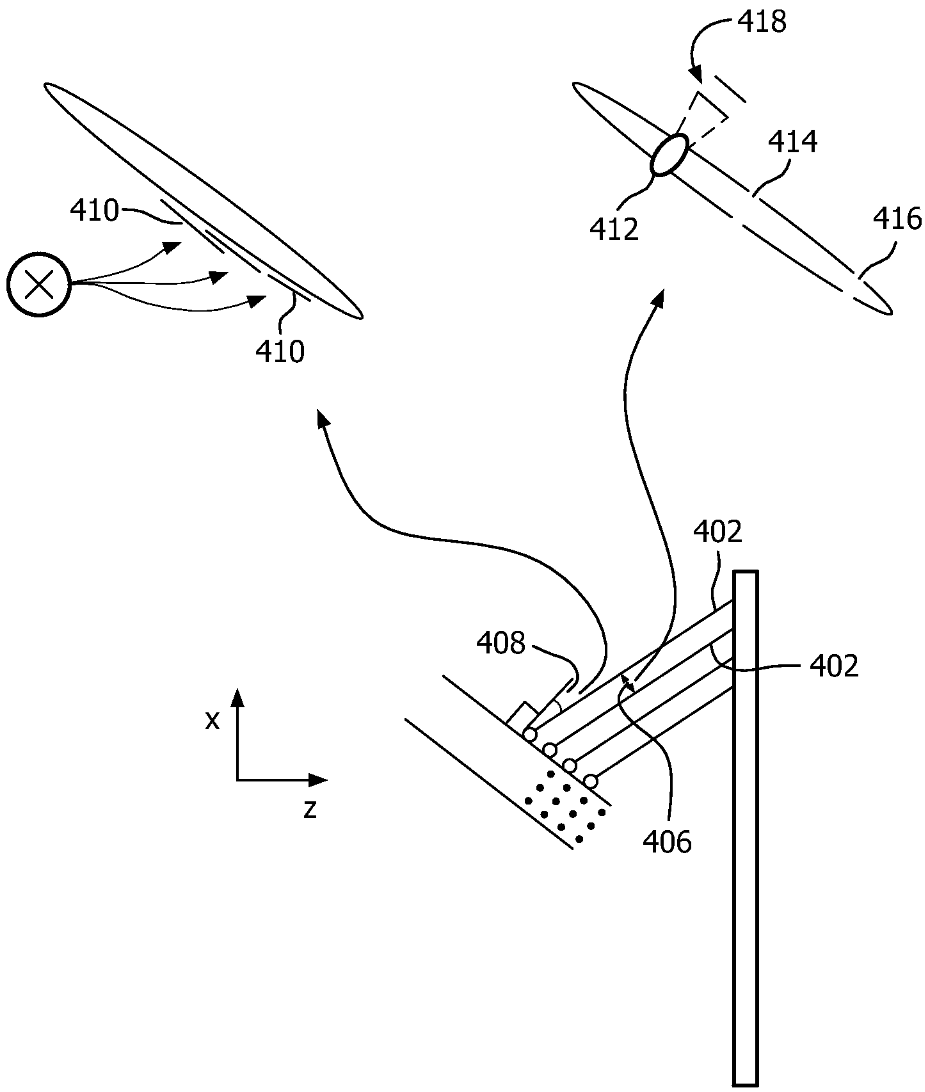

FIG. 4

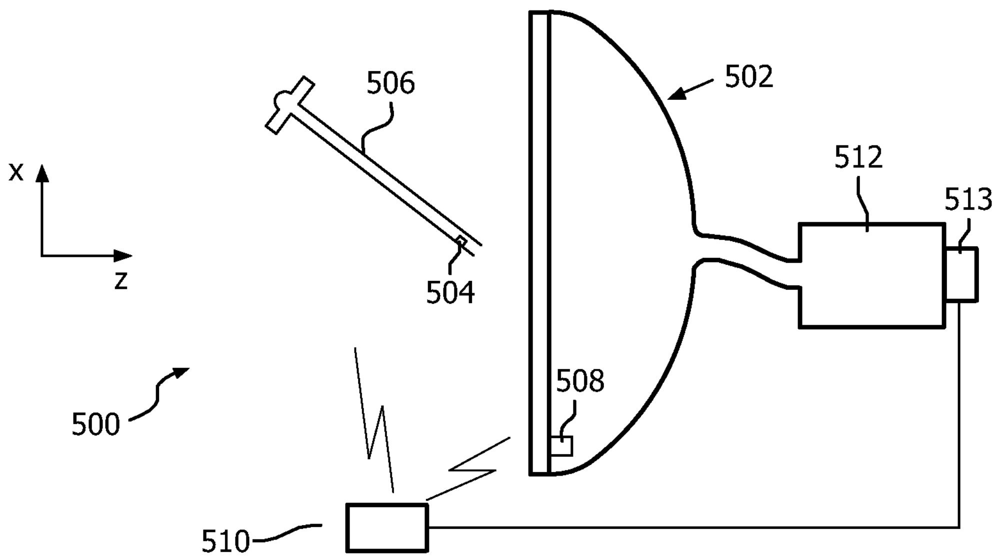
506
502
x
512
513
z
504
508
500
510

FIG. 5A

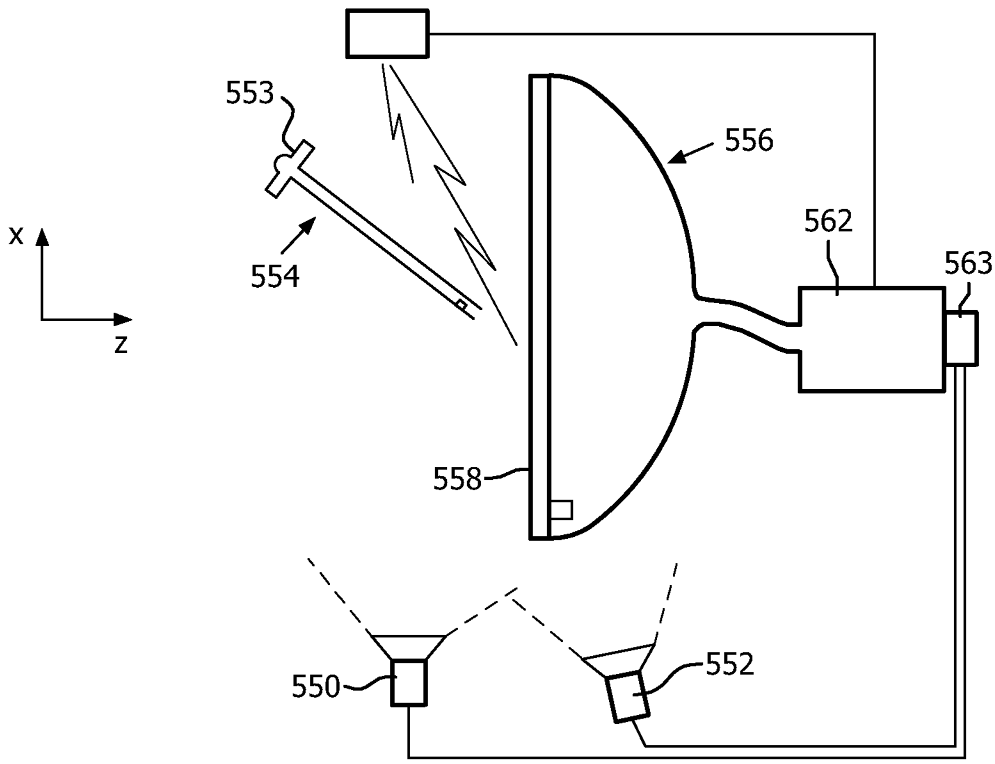
553
556
x
562
554
563
z
558
550
552

FIG. 5B

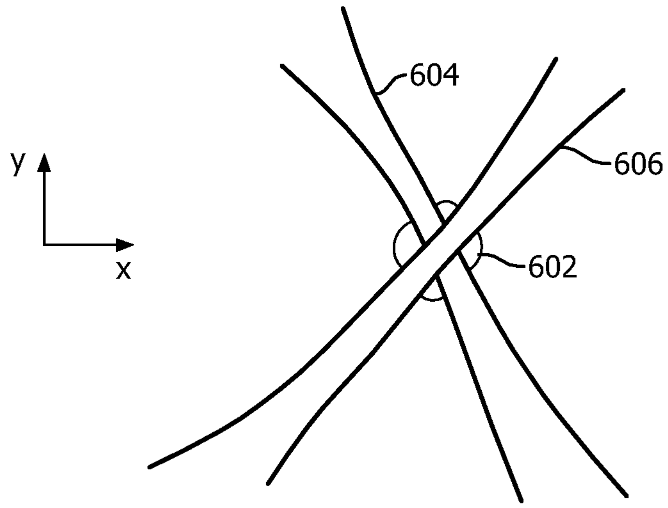
604
606
602
y
x

FIG. 6

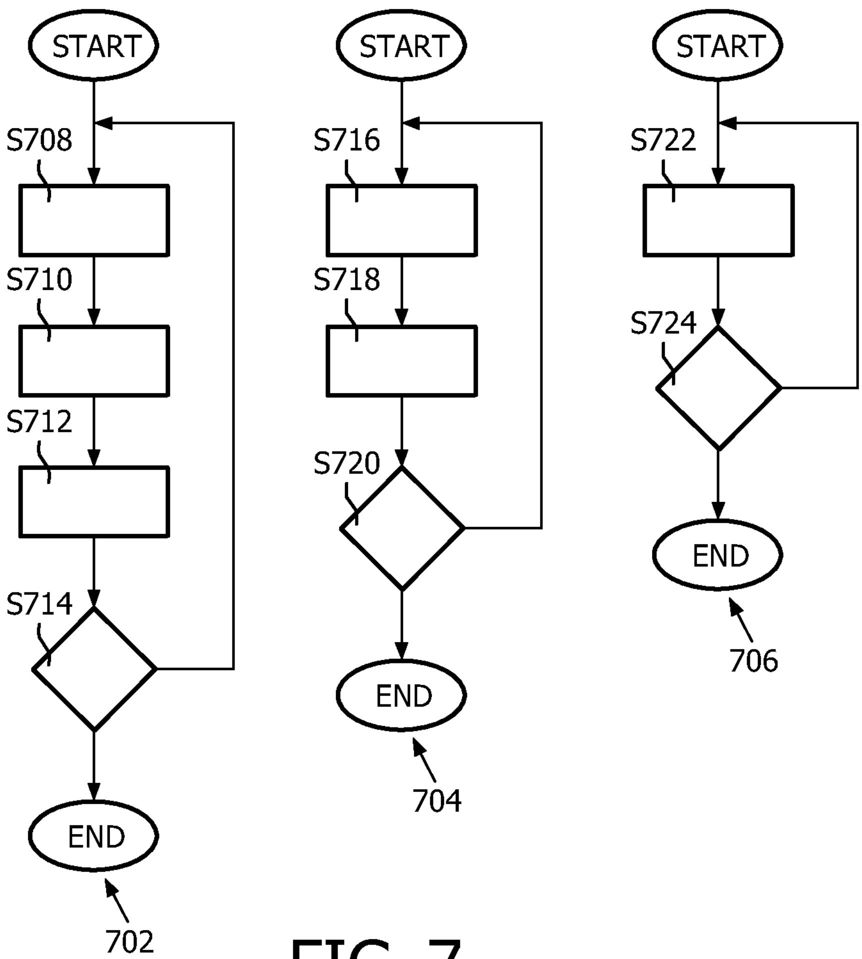
START
S708
S710
S712
S714
END
702
START
S716
S718
S720
END
704
START
S722
S724
END
706

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2012/053071

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61B8/08 G01S7/52 G01S15/89
ADD.

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)
A61B 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 practicable, search terms used)

EPO-Internal, WPI Data

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 2003/060700 A1 (SOLF TORSTEN [DE] ET AL) 27 March 2003 (2003-03-27) the whole document	1-23 24
Y A	US 2002/173720 A1 (SEO YASUTSUGU [JP] ET AL) 21 November 2002 (2002-11-21) paragraph [0056] figure 8	24 1-23

-/--

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

[X] See patent family annex.

* 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	Date of mailing of the international search report
28 September 2012	09/10/2012

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, Fax: (+31-70) 340-3016	Willig, Hendrik

1

Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CHEUNG S ET AL: "Enhancement of needle visibility in ultrasound-guided percutaneous procedures", ULTRASOUND IN MEDICINE AND BIOLOGY, NEW YORK, NY, US, vol. 30, no. 5, 1 May 2004 (2004-05-01), pages 617-624, XP004515003, ISSN: 0301-5629, DOI: 10.1016/J.ULTRASMEDBIO.2004.02.001 cited in the application the whole document -----	24
A	ALPER AYVACI ET AL: "Biopsy needle detection in transrectal ultrasound", COMPUTERIZED MEDICAL IMAGING AND GRAPHICS, PERGAMON PRESS, NEW YORK, NY, US, vol. 35, no. 7, 24 March 2011 (2011-03-24), pages 653-659, XP028282344, ISSN: 0895-6111, DOI: 10.1016/J.COMPMEDIMAG.2011.03.005 [retrieved on 2011-04-08] the whole document -----	1-24
A	US 2009/093719 A1 (PELISSIER LAURENT [CA] ET AL) 9 April 2009 (2009-04-09) paragraphs [0077] - [0082], [0085] - [0086] figures 5A,5B -----	1-24

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2012/053071

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2003060700 A1	27-03-2003	DE 10115341 A1 EP 1245191 A2 JP 2002306473 A US 2003060700 A1	02-10-2002 02-10-2002 22-10-2002 27-03-2003
US 2002173720 A1	21-11-2002	NONE	
US 2009093719 A1	09-04-2009	US 2009093719 A1 US 2012232380 A1	09-04-2009 13-09-2012