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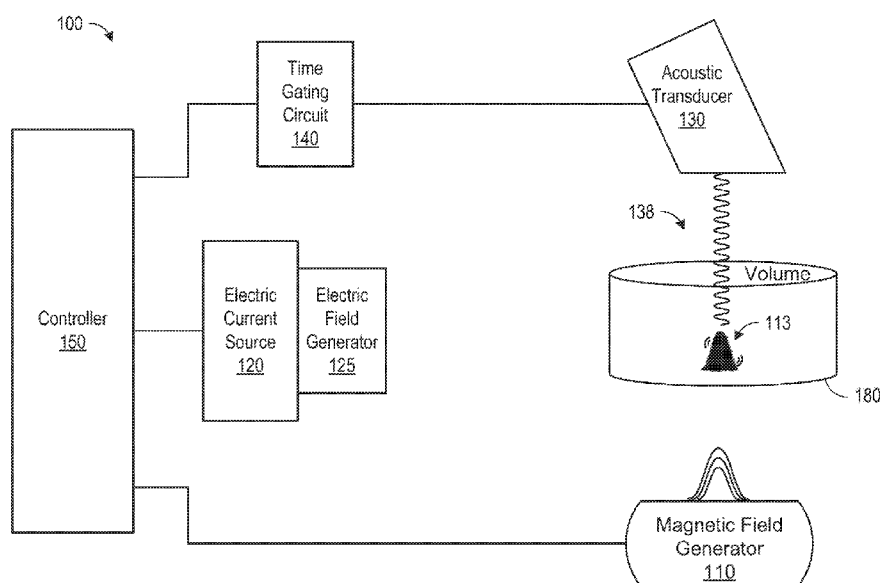


FIG. 1E

(57) Abstract: In one embodiment, a superlens is used to sub-diffraction-limit focus a magnetic field within a volume. A local magnetic field intensity maximum, or "hotspot," is thereby created that is focused in two spatial directions substantially parallel to the superlens. The hotspot extends from the superlens through one or more coplanar layers of the volume. An electric field is superimposed over the magnetic field within the volume to be imaged. The superposition of electric and magnetic fields induces localized Lorentz forces. The modulation of the magnetic and/or electric field causes the portion of the volume in the hotspot to vibrate and emit acoustic signals at a frequency suitable for acoustic imaging. An acoustic transducer receives the emitted acoustic signals. The location from which the acoustic signals are emitted is constrained in two dimensions by the superlens. Time gating the acoustic signals received from the hotspot is used to localize the received acoustic signals in the third dimension.

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Acoustic-Electromagnetic Tomography

[0001] All subject matter of the Priority Application(s) is incorporated herein by reference to the extent such subject matter is not inconsistent herewith.

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TECHNICAL FIELD

[0002] This disclosure relates to acoustic-electromagnetic volumetric imaging. For example, magnetic fields and electric fields may induce localized Lorentz forces within a volume to cause the volume to produce detectable acoustic signals for imaging.

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BRIEF DESCRIPTION OF THE DRAWINGS

[0003] FIG. 1A illustrates a block diagram of an acoustic-electromagnetic volumetric imaging system, according to one embodiment.

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[0004] FIG. 1B illustrates a magnetic field intensity maximum, or magnetic field hotspot, formed within a volume by the acoustic-electromagnetic volumetric imaging system of FIG. 1A.

[0005] FIG. 1C illustrates an electric field generator of the acoustic-electromagnetic volumetric imaging system of FIG. 1A permeating the volume with an electric field.

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[0006] FIG. 1D illustrates the portion of the volume at the location of the magnetic field hotspot vibrating due to a time-dependent electromagnetic force induced by the electric and magnetic fields therein.

[0007] FIG. 1E illustrates an acoustic transducer of the acoustic-electromagnetic volumetric imaging system of FIG. 1A receiving an acoustic signal produced by the time-dependent electromagnetic force vibrating the portion of the volume at the location of the magnetic field hotspot.

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[0008] FIG. 2 illustrates a block diagram of another embodiment of the acoustic-electromagnetic volumetric imaging system that utilizes a magnetic metamaterial superlens to produce a subwavelength-focused magnetic field within a volume.

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[0009] FIG. 3A illustrates a magnetic coil producing a relatively unfocused magnetic field within a volume, according to one embodiment.

[0010] FIG. 3B illustrates a magnetic coil and a superlens operating in concert to produce a subwavelength-focused magnetic field to a greater depth, according to one embodiment.

5 **[0011]** FIG. 4A illustrates a three-dimensional representation of a subwavelength magnetic field hotspot, according to one embodiment.

[0012] FIG. 4B illustrates locations of two time-gated cross-section acoustic signal data captures from the magnetic field hotspot of FIG. 4A.

[0013] FIG. 4C illustrates cross-sectional views of the relative magnitude of the magnetic field at the first and second time-gated cross-sections of FIG. 4B.

10 **[0014]** FIG. 5 illustrates a method for acoustic-electromagnetic volumetric imaging, according to one embodiment.

[0015] FIG. 6 illustrates a functional block diagram of an acoustic-electromagnetic volumetric imaging control system, according to one embodiment.

15 **DETAILED DESCRIPTION**

[0016] According to various embodiments, systems, apparatuses and methods are described herein that relate to acoustic-electromagnetic imaging. In one specific embodiment, a superlens is used to sub-diffraction-limit focus a magnetic field within a volume. A local field intensity maximum, or "hotspot," is thereby
20 created that is focused in two spatial directions substantially parallel to the superlens within the volume. The hotspot of intense magnetic field may extend through one or more coplanar layers of the volume relative to the superlens. The electric field permeating the volume is modulated at a modulating frequency.

[0017] The modulating electric field produces an electromagnetic force on
25 material within the magnetic field hotspot. The electromagnetic force causes the material within the magnetic field hotspot to vibrate and emit an acoustic signal. The frequency of the acoustic signal may be selected based on the modulation frequency of the electric field and the frequency of the magnetic field (which may be quasistatic in some embodiments to avoid thermal heating of the volume). An
30 acoustic transducer may receive the acoustic signals emitted from the vibrating portion of the volume within the magnetic field hotspot. The location from which the acoustic signals are emitted is constrained in two dimensions by the superlens and time-gating may be used to localize the received acoustic signals in the third

dimension. Ultrasonic imaging techniques may be used to generate three-dimensional images of the portion of the volume (or two-dimensional images if desired).

5 **[0018]** The specific embodiment above represents just one possible combination of components. Numerous alternatives and variations are within the scope of this disclosure. More generally, any of a wide variety of adjustable magnetic field generators may be used to produce a magnetic field intensity with a maximum in at least one cross-section of a volume to be imaged (i.e., a magnetic field hotspot). The magnetic field hotspot may permeate multiple cross-sections
10 of the volume to be imaged. The cross-sections may be defined as planes substantially orthogonal to the propagation direction of the magnetic field that forms the hotspot.

15 **[0019]** The location of the magnetic field intensity maximum for a given cross-section is defined relative to the field intensities of other locations of the same cross-section, not globally. That is, the field localization of a magnetic field intensity maximum of a cross-section is defined within the two-dimensional manifold of the cross-section itself, and not within the direction of magnetic field propagation. A magnetic field intensity maximum can be synonymously described as being at/in/on/within/of a cross-section of the volume, and each cross-section
20 can have a unique magnetic field intensity maximum. The magnetic field intensity maximums of multiple cross-sections may be substantially concentric when the cross-sections are defined orthogonal to the propagation direction of the magnetic field intensity maximum.

25 **[0020]** An electric current source may superimpose an electric field on the magnetic fields within the volume. The combination of the electric and magnetic fields causes particles within the volume to vibrate and produce an acoustic signal. At least one of the electric and magnetic fields may be modulated or otherwise varied with time.

30 **[0021]** An acoustic transducer may receive the acoustic signal produced by the time-dependent electromagnetic force on the volume induced by the electric and magnetic fields. The magnetic field intensity from the adjustable magnetic field generator may permeate multiple cross-sections, all of which may vibrate due to the applied magnetic field and electric field. The cross-sections of the magnetic

field hotspot may be defined perpendicular to the adjustable magnetic field generator. An electronic circuit may time-gate the output of the acoustic transducer in temporal correlation with time-dependent adjustments to the magnetic field intensity maximum produced by the adjustable magnetic field generator.

[0022] An electronic controller may control operation of the adjustable magnetic field generator, the electric current source, and the time-gating electronic circuit. For example, the electronic controller may synchronize operation of the various components to enable high-resolution acoustic data capture from acoustic signals generated from within the volume itself.

[0023] In various embodiments, the magnetic field may be subwavelength focused as a magnetostatic beam, or hotspot, within the volume. The electric field may be a relatively weak, unfocused electric field, modulated at a desired ultrasound frequency, that permeates the volume. Portions of the volume within the hotspot will vibrate with significant force due to the relatively high-magnitude magnetic field within the hotspot at a frequency corresponding to the modulation frequency of the relatively weak, unfocused electric field. Portions of the volume outside of the hotspot will vibrate with very little force due to the lack of strong magnetic or electric fields.

[0024] In various embodiments, the magnetic field intensity maximum produced by an adjustable magnetic field generator provides spatial bounds for imaging in two dimensions with a resolution corresponding to the diameter of the cross-section of the magnetic field intensity maximum. The time gating of the received acoustic signal by the electronic circuit provides a spatial bound for imaging in the third dimension. The resolution in the dimensions corresponding to the diameter of the cross section of the magnetic field intensity maximum (i.e., again, the magnetic field hotspot) may vary with respect to the dimension bounded by the time-gating. That is, the diameter of the magnetic field hotspot may vary based on the distance from the adjustable magnetic field generator. For example, in some embodiments the magnetic field intensity maximum may be a hotspot that decays exponentially (or as a power law) with respect to distance from the adjustable magnetic field generator. The combination of the electric and magnetic fields

induces a localized Lorentz force on the cross sections of the magnetic field hotspot to cause them to vibrate.

[0025] The volume may comprise a medium that is electromagnetically opaque at microwave frequencies, making it difficult or impossible to image with conventional microwave imaging techniques. For instance, volumes that include or are enclosed (or even partially enclosed) by media that is opaque at microwave frequencies may not be readily imaged using traditional microwave imaging (e.g., mapping the steady-state permittivity and/or conductivity distribution of the volume). Similar problems exist for millimeter-wave, terahertz and optical (including infrared) imaging techniques when the volume comprises a medium that is opaque (strongly scattering, absorptive, or reflective) at the imaging frequencies. For ultrasonic imaging, volumes may not be readily imaged if they include or are encased by a medium that is acoustically opaque, strongly scattering, absorptive, resonant, or highly reflective.

[0026] Examples of such volumes are not uncommon. For instance, the volume may include or be partially encased by an electrically conductive medium and/or include one or more metal-rich boundaries. The volume may include water with dissolved ionic salts that are not easily imaged with traditional imaging techniques. In some instances, the volume may be biological in nature, comprising, for example, soft tissues and/or bone material. Traditional ultrasonic imaging approaches cannot adequately image soft tissue that is obscured by, encased, or partially encased by bone material. For example, traditional ultrasonic imaging approaches cannot adequately image lung tissue within the rib cage or brain tissue within the skull. As another example, traditional ultrasound imaging techniques based on focused ultrasound beams cannot adequately image lungs, due to the high scattering and reflectivity of the numerous tissue/air interfaces present there. In contrast, the presently described systems and methods allow for the effective “insertion” of an ultrasonic probe through the bone material into the soft tissue, and operating it at sufficiently low acoustic frequencies where acoustic attenuation is substantially lower than at the acoustic frequencies used in traditional techniques. An ultrasound transducer receives time-gated ultrasound from the soft tissue as if it were being emitted from a point source within the soft tissue.

[0027] Generally, conventional imaging systems utilize high frequency RF and/or high frequency ultrasound because the image resolution is highly dependent on wavelength. Thus, it is generally difficult or impossible to image volumes that are opaque at the relevant frequencies for a given imaging system.

5 The use of lower frequencies in traditional systems is not possible because the image resolution would be too low.

[0028] As noted above, the image resolution of the presently described systems and methods is not dependent on the wavelength of the electric or magnetic fields. Rather, the resolution in the plane orthogonal to the direction of the magnetic field propagation is based on the time-gating intervals, and the resolution in the planar cross sections is based on the diameter of the magnetic field hotspot. For example, in a given time-gated cross-section the magnetic field hotspot may be centered at the local maximum of magnetic field within the plane and the diameter of the magnetic field hotspot may correspond to a defined falloff point of the magnetic field intensity within the plane (e.g., the 3dB, 6dB, or 10dB falloff points). Because the resolution of the systems and methods described herein is not dependent on the wavelength of the electric and magnetic fields, high-resolution imaging is possible using relatively low frequencies.

[0029] The acoustic transducer may comprise one or more ultrasound microphones and/or ultrasound receivers. The adjustable magnetic field generator may produce a quasistatic magnetic field and the electric current source may comprise an alternating current source modulated at ultrasonic frequencies (e.g., frequencies greater than 20 kilohertz). For example, the alternating electric current source may be modulated at frequencies between 750 kilohertz and 2 megahertz. The modulation frequency may be selected to correspond to a target acoustic frequency to be received by the acoustic transducer. For instance, the electric current source may be modulated at a frequency many times greater than the quasistatic magnetic field (e.g., tens, hundreds, or even thousands of times greater).

30 **[0030]** The adjustable magnetic field generator may comprise an array of adjustable magnetic field sources. Each of the magnetic field sources may comprise, for example, an inductor and/or an adjustable array of static magnetic field sources. In some embodiments, the adjustable magnetic field source may

comprise an array of electromechanically-actuated static magnetic field sources that are, for example, physically displaced to achieve magnetic field amplitude or direction modulation. In some embodiments, electromechanically-actuated static magnetic field sources are physically rotated during electromechanical actuation to achieve magnetic field amplitude, direction, or polarity modulation.

[0031] In some embodiments, the adjustable array of static magnetic field sources may be adjusted to maximize magnetic field two-dimensional localization in one particular cross section of the magnetic field hotspot. Static magnetic field sources, such as those used in an electromechanically adjustable array, may include permanent magnets, electromagnets, and/or superconducting coils.

[0032] The adjustable magnetic field generator may produce an alternating magnetic field at a frequency greater than, for example, 20 kilohertz. For instance, the alternating magnetic field may operate at 1 megahertz or more. In such embodiments, the electric current source may be a DC current source to generate a DC electric field within the volume to be imaged. Alternatively, an alternating current source may be used to generate an AC electric field. The alternating current source may operate at a frequency greater than that of the alternating magnetic field.

[0033] The electric current source may generate an RF electric field within the volume that, in combination with the magnetic field, induces localized Lorentz forces on particles within the volume to be imaged. The RF electric field may operate at any of a wide variety of frequencies including, for example, various frequencies of frequency bands between 1 kilohertz and 20 megahertz.

[0034] As described herein, an adjustable magnetic field generator may comprise a combination of magnetic field sources positioned relative to a magnetic metamaterial superlens. For example, a cylindrical superlens may be used to provide sub-diffraction-limited focus of the magnetic field to the hotspot. The magnetic metamaterial superlens may include magnetic metamaterial with a negative magnetic permeability for one or more polarizations of magnetic field. The magnetic permeability may be isotropic and negative for one or more polarizations of magnetic field.

[0035] A magnetic field source positioned relative to the magnetic metamaterial superlens may be moved (e.g., translated, moved farther or closer to the

superlens, and/or rotated) relative to the magnetic metamaterial superlens in one or more directions to move and/or change the shape of the hotspot (i.e., the magnetic field intensity maximum). In some embodiments, the magnetic metamaterial superlens may be adjustable or tunable via, for example, electric or electromechanical input controls.

[0036] As previously described, the electric and magnetic fields cause material within the hotspot to vibrate and emit acoustic signals. An ultrasonic imaging system may process time-gated acoustic signals to generate an image of the hotspot based on images of a plurality of cross-sections. Multiple images, or one larger image (e.g., a stitched image), can be obtained by moving the hotspot within the volume and capturing additional time-gated images of the volume at each sequential hotspot location.

[0037] Many possible combinations of the embodiments and elements described above may be used to generate an image of a portion of a volume. In one specific embodiment, a magnetic field source and a magnetic metamaterial superlens operate in conjunction to produce a magnetic field intensity as a "hotspot" within a volume. An electric current source generates an electric field within the volume. The electric field may be focused to the hotspot or unfocused; either way, within the hotspot, the magnetic field and electric field induce localized time-dependent electromagnetic forces on the volume (e.g., localized Lorentz forces) that causes particles within the hotspot to vibrate and emit an acoustic signal.

[0038] An acoustic transducer receives the acoustic signals. The electromagnetic force on the volume induced by the electric and magnetic fields is time-dependent. Accordingly, an electronic circuit may time-gate the output of the acoustic transducer in temporal correlation with adjustments to the magnetic field intensity maximum. An electronic controller can control the operation of the electrical current source, adjustability and/or tunability of the superlens, the time-gating electronic circuit, and/or the magnetic field source.

[0039] As previously described, the electric current source may be a DC current source to generate a DC electric field within the volume, or it may be an AC current source to generate an AC electric field within the volume. The electric and magnetic fields may operate at any of a wide range of frequencies that may be

selected to target a specific frequency of acoustic signal. For example, a target acoustic ultrasonic signal between 1 and 3 megahertz may be obtained by selecting corresponding electric and magnetic fields. Various harmonics and/or beat frequencies may be utilized and/or targeted in some embodiments.

5 **[0040]** In some embodiments, the acoustic transducer may comprise a single microphone that is coaxially located relative to an axis of the superlens and the generated hotspot. In other embodiments, the acoustic transducer may comprise an array of ultrasound receivers and/or may be non-coaxially located relative to the superlens.

10 **[0041]** The specific components and arrangements of the systems described herein are merely examples of possible embodiments. Various alternative systems, devices, and components may be utilized to induce an electromagnetic force within a volume to cause it to vibrate. A wide variety of systems and methods may be utilized to capture and localize the acoustic signals generated by
15 the vibrations. Ultrasonic imaging techniques may be used to generate an image of the portion of the volume that is vibrating.

[0042] It is appreciated that alternative combinations of systems and components may be used to generate a magnetic field intensity maximum and an electric field within a volume, and then receive acoustic signals produced by the
20 resulting electromagnetic force at the location of the magnetic field intensity maximum. The received acoustic signals may be used to generate ultrasonic images using, for example, time-gating techniques while controlling the generation of the magnetic and/or electric fields.

[0043] Thus, the presently described systems and methods utilize electric and
25 magnetic fields to induce portion of a volume to emit ultrasound that can be imaged. This allows for imaging of volumes that cannot be readily imaged by traditional RF-based and Ultrasound-based imaging systems. The presently described systems and methods provide for non-invasive imaging in a way that, in many ways, is the functional equivalent of inserting a high-resolution ultrasound
30 emitting probe into a precise location within a volume. As previously noted, volumes containing imaging-opaque media at the frequencies used by traditional imaging system may not be readily imaged by such systems. In contrast, the presently described systems and methods operate to “insert” a high-resolution

acoustic probe (e.g., ultrasound probe) into the volume in a non-invasive way. The systems and methods enable the effective “insertion” into volumes containing or encased by media that does not otherwise lend itself to imaging by traditional means.

5 **[0044]** In one specific embodiment, the magnetic field intensity maximum is a quasistatic magnetic field and the electric field comprises an alternating current electric field operating at or modulated at frequencies greater than 20 kilohertz to induce ultrasonic (i.e., greater than 20 kilohertz) emissions from the volume. For example, the alternating electric current source may be modulated at a frequency
10 greater than 1 megahertz. By reducing the frequency of the magnetic field (e.g., by utilizing a quasistatic magnetic field) thermal heating of the volume may be reduced while retaining the ability to induce an electromagnetic force within a target region of the volume. Thus, unlike many systems in which an electromagnetic field comprises electric field and magnetic field components at
15 the same frequency, many of the presently described embodiments contemplate disassociated electric and magnetic fields in the near-field that can be independently controlled, modulated, focused, etc.

[0045] The generalized descriptions of the systems and methods herein may be utilized and/or adapted for utilization in a wide variety of industrial, commercial,
20 and personal applications. For example, the systems and methods described herein may be utilized in any of a wide variety of medical, security, and other imaging environments.

[0046] Many existing computing devices and infrastructures may be used in combination with the presently described systems and methods. Some of the
25 infrastructure that can be used with embodiments disclosed herein is already available, such as general-purpose computers, computer programming tools and techniques, digital storage media, and communication links.

[0047] Moreover, the systems and methods described herein may utilize various technologies and principles from other fields, including, for example, those
30 relating to magnetic resonances, sub-diffraction-limit focusing, superlenses, near-field focusing, metamaterial superlenses, near-field magnetic coupling for wireless power transfer, and the like. Examples of related technologies are found in the following disclosures, which are hereby incorporated by reference in their entities:

Dmitriy Korobkin, et al. *Enhanced Near-Field Resolution in Midinfrared Using Metamaterials*, Journal of Optical Society of America B, Vol. 23, No. 3, March 2006, 468-478; Guy Lipworth, et al. *Magnetic Metamaterial Superlens for Increased Range Wireless Power Transfer*, Scientific Reports, 4:3642, 5 www.nature.com/scientificreports, 10 January 2014, 1-6; Da Huang, et al. *Magnetic Superlens-Enhanced Inductive Coupling for Wireless Power Transfer*, Journal of Applied Physics 111, 20 March 2012, 064902-1-8; Jian-Wen Dong, et al. *Metamaterial Slab as a Lens, a Cloak, or an Intermediate*, Physical Review B 83, 15 March 2011, 115124, 1-7; Yaroslav Urzhumov, et al. *Metamaterial-Enhanced Coupling Between Magnetic Dipoles for Efficient Wireless Power Transfer*, Physical Review B 83, 18 May 2011, 205114, 1-10; Manuel J. Freire, et al. *On the Applications of $\mu_r = -1$ Metamaterial Lenses for Magnetic Resonance Imaging*, Journal of Magnetic Resonance, <http://alojamientos.us.es/gmicronda/Miembros/Freire/freire.htm>, 2009; Thomas Taubner, et al., *Near-Field Microscopy Through a SiC Superlens*, Science Magazine Vol. 313, 15 September 15 2006, 1595.

[0048] Many of the embodiments described herein can be implemented with metamaterial devices. Metamaterial devices can be used to form lens, such as superlenses, that have negative permeability and/or negative permittivity 20 properties for at least some wavelengths of electromagnetic radiation. Examples of negative-permeability/permittivity metamaterials and uses thereof are described in the following disclosures, each of which is hereby incorporated by reference in its entirety: U.S. Patent App. No. 11/355,493 titled "Variable Metamaterial Apparatus" filed on February 16, 2006; U.S. Patent App. No. 10/525,191 titled 25 "Indefinite Materials" filed on August 29, 2003; U.S. Patent App. No. 11/658,358 titled "Metamaterials" filed on July 22, 2005; and Victor Veselago, et al. *Negative Refractive Index Materials*, Journal of Computational and Theoretical Nanoscience, Vol. 3, 1-30, 2006.

[0049] A computing device or controller may include a processor, such as a 30 microprocessor, a microcontroller, logic circuitry, or the like. A processor may include one or more special-purpose processing devices, such as application-specific integrated circuits (ASICs), programmable array logic (PAL), programmable logic array (PLA), programmable logic device (PLD), field-

programmable gate array (FPGA), or other customizable and/or programmable device. The computing device may also include a machine-readable storage device, such as non-volatile memory, static RAM, dynamic RAM, ROM, CD-ROM, disk, tape, magnetic, optical, flash memory, or another machine-readable storage medium. Various aspects of certain embodiments may be implemented using hardware, software, firmware, or a combination thereof.

[0050] The components of the disclosed embodiments, as generally described and illustrated in the figures herein, could be arranged and designed in a wide variety of different configurations. Furthermore, the features, structures, and operations associated with one embodiment may be applied to or combined with the features, structures, or operations described in conjunction with another embodiment. In many instances, well-known structures, materials, or operations are not shown or described in detail to avoid obscuring aspects of this disclosure.

[0051] The embodiments of the systems and methods provided within this disclosure are not intended to limit the scope of the disclosure but are merely representative of possible embodiments. In addition, the steps of a method do not necessarily need to be executed in any specific order, or even sequentially, nor do the steps need to be executed only once. Some aspects of the various embodiments are illustrated in the drawings and additional understanding can be gained therefrom.

[0052] FIG. 1A illustrates a block diagram of an acoustic-electromagnetic volumetric imaging system 100, according to one embodiment. The acoustic-electromagnetic volumetric imaging system 100 may include a magnetic field generator 110 to produce a magnetic field intensity maximum in one or more cross-sections of the volume 180. As an example, the magnetic field intensity maximum may comprise a magnetic field hotspot formed within the volume 180.

[0053] The magnetic field generator 110 may, for example, comprise an array of adjustable or static magnetic field sources. In other embodiments, the magnetic field generator 110 may comprise a magnetic metamaterial superlens and at least one magnetic field source positioned relative to the magnetic metamaterial superlens. The magnetic field generator 110 may produce a low frequency or even a quasistatic magnetic field in various embodiments. In other embodiments, the magnetic field generator 110 may produce a relative high

frequency or non-quasistatic magnetic field at a frequency greater than 20 kilohertz (e.g., 20 kilohertz, 1 megahertz, 3 megahertz, 10 megahertz, etc.).

[0054] An electric current source 120 and an associated electric field generator 125 may generate a focused or unfocused electromagnetic field (e.g., an RF field) that permeates the volume 180. In embodiments in which the magnetic field operates at frequencies greater than 20 kilohertz, the electric current source 120 and associated electric field generator 125 may produce a relatively low frequency or even a direct current (DC) electric field. In other embodiments, the magnetic field generator 110 may produce a low frequency or quasistatic magnetic field and the electric current source 120 and associated electric field generator 125 may produce a relatively high-frequency electric field (e.g., 100 kilohertz, 1 megahertz, between 5 and 10 megahertz, etc.).

[0055] In still other embodiments, both the electric and magnetic fields may operate at non-zero frequencies. In some such embodiments, the electric current source 120 may be modulated at a frequency of at least two times greater than the frequency of an alternating magnetic field generated by the magnetic field generator 110.

[0056] An acoustic transducer 130, or an array of acoustic transducers, may receive acoustic signals (e.g., ultrasonic acoustic signals) generated by vibrations of a portion of the volume 180 at a location of the magnetic field hotspot due to electromagnetic forces on particles within the magnetic field hotspot. The electromagnetic forces, such as Lorentz forces, are forces exerted on particles within the magnetic field hotspot that oscillate back and forth due to the mathematical cross of the electric and magnetic fields, at least one of which is an alternating field. The total force, $\mathbf{F}$, on a particle is given by *Equation 1* below.

$$\mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}$$

Equation 1

[0058] As shown above, the total applied electromagnetic force vector, $\mathbf{F}$, is a vector sum of the electric force component, $q\mathbf{E}$, also known as the Coulomb force, and the magnetic force component, $q\mathbf{v} \times \mathbf{B}$, also known as the Lorentz force, where $\mathbf{E}$ is the electric field vector, q is the charge of the particle, $\mathbf{v}$ is the velocity vector of the particle, and $\mathbf{B}$ is the magnetic field vector. As shown above, the magnetic force component, $q\mathbf{v}$, is the vector cross-product of the velocity vector,

and wherein the force on a particle is based on the charge, q , of a particle, the magnitude, E , of the electric field, the vector cross-product of the velocity, $\mathbf{v}$, and the magnetic field vector, $\mathbf{B}$. In the continuum description of a conductive medium, Equation 1 is replaced with its continuum equivalent:

5 **[0059]** $\mathbf{F} = \rho \mathbf{E} + \mathbf{J} \times \mathbf{B} = \rho \mathbf{E} + \sigma \mathbf{E} \times \mathbf{B}$

Equation 2

[0060] In *Equation 2*, F is the volumetric force density, ρ is the (electric) charge density, J is the (electric) current density, and σ is the electrical conductivity of the medium, assumed to be an isotropic scalar for example. The Lorentz force portion
10 of this force is then proportional to the cross-product of electric and magnetic fields.

[0061] Thus, in some embodiments, the magnetic field generator 110 may focus a relatively high-amplitude magneto static beam, or hotspot, within the volume 180. The electric field generator 125 may generate a relatively weak,
15 unfocused electric field that permeates the volume 180 modulated at a desired ultrasound frequency.

[0062] Portions of the volume 180 within the hotspot will vibrate with significant force due to the relatively high-magnitude magnetic field within the hotspot at a frequency corresponding to the modulation frequency of the relatively weak,
20 unfocused electric field. Portions of the volume 180 outside of the hotspot will vibrate with very little force due to the lack of strong magnetic or electric fields.

[0063] Acoustic signals are emitted from the portions of the volume 180 within the hotspot due to the vibrations at the modulation frequency of the electric field. The acoustic transducer 130 receives the acoustic signals. The acoustic signals
25 may be generated at a target ultrasonic frequency by selecting a corresponding electric field modulation frequency. A time-gating circuit 140 may time-gate the received acoustic signals to localize the received acoustic signals within the volume 180. Generally speaking, acoustic signals from portions of the hotspot closest to the acoustic transducer 130 will be received before acoustic signals
30 from portions of the hotspot farther from the acoustic transducer 130. Thus, the subwavelength-focused magnetic field provides for localization of the received acoustic signals in two dimensions while time-gating the received acoustic signals provides for localization in the third dimension. A controller 150 may control, e.g.,

synchronize, the operation of the magnetic field generator 110, electric current source 120, electric field generator 125, acoustic transducer 130, and/or the time-gating circuit 140.

[0064] FIG. 1B illustrates the magnetic field generator 110 of the acoustic-electromagnetic volumetric imaging system 100 of FIG. 1A generating a subwavelength-focused magnetic field 111 to produce a magnetic field hotspot 112 within the volume 180. As described herein, the magnetic field hotspot 112 may comprise a region within the volume 180 with a relatively high-intensity static or quasistatic magnetic field. For instance, the magnetic field may operate at less than 20 kilohertz (e.g., 10 kilohertz). In such an embodiment, Joule heating of the volume 180 is reduced because the relatively low-frequency magnetic field generator 110 reduces induced secondary electric fields within the volume 180.

[0065] FIG. 1C illustrates the electric field generator 125 of the acoustic-electromagnetic volumetric imaging system 100 of FIG. 1A permeating the volume 180 with an electric field 135. As previously described, the electric field 135 may be relatively weak and unfocused. The electric field 135 may be modulated at a relatively high frequency corresponding to a target acoustic signal to be received by the acoustic transducer 130.

[0066] FIG. 1D illustrates the portion of the volume 180 at the location of the magnetic field hotspot 113 of the acoustic-electromagnetic volumetric imaging system 100 of FIG. 1A vibrating due to a time-dependent electromagnetic force (e.g., a Lorentz force) induced by the electric field 135 and magnetic field 111 therein. As previously described, portions of the volume 180 within the location of the magnetic field hotspot 113 are vibrated with significant force due to the high-intensity magnetic field within the hotspot 113, while portions of the volume 180 outside of the magnetic field hotspot 113 do not vibrate or vibrate with minimal force due to weak electric and magnetic fields in those regions.

[0067] FIG. 1E illustrates the acoustic transducer 130 of the acoustic-electromagnetic volumetric imaging system 100 of FIG. 1A receiving an acoustic signal 138 produced by the time-dependent electromagnetic force vibrating the portion of the volume 180 at the location of the magnetic field hotspot 113. The acoustic signals originating from within the magnetic field hotspot 113 may be localized in one dimension based on the different distances between portions of

the magnetic field hotspot 113 and the acoustic transducer 130 by the time-gating circuit 140.

[0068] FIG. 2 illustrates a block diagram of another embodiment of the acoustic-electromagnetic volumetric imaging system 200 that utilizes a magnetic metamaterial superlens 213 to produce a subwavelength-focused magnetic field 218 to form a magnetic field hotspot 219 within a volume 280. The portion of the volume 280 within the magnetic field hotspot 219 may be vibrated to emit an acoustic signal corresponding to the vector sum of the frequencies of the magnetic field 218 and an electric field produced by the electric field generator 225.

[0069] In various embodiments, the magnetic field 218 may be selected to operate at a relatively low frequency (e.g., 10 kilohertz or less) to reduce Joule heating by induced secondary electric fields within the volume 280. The controller 250 may cause the electric current source 220 to drive the electric field generator 225 at a modulating frequency based on a target acoustic signal to be originated by the vibration of the portion of the volume 280 within the magnetic field hotspot 219.

[0070] The acoustic transducer 230 is configured to receive acoustic signals originated by the vibrating portion of the volume 280 within the magnetic field hotspot 219. The time-gating circuit 240 provides spatial localization of the received ultrasound in one dimension while the perimeter of each time-gated cross-section of the magnetic field hotspot 219 provides spatial localization in the other two dimensions. The controller 250 may synchronize the operation of the magnetic field source 211, the electric current source 220, the electric field generator 225, the acoustic transducer 230, and/or the time-gating circuit 240.

[0071] FIG. 3A illustrates a magnetic coil 300 producing a relatively unfocused magnetic field 310 within a volume, according to one embodiment. A relatively low-frequency magnetic field has a relatively large wavelength that cannot be subwavelength-focused using conventional beamforming. As shown, the relative magnitudes of the magnetic field at various depths is relatively low.

[0072] FIG. 3B illustrates the magnetic coil 300 and a superlens 325 operating in concert to produce a subwavelength-focused magnetic field 350 with relatively high magnitudes at greater depths into the volume, according to various

embodiments. In various embodiments, the acoustic-electromagnetic volumetric imaging system leverages the subwavelength magnetic field abilities of the superlens to produce a magnetic field intensity maximum, or hotspot, within a volume. In some embodiments, a super lens may also be used to focus an electric field, while in other embodiments, the electric field may be unfocused.

[0073] FIG. 4A illustrates a three-dimensional representation of a subwavelength magnetic field hotspot 400 within a volume, according to one embodiment.

[0074] FIG. 4B illustrates locations of two time-gated cross-sections 420 and 425 of acoustic signal data captured from the magnetic field hotspot of FIG. 4A. Spatial localization and corresponding resolution is based on the thickness of each of the time-gated cross-sections 420 and 425, which corresponds to the length of the time window during which acoustic signals are received for each of the time-gated cross-sections 420 and 425.

[0075] FIG. 4C illustrates time-gated cross-sections 425 and 420 from the corresponding time-gated cross-sections identified in FIG. 4B. As illustrated, the received acoustic signals are spatially localized in the other two dimensions based on the areas of the cross-sections 425 and 420 of the subwavelength magnetic field hotspot of FIG. 1A. As illustrated, the diameter of each of the time-gated cross-sections 425 and 420 may be different based on the relative depth into the volume from which they are captured.

[0076] FIG. 5 illustrates a method 500 for acoustic-electromagnetic volumetric imaging, according to one embodiment. A magnetic field generator (e.g., a magnetic field source and superlens, or an array of magnetic field coils) may produce, at 510, a high-intensity magnetic field intensity maximum, or magnetic field hotspot, within a portion of a volume. An electric field generator may generate, at 520, an electric field within at least the portion of the volume at the location of the magnetic field hotspot. For example, the electric field may be weak and relatively unfocused. One or both of the magnetic field and the electric field may be modulated at frequencies corresponding to a target acoustic emission frequency.

[0077] The combination of the electric field and the magnetic field cause the portion of the volume at the location of the magnetic field hotspot to vibrate and

emit acoustic signals. An acoustic transducer may receive, at 530, acoustic signals produced by the time-dependent electromagnetic forces on the portion of the volume at the magnetic field intensity maximum. A time-gating circuit may time-gate, at 540, an output of the acoustic transducer (or transducer array) in temporal correlation with the time-dependent adjustments to the magnetic field intensity maximum.

[0078] For example, the magnetic field intensity maximum may be positioned at a first location within the volume. Time-gated acoustic signals may be captured from the magnetic field intensity maximum positioned at the first location within the volume. The magnetic field intensity maximum may be moved to any number of additional locations within the volume by, for example: moving the volume relative to the acoustic-electromagnetic volumetric imaging system, moving or rotating the magnetic field generator, moving or rotating a superlens, and/or repositioning the acoustic transducer. Time-gated acoustic signals may be captured from each of the various locations of the magnetic field intensity maximums.

[0079] The plurality of captured time-gated acoustic signals from the various locations may be processed, at 550, to generate a three-dimensional image of various portions of the volume. For example, a subwavelength magnetic field hotspot may be raster-scanned within a volume permeated by a weak, unfocused electric field. Emitted acoustic signals from each location of the raster-scanned magnetic field hotspot may be captured and time-gated. The time-gated acoustic data from each location of the raster-scanned magnetic field hotspot may be processed to generate a three-dimensional image of the entire volume.

[0080] FIG. 6 illustrates a functional block diagram of an acoustic-electromagnetic volumetric imaging control system 600, according to one embodiment. The acoustic-electromagnetic volumetric imaging control system 600 may include a processor 630, memory 640, and, optionally, a network interface 650. A bus 620 may connect the memory 640 and processor 630 to a computer-readable storage medium 660, such as a non-transitory computer-readable storage medium. The computer-readable storage medium 660 may include a plurality of modules 680-689 executable by the processor 630 for implementing operations for acoustic-electromagnetic volumetric imaging.

[0081] A magnetic field source control module 680 may provide instructions for the processor 630 to control the generation of a magnetic field by a magnetic field source to produce a subwavelength magnetic field hotspot within a volume. A magnetic field focusing control module 682 may provide instructions for the processor 630 to control an adjustable array of magnetic field sources (e.g., an array of magnetic field coils) or an adjustable or tunable magnetic metamaterial superlens.

[0082] An electric field control module 684 provides instructions for the processor 630 to control the generation and modulation of an electric field by an electric field source. A transducer control module 686 provides instructions for the processor 630 to control the reception of acoustic signals by an acoustic transducer or array of acoustic transducers. A time-gating control module 688 provides instructions for the processor 630 to control time-gating of received acoustic signals. An image creation module 689 provides instructions for the processor 630 to generate a three-dimensional image based on time-gated acoustic signals from one or more magnetic field hotspots at one or more locations at one or more times within a volume.

[0083] In various embodiments, one or more of the modules 680-689 and/or the associated functionalities may be omitted from the acoustic-electromagnetic volumetric imaging control system 600. Moreover, one or more of the modules 680-689 may be separated into distinct sub-modules, combined into a single module, and/or implemented by a different processor or system.

[0084] This disclosure has been made with reference to various exemplary embodiments, including the best mode. Those skilled in the art will recognize that changes and modifications may be made to the exemplary embodiments without departing from the scope of the present disclosure. While the principles of this disclosure have been shown in various embodiments, many modifications of structure, arrangements, proportions, elements, materials, and components may be adapted for a specific environment and/or operating requirements without departing from the principles and scope of this disclosure. These and other changes or modifications are intended to be included within the scope of the present disclosure.

[0085] Aspects of the subject matter described herein are set out in the following numbered clauses:

1. An acoustic-electromagnetic volumetric imaging system, comprising:
5 an adjustable magnetic field generator to produce a magnetic field intensity having a maximum in at least one cross-section of a volume to be imaged;
an electric current source to generate an electric field within the volume;
an acoustic transducer to receive acoustic signals produced within the volume by a time-dependent electromagnetic force on the volume induced by the
10 electric and magnetic fields;
an electronic circuit to perform time-gating of an output of the acoustic transducer in temporal correlation with time-dependent adjustments to the magnetic field intensity maximum produced by the adjustable magnetic field generator; and
15 an electronic controller to control operation of the adjustable magnetic field generator, the electric current source, and the time-gating electronic circuit.
2. The system of clause 1, wherein the volume comprises a medium that is electromagnetically opaque at microwave frequencies.
3. The system of clause 1, wherein the volume comprises a medium
20 that is optically opaque at optical frequencies.
4. The system of clause 1, wherein the volume comprises a medium that is acoustically opaque at high-frequency ultrasound frequencies.
5. The system of clause 1, wherein the volume comprises a medium that is acoustically opaque at ultrasonic frequencies above approximately 40
25 kilohertz.
6. The system of clause 1, wherein the volume comprises a medium that is acoustically opaque at ultrasonic frequencies between approximately 1 megahertz and 10 megahertz.
7. The system of clause 1, wherein the volume comprises a medium
30 that is acoustically opaque at ultrasonic frequencies between approximately 10 megahertz and 100 megahertz.

8. The system of clause 1, wherein the volume comprises a medium that is acoustically opaque at ultrasonic frequencies greater than approximately 100 megahertz.
9. The system of clause 1, wherein the volume comprises an
5 electrically conductive medium.
10. The system of clause 9, wherein the electrically conductive medium comprises water with dissolved ionic salts.
11. The system of clause 9, wherein the electrically conductive medium comprises a biological tissue.
- 10 12. The system of clause 1, wherein the volume comprises biological tissue.
13. The system of clause 1, wherein the volume comprises bone material.
14. The system of clause 1, wherein the volume comprises biological
15 tissue at least partially encased in bone material.
15. The system of clause 1, wherein the volume comprises soft tissue at least partially encased in bone material.
16. The system of clause 15, wherein the soft tissue comprises lung tissue and the bone material comprises a portion of a rib cage.
- 20 17. The system of clause 15, wherein the soft tissue comprises brain tissue and the bone material comprises a portion of a skull.
18. The system of clause 1, wherein the volume is at least partially encased in a metal-rich boundary.
19. The system of clause 1, wherein the volume comprises a metal-rich
25 boundary.
20. The system of clause 1, wherein the volume is at least partially encased in a boundary opaque to high-frequency electromagnetic waves.
21. The system of clause 1, wherein the volume is at least partially encased in a boundary opaque to ultrasound.
- 30 22. The system of clause 1, wherein the at least one of the plurality of cross-sections is defined as coplanar relative to the adjustable magnetic field generator.

23. The system of clause 1, wherein the electronic controller synchronizes operation of the adjustable magnetic field generator, the electric current source, and the time-gating electronic circuit.

24. The system of clause 1, wherein the time-dependent
5 electromagnetic force on the volume comprises a Lorentz force.

25. The system of clause 1, wherein the magnetic field intensity maximum is a hotspot that decays exponentially with respect to distance from the adjustable magnetic field generator.

26. The system of clause 1, wherein the acoustic transducer comprises
10 an ultrasound microphone.

27. The system of clause 1, wherein the acoustic transducer comprises an array of ultrasound receivers.

28. The system of clause 1, wherein the adjustable magnetic field generator produces a quasistatic magnetic field, and
15 wherein the electric current source comprises an alternating electric current source modulated at frequencies greater than 20 kilohertz.

29. The system of clause 28, wherein the alternating electric current source is modulated at frequencies greater than 1 megahertz.

30. The system of clause 28, wherein the alternating electric current
20 source is modulated at a frequency corresponding to a target frequency at which to receive acoustic signals via the acoustic transducer.

31. The system of clause 28, wherein the alternating electric current source is modulated at a frequency at least ten times greater than the quasistatic magnetic field.

25 32. The system of clause 28, wherein the alternating electric current source is modulated at a frequency at least one hundred times greater than the quasistatic magnetic field.

33. The system of clause 28, wherein the alternating electric current source is modulated at a frequency at least one thousand times greater than the
30 quasistatic magnetic field.

34. The system of clause 28, wherein the adjustable magnetic field generator comprises an array of adjustable magnetic field sources.

35. The system of clause 34, wherein each of the adjustable magnetic field sources comprises a magnetic-field-producing inductor to receive electric current at an adjustable magnitude and switchable polarity.

5 36. The system of clause 35, wherein the electronic controller is configured to drive the adjustable magnetic-field-producing inductors with adjustable current magnitudes and polarities to maximize magnetic field two-dimensional localization within the at least one cross-section of the volume.

37. The system of clause 28, wherein the adjustable magnetic field generator comprises an adjustable array of static magnetic field sources.

10 38. The system of clause 37, wherein the adjustable array of static magnetic field sources is an array of electromechanically-actuated static magnetic field sources.

39. The system of clause 38, wherein the electromechanically-actuated static magnetic field sources are physically displaced during electromechanical actuation to achieve magnetic field amplitude or direction modulation.

40. The system of clause 38, wherein the electromechanically-actuated static magnetic field sources are physically rotated during electromechanical actuation to achieve magnetic field amplitude, direction, or polarity modulation.

20 41. The system of clause 37, wherein the adjustable array of static magnetic field sources is adjusted to maximize magnetic field two-dimensional localization within the at least one cross-section of the volume.

42. The system of clause 37, wherein at least one of the static magnetic field sources includes at least one permanent magnet.

25 43. The system of clause 37, wherein at least one of the static magnetic field sources includes at least one electromagnet.

44. The system of clause 43, wherein at least one of the electromagnets is formed from superconducting coils energized with superconducting current.

30 45. The system of clause 1, wherein the adjustable magnetic field generator produces alternating magnetic field at a frequency greater than 20 kilohertz.

46. The system of clause 45, wherein the electric current source is a DC current source to generate a DC electric field within the volume.

47. The system of clause 45, wherein the alternating magnetic field is at a frequency greater than 1 megahertz.

48. The system of clause 45, wherein the electric current source is an alternating current source to generate an alternating electric field within the
5 volume.

49. The system of clause 48, wherein the AC electric current source is modulated at a frequency at least two times greater than that of the alternating magnetic field.

50. The system of clause 45, wherein the electric current source is a
10 radio frequency (RF) current source to generate an RF electric field within the volume.

51. The system of clause 50, wherein an RF modulating frequency of the RF current source is approximately 100 kilohertz.

52. The system of clause 50, wherein an RF modulating frequency of
15 the RF current source is between approximately 100 kilohertz and 1 megahertz.

53. The system of clause 50, wherein an RF modulating frequency of the RF current source is between approximately 1 megahertz and 5 megahertz.

54. The system of clause 50, wherein an RF modulating frequency of the RF current source is between approximately 5 megahertz and 10 megahertz.

55. The system of clause 50, wherein an RF modulating frequency of
20 the RF current source is between approximately 10 megahertz and 20 megahertz.

56. The system of clause 45, wherein the adjustable magnetic field generator comprises a magnetic metamaterial superlens and at least one magnetic field source proximate the superlens.

57. The system of clause 56, wherein the superlens is cylindrical, and
25 wherein the at least one cross-section is defined relative to the cylindrical superlens as a concentric cylindrical layer.

58. The system of clause 56, wherein the superlens is positioned between the single magnetic field source and the volume to be imaged.

59. The system of clause 56, wherein the magnetic metamaterial
30 superlens comprises magnetic metamaterial with a negative magnetic permeability for at least one polarization of magnetic field.

60. The system of clause 59, wherein the magnetic permeability is negative for all polarizations of magnetic field.

61. The system of clause 60, wherein the magnetic permeability is isotropic and negative for all polarizations of the magnetic field.

5 62. The system of clause 61, wherein the magnetic permeability is approximately negative one (-1).

63. The system of clause 56, wherein the at least one magnetic field source proximate the superlens comprises a single magnetic field source.

10 64. The system of clause 63, wherein the single magnetic field source is electromechanically actuated to move along the magnetic metamaterial superlens in at least one direction, resulting in a respective translational movement of the magnetic field intensity maximum in the at least one cross-section of the volume.

15 65. The system of clause 63, wherein the single magnetic field source is electromechanically actuated to move perpendicular to a surface of the magnetic metamaterial superlens, resulting in a respective depth change of the magnetic field intensity maximum to at least one different cross-section of the volume.

20 66. The system of clause 63, wherein the single magnetic field source is electromechanically actuated to rotate relative to the magnetic metamaterial superlens, resulting in a reorientation of the magnetic field in the magnetic field intensity maximum in the at least one cross-section of the volume.

67. The system of clause 56, wherein the magnetic metamaterial superlens is adjustable.

68. The system of clause 56, wherein magnetic metamaterial of the magnetic metamaterial superlens is a tunable metamaterial.

25 69. The system of clause 68, wherein the tunable metamaterial is electronically tunable.

70. The system of clause 68, wherein the tunable metamaterial is electromechanically tunable.

30 71. The system of clause 1, further comprising:
an ultrasonic imaging system to process the acoustic signals received via the acoustic transducer to generate an image of at least a portion of the at least one cross-section.

72. An acoustic-electromagnetic volumetric imaging system, comprising:
a magnetic field source to produce a magnetic field;
a magnetic metamaterial superlens to focus the magnetic field to produce a magnetic field intensity maximum in at least one cross-section of a volume to be
5 imaged;
an electric current source to generate an electric field within the volume;
an acoustic transducer to receive acoustic signals produced within the volume by a time-dependent electromagnetic force on the volume induced by the electric and magnetic fields;
10 an electronic circuit to perform time-gating of an output of the acoustic transducer in temporal correlation with time-dependent adjustments to the magnetic field intensity maximum; and
an electronic controller to control operation of the electric current source, the time-gating electronic circuit, and at least one of the magnetic field source and
15 the superlens.
73. The system of clause 72, wherein the volume comprises a medium that is electromagnetically opaque at microwave frequencies.
74. The system of clause 72, wherein the volume comprises a medium that is optically opaque at optical frequencies.
- 20 75. The system of clause 72, wherein the volume comprises a medium that is acoustically opaque at high-frequency ultrasound frequencies.
76. The system of clause 72, wherein the volume comprises a medium that is acoustically opaque at ultrasonic frequencies above approximately 40 kilohertz.
- 25 77. The system of clause 72, wherein the volume comprises a medium that is acoustically opaque at ultrasonic frequencies between approximately 1 megahertz and 10 megahertz.
78. The system of clause 72, wherein the volume comprises a medium that is acoustically opaque at ultrasonic frequencies between approximately 10
30 megahertz and 100 megahertz.
79. The system of clause 72, wherein the volume comprises a medium that is acoustically opaque at ultrasonic frequencies greater than approximately 100 megahertz.

80. The system of clause 72, wherein the volume comprises an electrically conductive medium.

81. The system of clause 80, wherein the electrically conductive medium comprises water with dissolved ionic salts.

5 82. The system of clause 80, wherein the electrically conductive medium comprises a biological tissue.

83. The system of clause 72, wherein the volume comprises biological tissue.

10 84. The system of clause 72, wherein the volume comprises bone material.

85. The system of clause 72, wherein the volume comprises soft tissue at least partially encased in bone material.

86. The system of clause 85, wherein the soft tissue comprises lung tissue and the bone material comprises a portion of a rib cage.

15 87. The system of clause 85, wherein the soft tissue comprises brain tissue and the bone material comprises a portion of a skull.

88. The system of clause 72, wherein the volume is at least partially encased in a metal-rich boundary.

20 89. The system of clause 72, wherein the volume comprises a metal-rich boundary.

90. The system of clause 72 wherein the volume is at least partially encased in a boundary opaque to high-frequency electromagnetic waves.

91. The system of clause 72, wherein the volume is at least partially encased in a boundary opaque to ultrasound.

25 92. The system of clause 72, wherein the at least one of the plurality of cross-sections is defined coplanar relative to the superlens.

93. The system of clause 72, wherein the time-dependent electromagnetic force on the volume comprises a Lorentz force.

30 94. The system of clause 72, wherein the magnetic field intensity maximum is a hotspot that decays exponentially with respect to distance from the superlens.

95. The system of clause 72, wherein the acoustic transducer comprises an ultrasound microphone.

96. The system of clause 72, wherein the acoustic transducer comprises an array of ultrasound receivers.

97. The system of clause 72, wherein the magnetic field source produces alternating magnetic field modulated at frequencies greater than 20
5 kilohertz.

98. The system of clause 72, wherein the electric current source is a DC current source to generate a DC electric field within the volume.

99. The system of clause 72, wherein the magnetic field is modulated at a frequency below 20 kilohertz.

100. The system of clause 72, wherein the electric current source is an alternating current source to generate an alternating electric field within the
10 volume.

101. The system of clause 72, wherein the electric current source is a radio frequency (RF) current source to generate an RF electric field within the
15 volume.

102. The system of clause 101, wherein an RF modulating frequency of the RF current source is approximately 100 kilohertz.

103. The system of clause 101, wherein an RF modulating frequency of the RF current source is between approximately 100 kilohertz and 1 megahertz.

104. The system of clause 101, wherein an RF modulating frequency of the RF current source is between approximately 1 megahertz and 5 megahertz.
20

105. The system of clause 101, wherein an RF modulating frequency of the RF current source is between approximately 5 megahertz and 10 megahertz.

106. The system of clause 101, wherein an RF modulating frequency of the RF current source is between approximately 10 megahertz and 20 megahertz.
25

107. The system of clause 72, wherein the superlens is cylindrical, and wherein the at least one cross-section is defined relative to the cylindrical superlens as a concentric cylindrical layer.

108. The system of clause 72, wherein the magnetic metamaterial superlens comprises magnetic metamaterial with a negative magnetic permeability for at least one polarization of magnetic field.
30

109. The system of clause 108, wherein the magnetic permeability is negative for all polarizations of magnetic field.

110. The system of clause 109, wherein the magnetic permeability is isotropic and negative for all polarizations of the magnetic field.

111. The system of clause 110, wherein the magnetic permeability is approximately negative one (-1).

5 112. The system of clause 72, wherein the magnetic field source comprises a plurality of magnetic field sources operating in concert.

113. The system of clause 72, wherein the magnetic field source comprises a single magnetic field source.

10 114. The system of clause 72, wherein the magnetic field source is electromechanically actuated to move along the magnetic metamaterial superlens in at least one direction, resulting in a respective translational movement of the magnetic field intensity maximum in the at least one cross-section of the volume.

15 115. The system of clause 72, wherein the magnetic field source is electromechanically actuated to move perpendicular to a surface of the magnetic metamaterial superlens, resulting in a respective depth change of the magnetic field intensity maximum to at least one different cross-section of the volume.

20 116. The system of clause 72, wherein the magnetic field source is electromechanically actuated to rotate relative to the magnetic metamaterial superlens, resulting in a reorientation of the magnetic field in the magnetic field intensity maximum in the at least one cross-section of the volume.

117. The system of clause 72, wherein the magnetic metamaterial superlens is adjustable.

118. The system of clause 72, wherein magnetic metamaterial of the magnetic metamaterial superlens is a tunable metamaterial.

25 119. The system of clause 118, wherein the tunable metamaterial is electronically tunable.

120. The system of clause 118, wherein the tunable metamaterial is electromechanically tunable.

30 121. The system of clause 72, further comprising:
an ultrasonic imaging system to process the acoustic signals received via the acoustic transducer to generate an image of at least a portion of the at least one cross-section.

122. A method comprising:
producing, via a magnetic field generator, a magnetic field intensity maximum in at least one cross-section of a volume to be imaged;
generating, via an electric current source, an electric field within the
5 volume;
receiving, via an acoustic transducer, acoustic signals produced within the volume by time-dependent electromagnetic force on the volume induced by the electric and magnetic fields;
time-gating, via an electronic circuit, an output of the acoustic transducer in
10 temporal correlation with time-dependent adjustments to the magnetic field intensity maximum; and
controlling, via an electronic controller, the magnetic field generator, the electric current source, and the electronic circuit.
123. The method of clause 122, wherein the volume comprises a medium
15 that is electromagnetically opaque at microwave frequencies.
124. The method of clause 122, wherein the volume comprises a medium that is optically opaque at optical frequencies.
125. The method of clause 122, wherein the volume comprises a medium that is acoustically opaque at high-frequency ultrasound frequencies.
- 20 126. The method of clause 122, wherein the volume comprises a medium that is acoustically opaque at ultrasonic frequencies above approximately 40 kilohertz.
127. The method of clause 122, wherein the volume comprises a medium that is acoustically opaque at ultrasonic frequencies between approximately 1
25 megahertz and 10 megahertz.
128. The method of clause 122, wherein the volume comprises a medium that is acoustically opaque at ultrasonic frequencies between approximately 10 megahertz and 100 megahertz.
129. The method of clause 122, wherein the volume comprises a medium
30 that is acoustically opaque at ultrasonic frequencies greater than approximately 100 megahertz.
130. The method of clause 122, wherein the volume comprises an electrically conductive medium.

131. The method of clause 130, wherein the electrically conductive medium comprises water with dissolved ionic salts.

132. The method of clause 130, wherein the electrically conductive medium comprises a biological tissue.

5 133. The method of clause 122, wherein the volume comprises biological tissue.

134. The method of clause 122, wherein the volume comprises bone material.

10 135. The method of clause 122, wherein the volume comprises soft tissue at least partially encased in bone material.

136. The method of clause 135, wherein the soft tissue comprises lung tissue and the bone material comprises a portion of a rib cage.

137. The method of clause 135, wherein the soft tissue comprises brain tissue and the bone material comprises a portion of a skull.

15 138. The method of clause 122, wherein the volume is at least partially encased in a metal-rich boundary.

139. The method of clause 122, wherein the volume comprises a metal-rich boundary.

20 140. The method of clause 122, wherein the volume is at least partially encased in a boundary opaque to high-frequency electromagnetic waves.

141. The method of clause 122, wherein the volume is at least partially encased in a boundary opaque to ultrasound.

142. The method of clause 122, wherein the at least one of the plurality of cross-sections is defined coplanar relative to the magnetic field generator.

25 143. The method of clause 122, further comprising:
synchronizing, via the electronic controller, the operation of the magnetic field generator, the electric current source, and the electronic circuit.

144. The method of clause 122, wherein the time-dependent electromagnetic force on the volume comprises a Lorentz force.

30 145. The method of clause 122, wherein the magnetic field intensity maximum is a hotspot that decays exponentially with respect to distance from the magnetic field generator.

146. The method of clause 122, wherein the acoustic transducer comprises an ultrasound microphone.

147. The method of clause 122, wherein the acoustic transducer comprises an array of ultrasound receivers.

5 148. The method of clause 122, further comprising moving the magnetic field intensity maximum within the volume to each of a plurality of locations.

149. The method of clause 148, receiving acoustic signals from each of the plurality of locations to which the magnetic field intensity maximum is moved.

10 150. The method of clause 122, wherein producing the magnetic field intensity maximum comprises producing a quasistatic magnetic field, and wherein generating the electric field within the volume comprises generating an electric field via an alternating electric current modulated at frequencies greater than 20 kilohertz.

15 151. The method of clause 150, wherein the alternating electric current source is modulated at frequencies greater than 1 megahertz.

152. The method of clause 150, wherein the alternating electric current source is modulated at a frequency corresponding to a target frequency at which to receive acoustic signals via the acoustic transducer.

20 153. The method of clause 150, wherein the alternating electric current source is modulated at a frequency at least ten times greater than the quasistatic magnetic field.

154. The method of clause 150, wherein the alternating electric current source is modulated at a frequency at least one hundred times greater than the quasistatic magnetic field.

25 155. The method of clause 150, wherein the alternating electric current source is modulated at a frequency at least one thousand times greater than the quasistatic magnetic field

156. The method of clause 150, wherein the magnetic field generator comprises an array of adjustable magnetic field sources.

30 157. The method of clause 156, wherein each of the adjustable magnetic field sources comprises a magnetic-field-producing inductor to receive electric current at an adjustable magnitude and switchable polarity.

158. The method of clause 157, further comprising:

driving the adjustable magnetic-field-producing inductors with adjustable current magnitudes and polarities to maximize magnetic field two-dimensional localization within the at least one cross-section of the volume.

159. The method of clause 150, wherein the magnetic field generator
5 comprises an adjustable array of static magnetic field sources.

160. The method of clause 159, wherein the adjustable array of static magnetic field sources is an array of electromechanically-actuated static magnetic field sources.

161. The method of clause 160, further comprising:
10 electromechanically actuating the static magnetic field sources to physically displace them to achieve field amplitude modulation.

162. The method of clause 160, further comprising:
electromechanically actuating the static magnetic field sources to physically rotate them to achieve field amplitude modulation and polarity switching.

163. The method of clause 159, further comprising:
15 adjusting the adjustable array of static magnetic field sources to maximize magnetic field two-dimensional localization within the at least one cross-section of the volume.

164. The method of clause 159, wherein each of the static magnetic field
20 sources includes at least one permanent magnet.

165. The method of clause 159, wherein each of the static magnetic field sources includes at least one electromagnet.

166. The method of clause 165, wherein each of the electromagnets is formed from superconducting coils energized with superconducting current.

25 167. The method of clause 122, wherein producing the magnetic field intensity maximum comprises producing an alternating magnetic field alternating at a frequency greater than 20 kilohertz.

168. The method of clause 167, wherein generating the electric field comprises generating a DC electric field within the volume via a DC electric
30 current source.

169. The method of clause 167, wherein the alternating magnetic field is at a frequency greater than 1 megahertz.

170. The method of clause 167, wherein generating the electric field comprises generating an AC electric field within the volume via an AC electric current source.

5 171. The method of clause 170, wherein the AC electric current source is modulated at a frequency at least two times greater than that of the alternating magnetic field.

172. The method of clause 170, wherein the AC electric current source is a radio frequency (RF) current source.

10 173. The method of clause 172, wherein an RF modulating frequency of the RF current source is approximately 100 kilohertz.

174. The method of clause 172, wherein an RF modulating frequency of the RF current source is between approximately 100 kilohertz and 1 megahertz.

175. The method of clause 172, wherein an RF modulating frequency of the RF current source is between approximately 1 megahertz and 5 megahertz.

15 176. The method of clause 172, wherein an RF modulating frequency of the RF current source is between approximately 5 megahertz and 10 megahertz.

177. The method of clause 172, wherein an RF modulating frequency of the RF current source is between approximately 10 megahertz and 20 megahertz.

20 178. The method of clause 167, wherein the magnetic field generator comprises a magnetic metamaterial superlens and at least one magnetic field source proximate the superlens.

179. The method of clause 178, wherein the superlens is cylindrical, and wherein the at least one cross-section is defined relative to the cylindrical superlens as a concentric cylindrical layer.

25 180. The method of clause 178, wherein the superlens is positioned between the single magnetic field source and the volume to be imaged.

181. The method of clause 178, wherein the magnetic metamaterial superlens comprises magnetic metamaterial with a negative magnetic permeability for at least one polarization of magnetic field.

30 182. The method of clause 181, wherein the magnetic permeability is negative for all polarizations of magnetic field.

183. The method of clause 182, wherein the magnetic permeability is isotropic and negative for all polarizations of the magnetic field.

184. The method of clause 183, wherein the magnetic permeability is approximately negative one (-1).

185. The method of clause 178, wherein the at least one magnetic field source proximate the superlens comprises a single magnetic field source.

5 186. The method of clause 185, further comprising:
electromechanically actuating the single magnetic field source to move the single magnetic field source along the magnetic metamaterial superlens in at least one direction, resulting in a respective translational movement of the magnetic field intensity maximum in the at least one cross-section of the volume.

10 187. The method of clause 186, further comprising:
processing, via an ultrasound imaging system, acoustic signals received via the acoustic transducer during a plurality of successive translational movements of the magnetic field intensity maximum.

15 188. The method of clause 185, further comprising:
electromechanically actuating the single magnetic field source to move the single magnetic field source perpendicular to a surface of the magnetic metamaterial superlens, resulting in a respective depth change of the magnetic field intensity maximum to at least one different cross-section of the volume.

20 189. The method of clause 188, further comprising:
processing, via an ultrasound imaging system, acoustic signals received via the acoustic transducer during a plurality of successive depth changes of the magnetic field intensity maximum.

25 190. The method of clause 185, further comprising:
electromechanically actuating the single magnetic field source to rotate the single magnetic field source relative to the magnetic metamaterial superlens, resulting in a reorientation of the magnetic field in the magnetic field intensity maximum in the at least one cross-section of the volume.

30 191. The method of clause 188, further comprising:
processing, via an ultrasound imaging system, acoustic signals received via the acoustic transducer during a plurality of successive magnetic field reorientations of the magnetic field intensity maximum.

192. The method of clause 178, wherein the magnetic metamaterial superlens is adjustable.

193. The method of clause 178, wherein magnetic metamaterial of the magnetic metamaterial superlens is a tunable metamaterial.

194. The method of clause 193, wherein the tunable metamaterial is electronically tunable.

5 195. The method of clause 193, wherein the tunable metamaterial is electromechanically tunable.

196. The method of clause 122, further comprising:

processing, via an ultrasonic imaging system, the acoustic signals received via the acoustic transducer to generate an image of at least a portion of the at
10 least one cross-section.

197. The method of clause 122, further comprising:

conceptually dividing a portion of the volume into a plurality of voxels, a first of which corresponds to the magnetic field intensity maximum;
receiving acoustic signals during a plurality of successive time periods
15 corresponding to movements of the magnetic field intensity maximum to successive voxels; and

processing, via an ultrasonic imaging system, the received acoustic signals from each of the successive time periods to generate an image of the portion of the volume.

20

[0086] This disclosure is to be regarded in an illustrative rather than a restrictive sense, and all such modifications are intended to be included within the scope thereof. Likewise, benefits, other advantages, and solutions to problems have been described above with regard to various embodiments. However, benefits, advantages, solutions to problems, and any element(s) that may cause any
25 benefit, advantage, or solution to occur or become more pronounced are not to be construed as a critical, required, or essential feature or element. This disclosure should, therefore, be determined to encompass at least the following claims.

What is claimed is:

1. An acoustic-electromagnetic volumetric imaging system, comprising:
an adjustable magnetic field generator to produce a magnetic field intensity
5 having a maximum in at least one cross-section of a volume to be imaged;
an electric current source to generate an electric field within the volume;
an acoustic transducer to receive acoustic signals produced within the
volume by a time-dependent electromagnetic force on the volume induced by the
electric and magnetic fields;
10 an electronic circuit to perform time-gating of an output of the acoustic
transducer in temporal correlation with time-dependent adjustments to the
magnetic field intensity maximum produced by the adjustable magnetic field
generator; and
an electronic controller to control operation of the adjustable magnetic field
15 generator, the electric current source, and the time-gating electronic circuit.
2. The system of claim 1, wherein the volume comprises biological
tissue at least partially encased in bone material.
3. The system of claim 1, wherein the volume is at least partially
encased in a metal-rich boundary.
- 20 4. The system of any of claims 1-3, wherein the at least one of the
plurality of cross-sections is defined as coplanar relative to the adjustable
magnetic field generator.
5. The system of any of claims 1-4, wherein the electronic controller
synchronizes operation of the adjustable magnetic field generator, the electric
25 current source, and the time-gating electronic circuit.
6. The system of any of claims 1-5, wherein the adjustable magnetic
field generator produces a quasistatic magnetic field, and
wherein the electric current source comprises an alternating electric current
source modulated at frequencies greater than 20 kilohertz.
- 30 7. The system of claim 6, wherein the alternating electric current
source is modulated at frequencies greater than 1 megahertz.
8. The system of claim 6, wherein the alternating electric current
source is modulated at a frequency corresponding to a target frequency at which
to receive acoustic signals via the acoustic transducer.

9. The system of claim 6, wherein the alternating electric current source is modulated at a frequency at least ten times greater than the quasistatic magnetic field.

10. The system of claim 6, wherein the adjustable magnetic field generator comprises an adjustable array of static magnetic field sources.

11. The system of claim 10, wherein the adjustable array of static magnetic field sources is an array of electromechanically-actuated static magnetic field sources.

12. The system of claim 11, wherein the electromechanically-actuated static magnetic field sources are physically rotated during electromechanical actuation to achieve magnetic field amplitude, direction, or polarity modulation.

13. The system of any of claims 1-5, wherein the adjustable magnetic field generator produces alternating magnetic field at a frequency greater than 20 kilohertz.

14. The system of claim 13, wherein the electric current source is a DC current source to generate a DC electric field within the volume.

15. The system of claim 13, wherein the alternating magnetic field is at a frequency greater than 1 megahertz.

16. The system of claim 13, wherein the electric current source is an alternating current source to generate an alternating electric field within the volume.

17. The system of claim 16, wherein the AC electric current source is modulated at a frequency at least two times greater than that of the alternating magnetic field.

18. The system of claim 13, wherein the electric current source is a radio frequency (RF) current source to generate an RF electric field within the volume.

19. The system of claim 18, wherein an RF modulating frequency of the RF current source is between approximately 10 megahertz and 20 megahertz.

20. The system of any of claims 1-19, further comprising:

an ultrasonic imaging system to process the acoustic signals received via the acoustic transducer to generate an image of at least a portion of the at least one cross-section.

21. A method comprising:
producing, via a magnetic field generator, a magnetic field intensity maximum in at least one cross-section of a volume to be imaged;
generating, via an electric current source, an electric field within the
5 volume;
receiving, via an acoustic transducer, acoustic signals produced within the volume by time-dependent electromagnetic force on the volume induced by the electric and magnetic fields;
time-gating, via an electronic circuit, an output of the acoustic transducer in
10 temporal correlation with time-dependent adjustments to the magnetic field intensity maximum; and
controlling, via an electronic controller, the magnetic field generator, the electric current source, and the electronic circuit.
22. The method of claim 21, wherein the at least one of the plurality of
15 cross-sections is defined coplanar relative to the magnetic field generator.
23. The method of any of claims 21-22, wherein the time-dependent electromagnetic force on the volume comprises a Lorentz force.
24. The method of any of claims 21-23, wherein producing the magnetic field intensity maximum comprises producing a quasistatic magnetic field, and
20 wherein generating the electric field within the volume comprises generating an electric field via an alternating electric current modulated at frequencies greater than 20 kilohertz.
25. The method of claim 24, wherein the magnetic field generator comprises an adjustable array of static magnetic field sources.
- 25 26. The method of any of claims 21-23, wherein producing the magnetic field intensity maximum comprises producing an alternating magnetic field alternating at a frequency greater than 20 kilohertz.
27. The method of claim 26, wherein generating the electric field comprises generating an AC electric field within the volume via an AC electric
30 current source.
28. The method of claim 27, wherein the AC electric current source is a radio frequency (RF) current source.

29. The method of claim 26, wherein the magnetic field generator comprises a magnetic metamaterial superlens and at least one magnetic field source proximate the superlens.

30. The method of claim 29, wherein the at least one magnetic field
5 source proximate the superlens comprises a single magnetic field source.

31. The method of claim 29, wherein magnetic metamaterial of the magnetic metamaterial superlens is a tunable metamaterial.

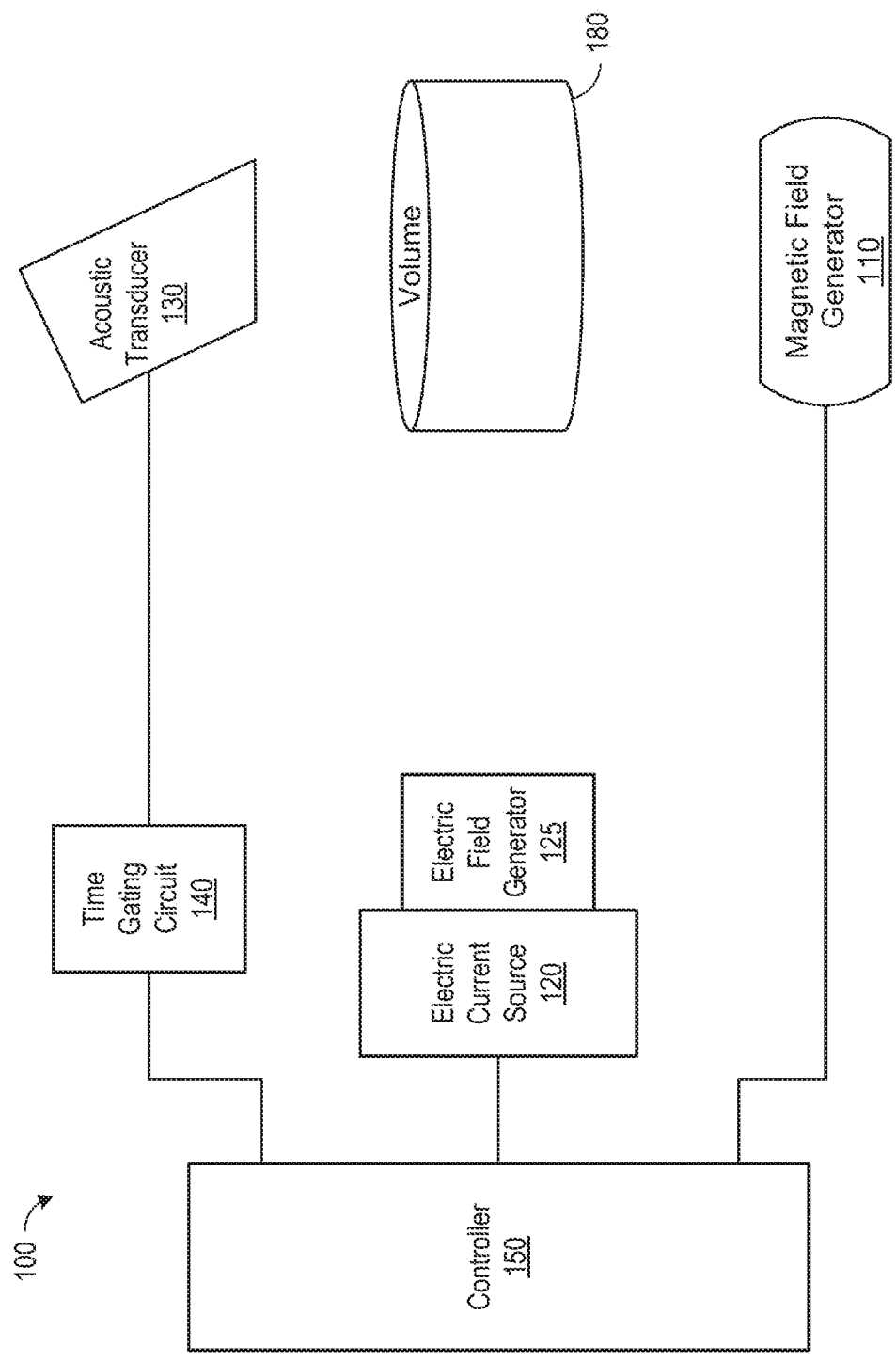


FIG. 1A

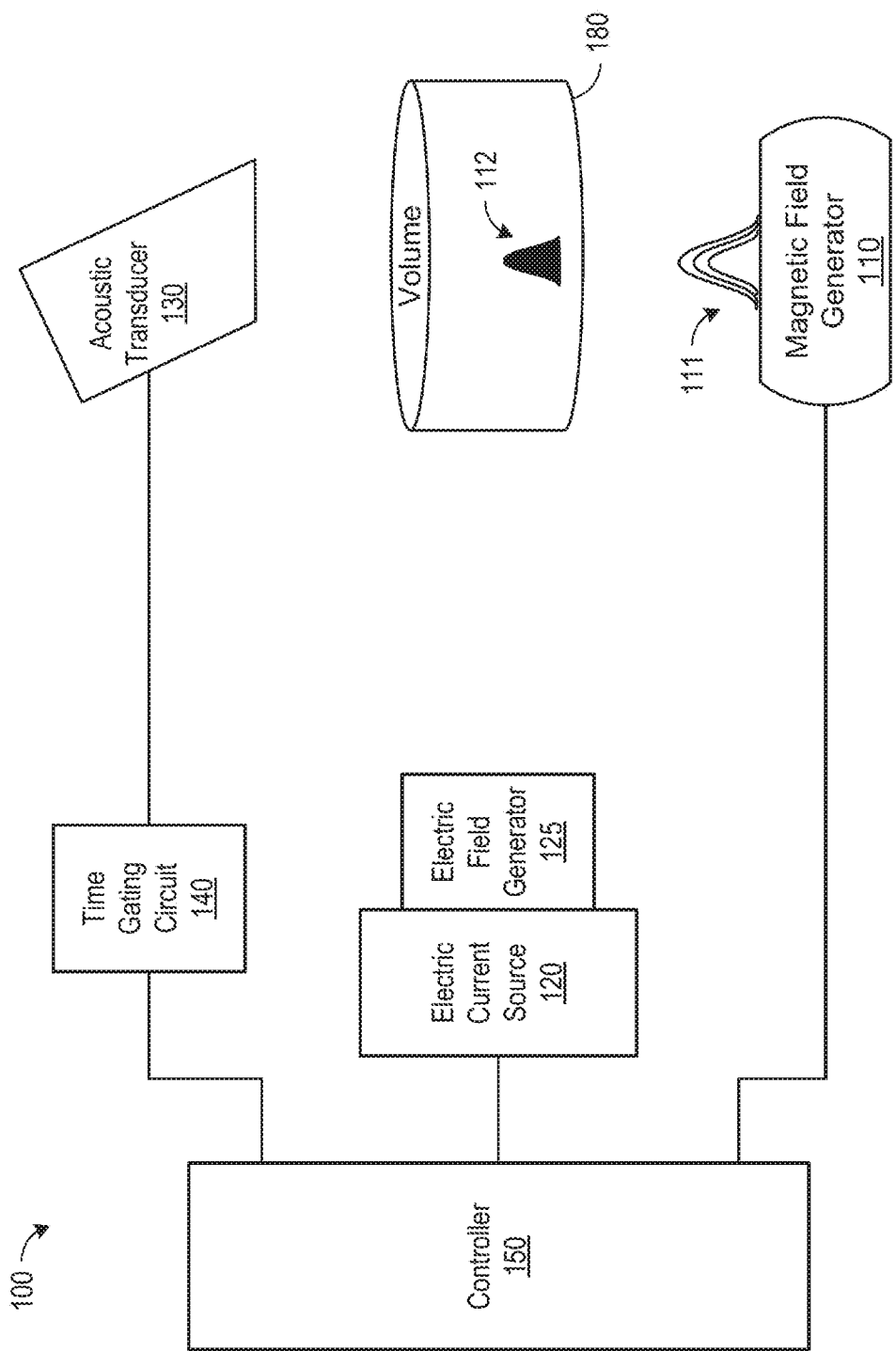


FIG. 1B

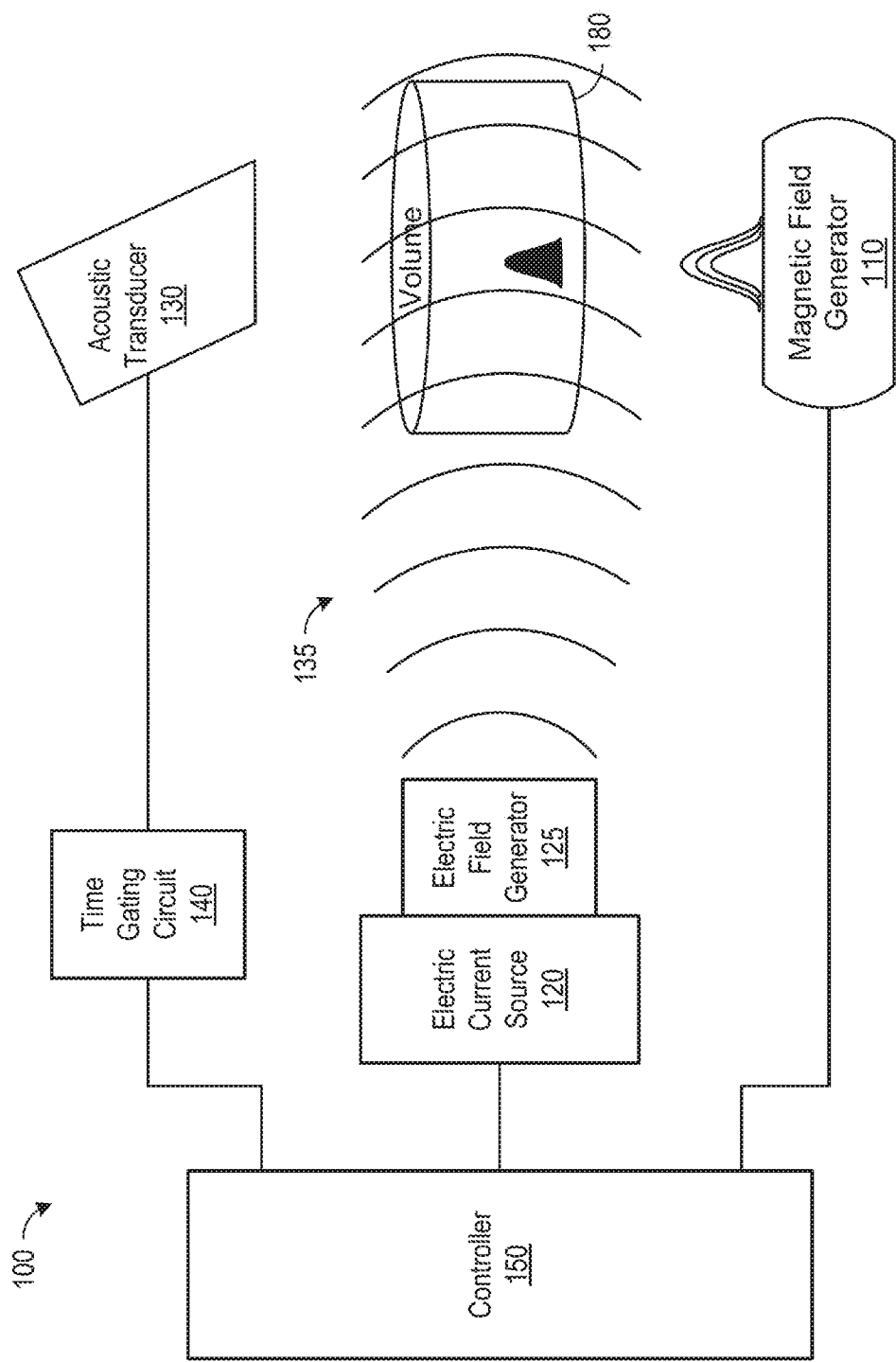


FIG. 1C

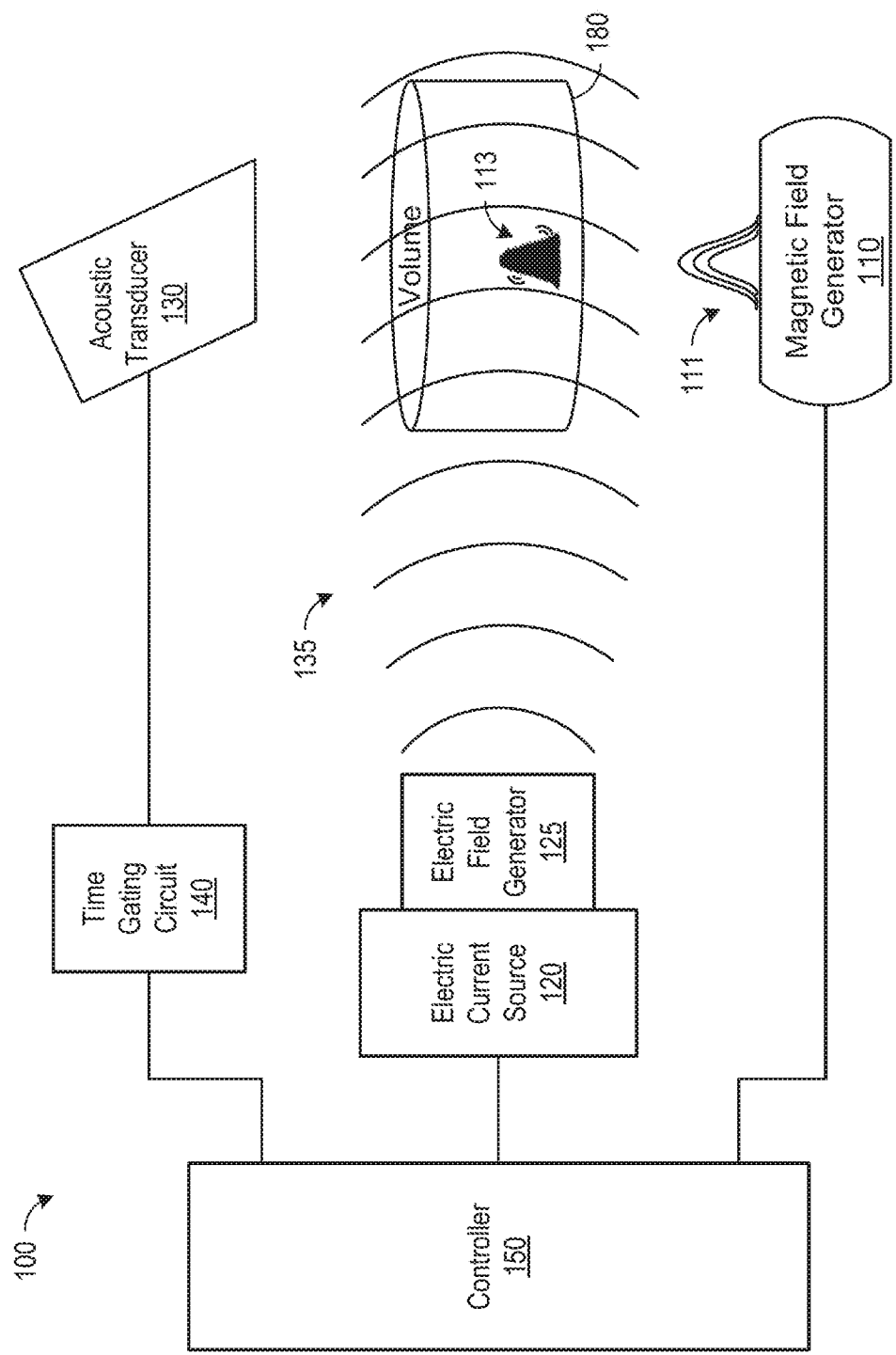


FIG. 1D

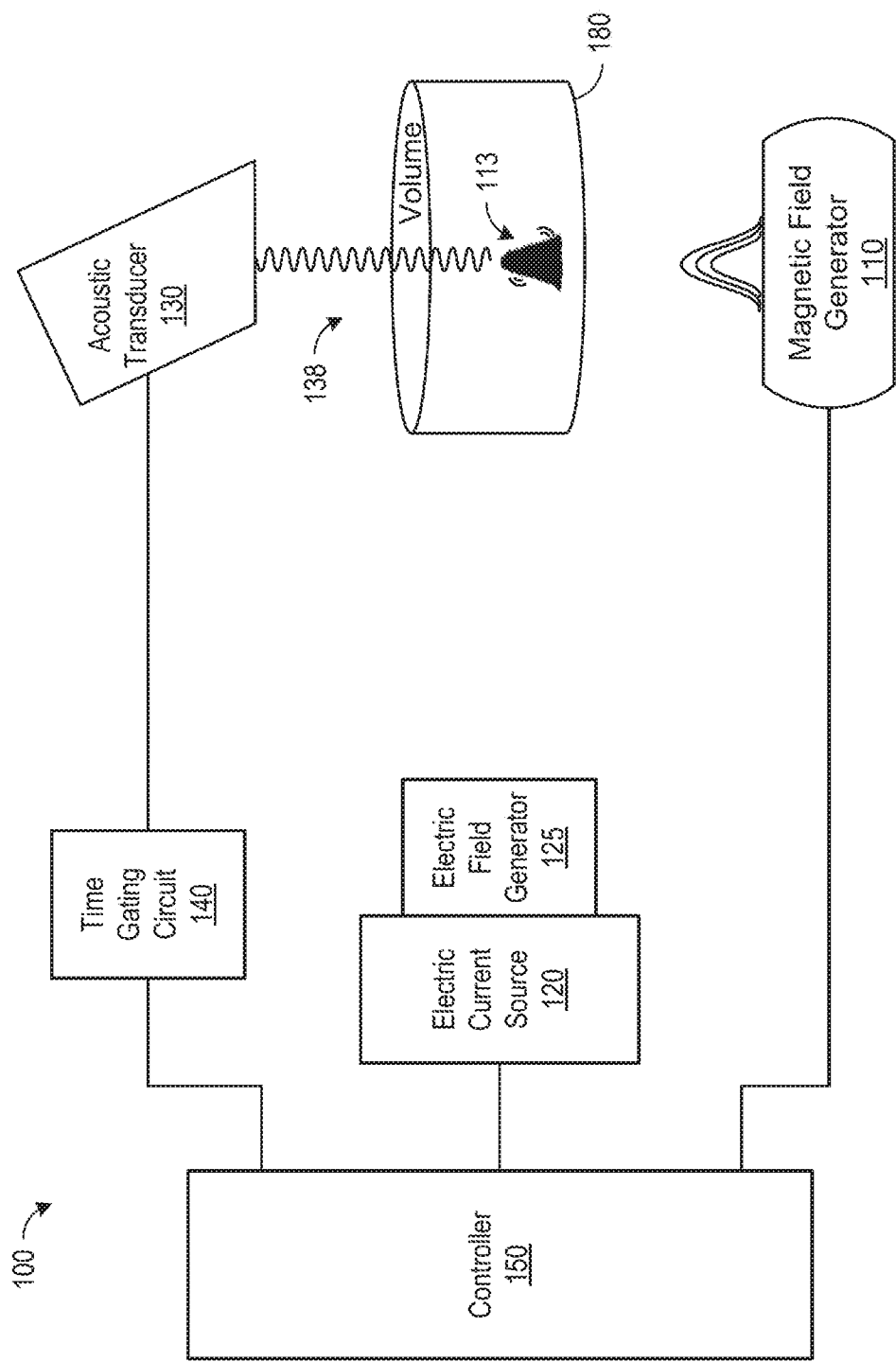


FIG. 1E

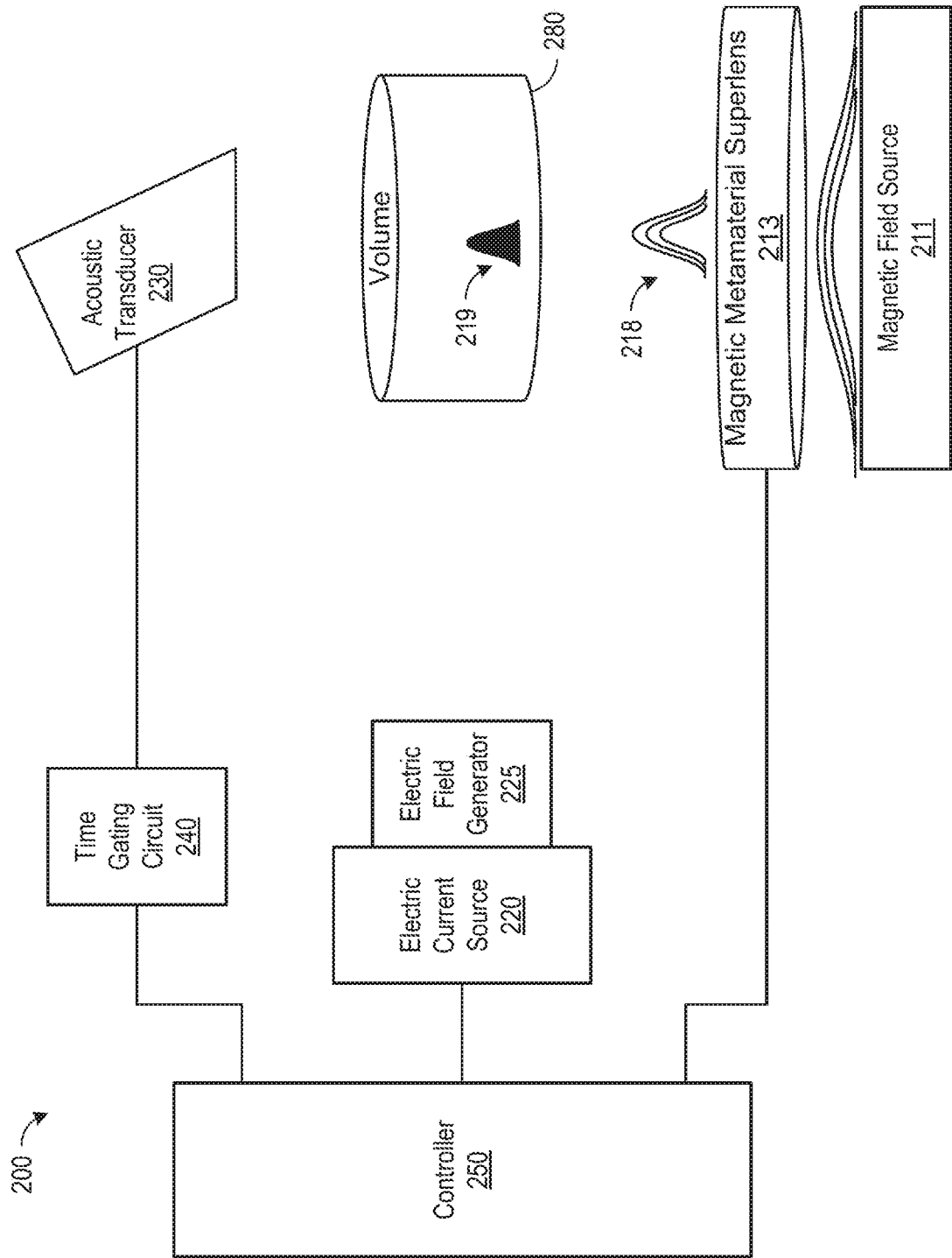


FIG. 2

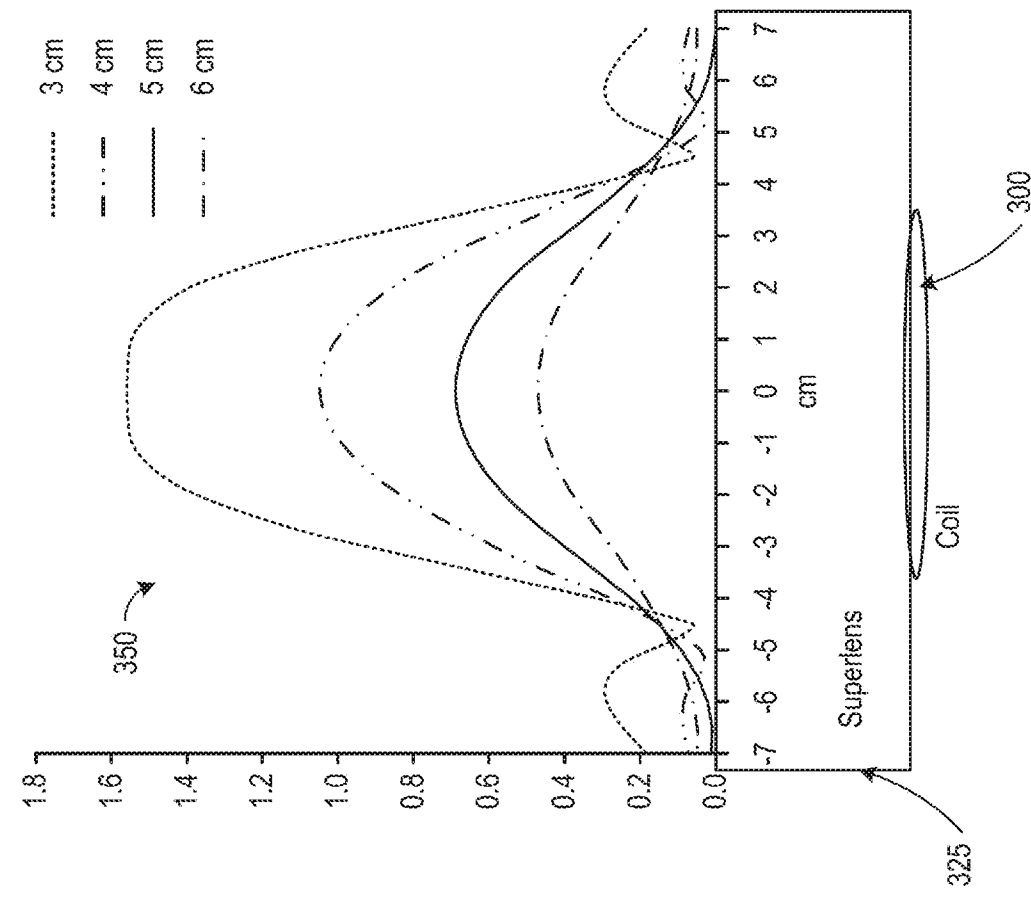


FIG. 3A

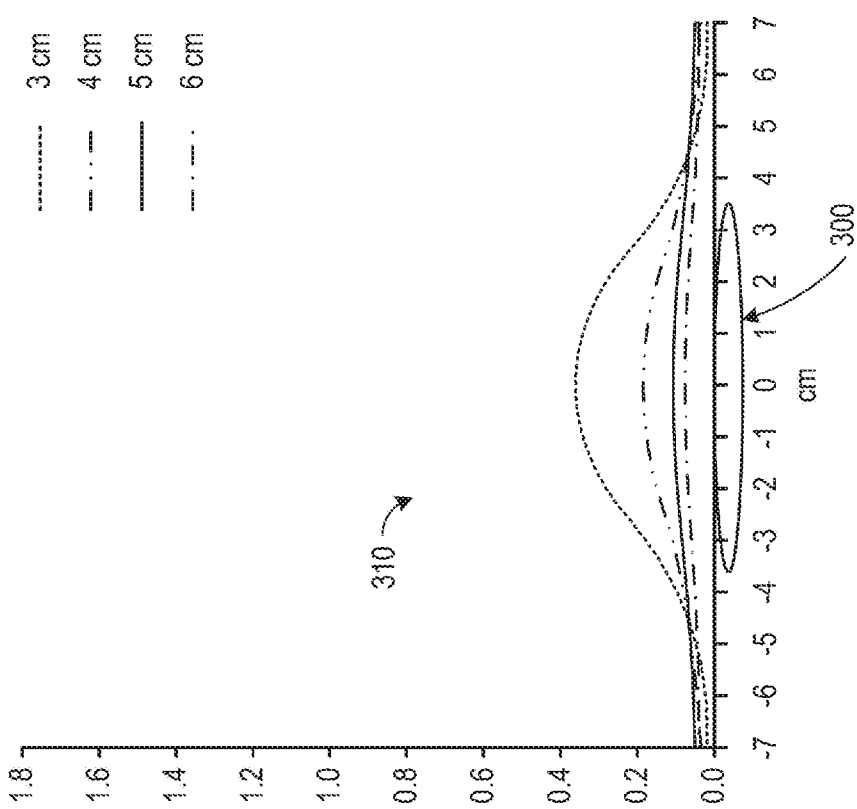


FIG. 3B

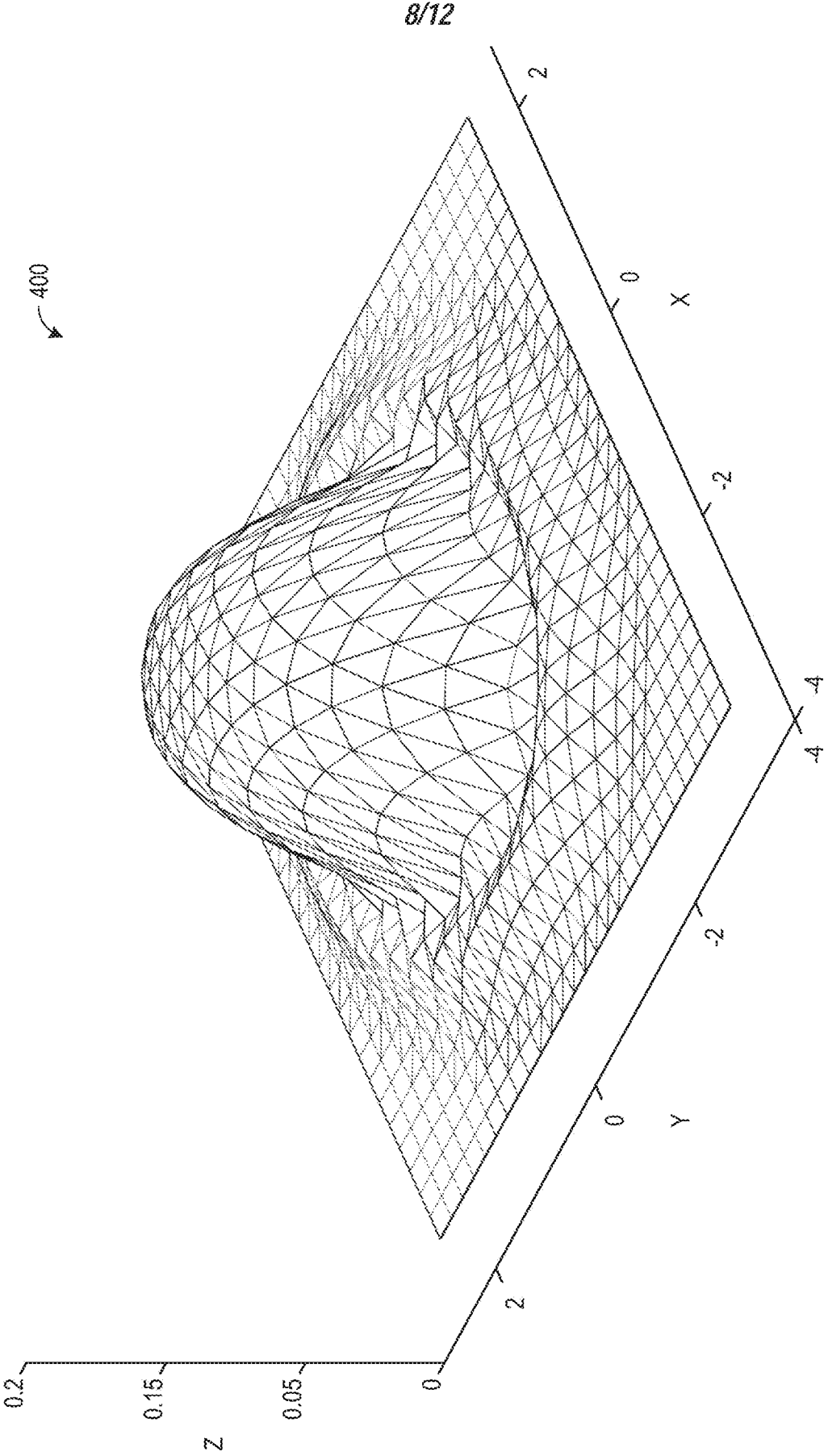


FIG. 4A

9/12

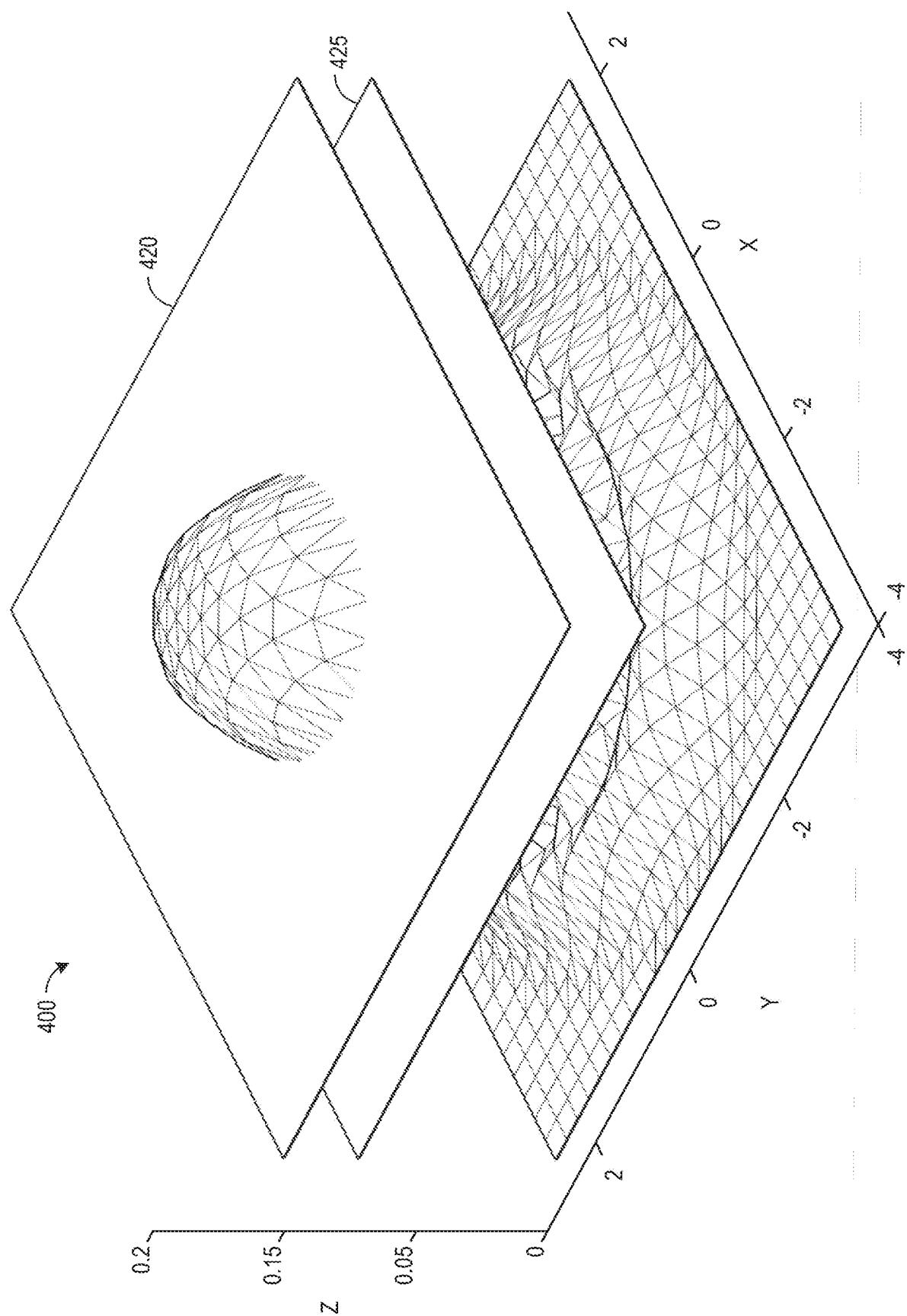


FIG. 4B

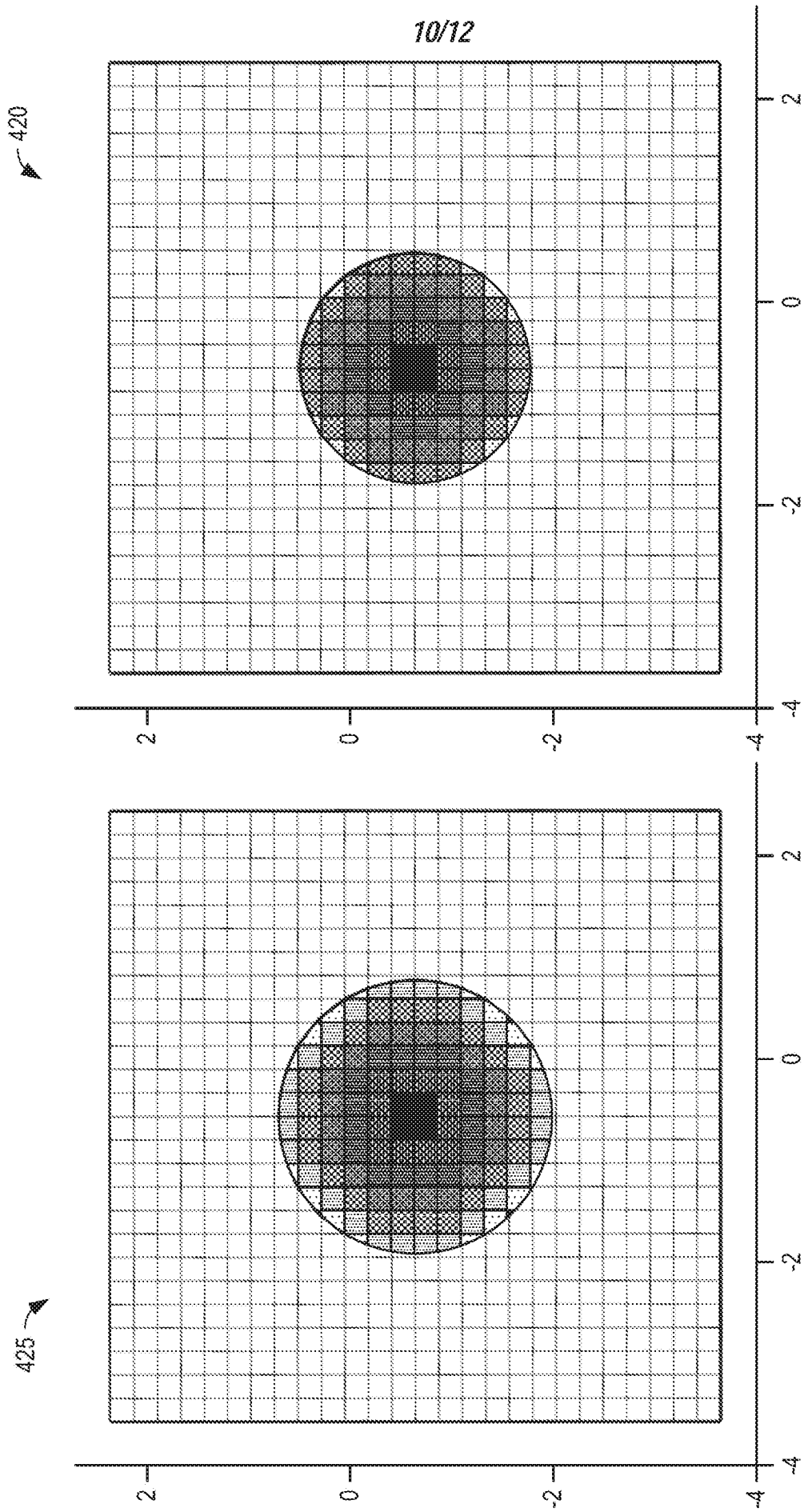


FIG. 4C

11/12

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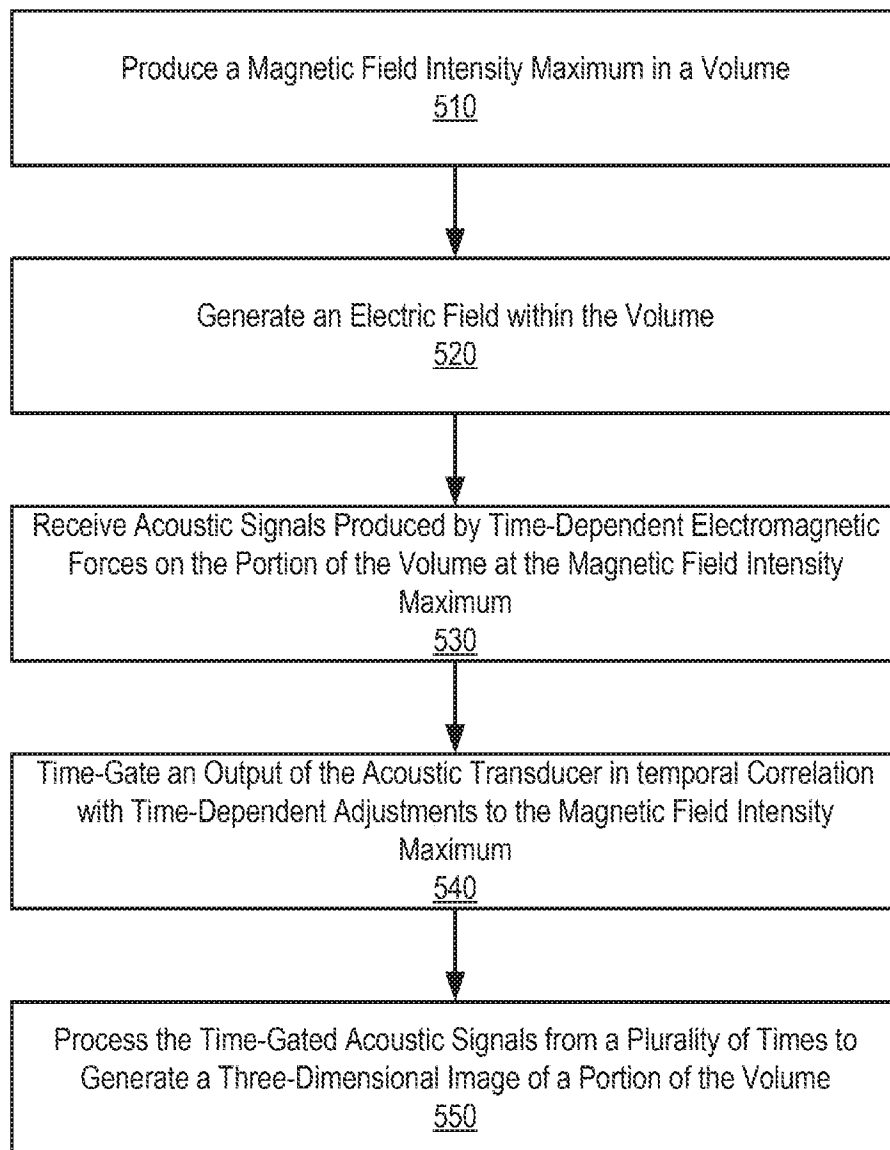


FIG. 5

12/12

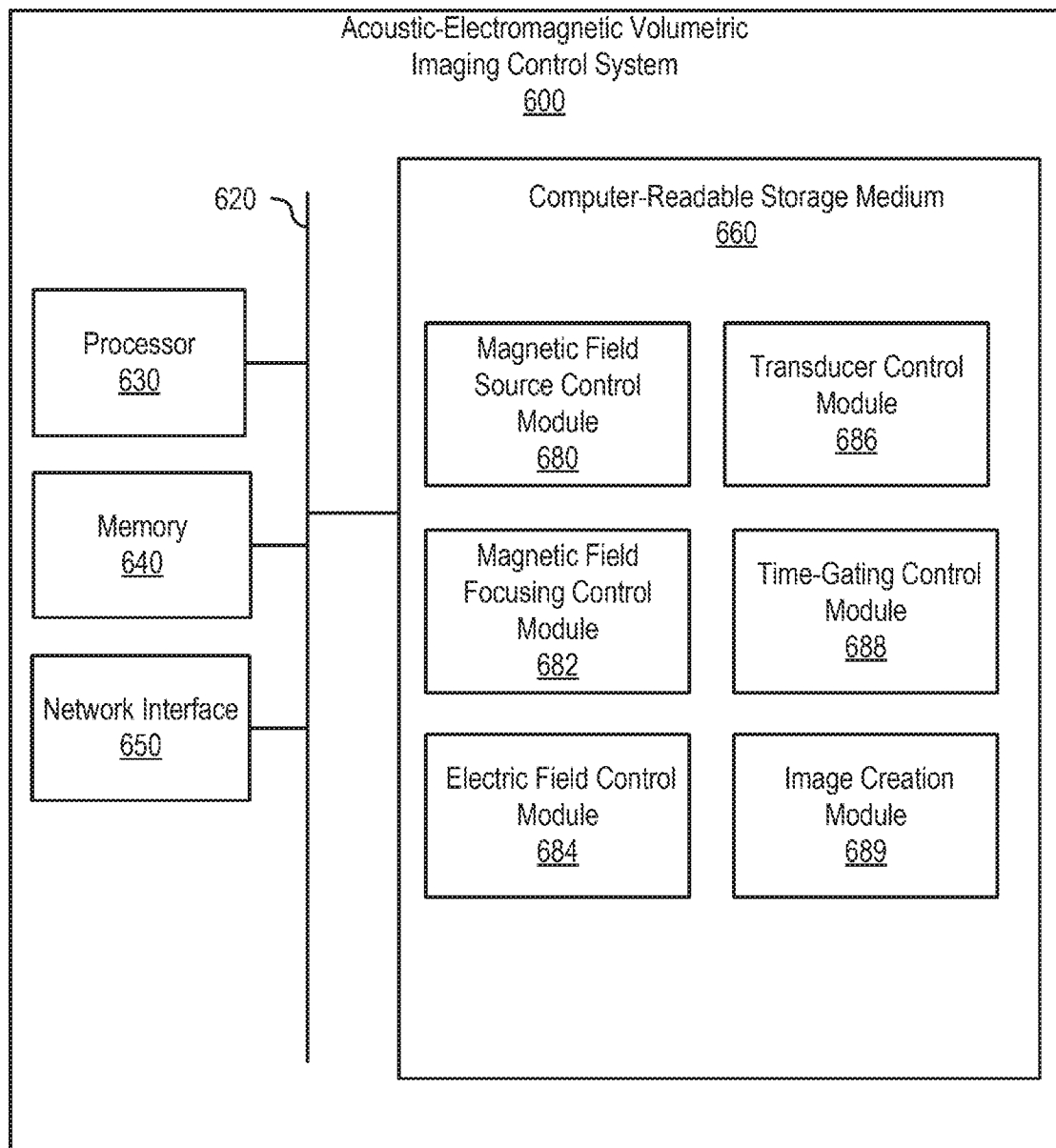


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2019/030368**A. CLASSIFICATION OF SUBJECT MATTER****A61B 5/00(2006.01)i**

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 5/00; A61B ; A61B 8/00; A61B 8/14; A61H 1/00; A61N 1/08; A61N 1/36

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: acoustic, electromagnetic, volume, image, magnet, electric, field, transducer

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2016-0143540 A1 (NEVZAT GUNERI GENCER et al.) 26 May 2016 See paragraphs [05]-[45], claim 24 and figure 3.	1-3, 21, 23
Y		4, 22
Y	US 2009-0306728 A1 (WRIGHT et al.) 10 December 2009 See claim 43.	4, 22
A	US 7666152 B2 (EIN-GAL) 23 February 2010 See the whole document.	1-4, 21-23
A	WO 2004-105582 A2 (MAGNETUS, LLC) 09 December 2004 See the whole document.	1-4, 21-23
A	US 2003-0060738 A1 (EIN-GAL) 27 March 2003 See the whole document.	1-4, 21-23

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

16 August 2019 (16.08.2019)

Date of mailing of the international search report

16 August 2019 (16.08.2019)

Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea



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INTERNATIONAL SEARCH REPORTInternational application No.
PCT/US2019/030368**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.: 7-12,14-19,25,27-31
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:
Claims 7-12,14-19,25,27-31 are unclear, because they refer to multiple dependent claims which do not comply with PCT Rule 6.4(a).
3. ☒ Claims Nos.: 5,6,13,20,24,26
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:

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 an additional fees, this Authority did not invite payment of any 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.:

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

Information on patent family members

International application No.

PCT/US2019/030368

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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