

METHOD AND SYSTEM FOR PERFORMING CONTACTLESS DETECTION OF
ULTRASOUND WAVES FROM A TARGET TO GENERATE AN ULTRASOUND
IMAGE BASED ON THE TARGET

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Cross-Reference To Related Application

[0001] This application claims the benefit of priority of Singapore patent application No. 10202400149Q, filed 17 January 2024, the content of it being hereby incorporated by reference in its entirety for all purposes.

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Technical Field

[0002] Various embodiments relate to a method and a system for performing contactless detection of ultrasound waves from a target to generate an ultrasound image based on the target. Various embodiments also relate to a processing unit operable with an optical coherence tomography (OCT) apparatus to carry out the mentioned method.

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Background

[0003] The detection of ultrasound propagation plays a vital role in both industrial and biomedical applications for various diagnostic and material characterization purposes. In industrial applications, ultrasound detection is mainly used for non-destructive testing (NDT) and evaluation. In the biomedical field, it enables numerous imaging modalities, such as ultrasonography and photoacoustic (PA) imaging. These methods provide non-invasive insights into the body, assisting in the diagnosis of various conditions.

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[0004] The conventional methods for ultrasound detection typically require direct contact with the biological sample or industrial component, presenting limitations in situations where noncontact is preferable or necessary. A noncontact method avoids discomfort and contamination risk in medical settings. It is also useful for inspecting hazardous parts where contact may be impractical. For example, advancements in PA Microscopy (PAM) have been achieved, encompassing both interferometric and non-interferometric PA remote

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sensing (PARS) techniques. These developments provide critical non-invasive imaging capabilities essential for detailed cellular and tissue analysis.

[0005] However, existing noncontact methods often either lack the ability to specify the exact location of the detection point or to provide a sufficiently sampled ultrasound signal with MHz temporal resolution. Both precise spatial sensing localization and high temporal resolution (MHz) are critical prerequisites for obtaining depth-resolved ultrasound images with precise acoustic resolution through acoustic reconstruction. For example, optical-resolution PA microscopy has limited operating configurations and applications as its setup necessitates an overlap of the excitation and sensing beams. Further, there is a lack of high-quality depth-resolved imaging capability due to raw data possessing insufficient temporal resolution or undefined depth-resolved sensing locations.

[0006] Thus, there is a need for a method and system for improved contactless (optical) detection of ultrasound signals, including photoacoustic (PA) waves, to at least address the problems mentioned above.

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Summary

[0007] According to an embodiment, a method for performing contactless detection of ultrasound waves from a target to generate an ultrasound image based on the target is provided. The method includes emitting an optical coherence tomography (OCT) beam sequentially at a plurality of stationary beam locations across a sensing region of the ultrasound waves; at each of the plurality of stationary beam locations, measuring OCT signals periodically for an acquisition cycle; for each of the plurality of stationary beam locations, extracting intermediate phase data from the measured OCT signals; for the plurality of stationary beam locations, concatenating the intermediate phase data to generate displacement data; deriving ultrasound data from time derivatives of the displacement data; and applying a reconstruction algorithm on the ultrasound data to generate the ultrasound image based on the target. The acquisition cycle starts at T_0 being a first time point when the ultrasound waves are initially emitted from the target and ends at T_N being a N^{th} time point when or after the ultrasound waves are propagated through the

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sensing region substantially in entirety. The intermediate phase data may include ultrasound-induced displacement information.

[0008] According to an embodiment, a system for performing contactless detection of ultrasound waves from a target to generate an ultrasound image based on the target is provided. The system includes an optical coherence tomography (OCT) apparatus and a processing unit in communication with the OCT apparatus. The OCT apparatus includes a swept-source laser module configured to emit an OCT beam sequentially at a plurality of stationary beam locations across a sensing region of the ultrasound waves, a scanner configured to receive the OCT beam or part thereof reflected from different depths at each of the plurality of stationary beam locations, and an interferometer configured to measure OCT signals, based on the reflected OCT beam or part thereof, periodically for an acquisition cycle at each of the plurality of stationary beam locations. The acquisition cycle starts at T_0 being a first time point when the ultrasound waves are initially emitted from the target and ends at T_N being a N^{th} time point when or after the ultrasound waves are propagated through the sensing region substantially in entirety. The processing unit is configured to: for each of the plurality of stationary beam locations, extract intermediate phase data from the measured OCT signals, for the plurality of stationary beam locations, concatenate the intermediate phase data to generate displacement data and derive ultrasound data from time derivatives of the displacement data, and apply a reconstruction algorithm on the ultrasound data to generate the ultrasound image based on the target. The intermediate phase data may include ultrasound-induced displacement information.

[0009] According to an embodiment, a processing unit operable with an optical coherence tomography (OCT) apparatus to carry out the method for performing contactless detection of ultrasound waves from a target to generate an ultrasound image based on the target, according to an embodiment, is provided.

Brief Description of the Drawings

[0010] In the drawings, like reference characters generally refer to like parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description,

various embodiments of the invention are described with reference to the following drawings, in which:

5 [0011] FIG. 1A shows a flow chart illustrating a method for performing contactless detection of ultrasound waves from a target to generate an ultrasound image based on the target, according to various embodiments.

[0012] FIG. 1B shows a schematic view of a system for performing contactless detection of ultrasound waves from a target to generate an ultrasound image based on the target, according to various embodiments.

10 [0013] FIG. 2 shows a schematic view of a proposed system structure, according to an example.

[0014] FIG. 3 shows a cross-sectional OCT image illustrating a produced Virtual Acoustic Detector Array (VADA) by the proposed system structure of FIG. 2, according to one embodiment.

15 [0015] FIGS. 4A to 4D shows schematic cross-sectional views of OCT raw data acquisition, according to an example.

[0016] FIG. 5A shows a schematic view illustrating ultrasound raw data extraction from the OCT raw data acquired as shown in FIGS. 4A to 4D.

[0017] FIG. 5B shows a flow chart illustrating steps of ultrasound raw data extraction of FIG. 5A.

20 [0018] FIG. 6A shows a cross-sectional OCT image of a finger, according to an example.

[0019] FIG. 6B shows a cross-sectional view of the constructed VADA on the OCT image of FIG. 6A and the corresponding US raw data.

[0020] FIG. 7A shows a schematic cross-sectional view of OCT raw data acquisition, without US data detected, according to an example.

25 [0021] FIGS. 7B to 7D respectively show the time-domain plot, frequency-domain plot and phase plot of the OCT image pixel at (X_0, Z_0) without US data detected.

[0022] FIG. 7E shows a schematic cross-sectional view of OCT raw data acquisition, with US data detected, according to an example.

30 [0023] FIGS. 7F to 7H respectively show the time-domain plot, frequency-domain plot and phase plot of the OCT image pixel at (X_0, Z_0) with US data detected.

[0024] FIG. 8A shows a representation of a US source, according to one example.

[0025] FIG. 8B shows a cross-sectional view of the constructed VADA on the OCT image of FIG. 8A and the corresponding US raw data.

[0026] FIG. 9A shows a flow representation illustrating image quality being enhanced by locating VADA detectors in an axial/depth direction, according to one example.

5 [0027] FIG. 9B shows a flow representation illustrating image quality being enhanced by locating VADA detectors in the axial/depth direction, according to another example.

[0028] FIG. 10 shows a schematic view illustrating the relationship between the OCT signal strength versus time exclusively provided by SS-OCT, according to an example.

10 [0029] FIG. 11 shows a schematic view of an experimental setup involving a tape sample placed under an OCT beam, according to an example.

[0030] FIG. 12A shows a sequence of OCT image overlaid with the maximum amplitude projection of the US data at each VADA element, obtained from the experiment carried out as shown in FIG. 11.

15 [0031] FIG. 12B shows a plot illustrating the raw US data at one VADA element denoted in FIG. 12A.

[0032] FIG. 12C shows an imagery representation of the reconstructed US source based on the experiment carried out as shown in FIG. 11.

[0033] FIGS. 13A to 13C show planar MAP views of the depth-resolved 3-dimensional image of FIG. 12C in the x-y plane, x-z plane and y-z plane, respectively.

20 [0034] FIG. 14 shows a 2-dimensional image of the target obtained using an existing method similar to OR-PAM.

Detailed Description

25 [0035] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The
30 various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0036] Embodiments described in the context of one of the methods or devices are analogously valid for the other methods or devices. Similarly, embodiments described in the context of a method are analogously valid for a device, and vice versa.

[0037] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0038] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0039] In the context of various embodiments, the phrase “at least substantially” or “substantially” may include “exactly” and a reasonable variance.

[0040] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0041] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0042] As used herein, the phrase of the form of “at least one of A or B” may include A or B or both A and B. Correspondingly, the phrase of the form of “at least one of A or B or C”, or including further listed items, may include any and all combinations of one or more of the associated listed items.

[0043] As used herein, the expression “configured to” may mean “constructed to” or “arranged to”.

[0044] Various embodiments may provide a Virtual Acoustic Detector Arrays (VADA) for all-optical ultrasound (US) sensing for acoustic imaging. There is provided a system and method for detecting US waves and generating US images without physical contact with the biological sample (e.g. hand skin) or any industrial part under inspection. More specifically, Swept-Source Optical Coherence Tomography (SS-OCT) may be employed to detect US waves and create US images in a non-contact manner. With this system, the VADA may be reconstructed to receive US raw data at high temporal resolution from

specified sensing locations in both lateral scanning and the axial direction. These capabilities are prerequisites for generating depth-resolved ultrasound images with precise acoustic resolution through reconstruction algorithms. The VADA may allow for flexible determination of detector locations while preserving signal quality, adding versatility in aligning the US excitation source with the detection path. As a result, the VADA may achieve both precise spatial sensing localization and high temporal resolution, which is essential for various depth-resolved acoustic imaging applications. This may contrast with current PARS methods requiring co-focusing of excitation and probe beams and using maximum amplitude projection for pixel values, as seen in optical resolution-PAM implementation. This advancement over existing work broadens the scope of potential configurations and may extend the range of applications in ultrasound sensing and imaging.

[0045] FIG. 1A shows a flow chart illustrating a method 100 for performing contactless detection of ultrasound waves from a target to generate an ultrasound image based on the target, according to various embodiments. As seen in FIG. 1A, at Step 102, an optical coherence tomography (OCT) beam is emitted sequentially at a plurality of stationary beam locations across a sensing region of the ultrasound waves. At Step 104, at each of the plurality of stationary beam locations, OCT signals are measured periodically for an acquisition cycle. The acquisition cycle starts at T_0 being a first time point when the ultrasound waves are initially emitted from the target and ends at T_N being a N^{th} time point when or after the ultrasound waves are propagated through the sensing region substantially in entirety. At Step 106, for each of the plurality of stationary beam locations, intermediate phase data is extracted from the measured OCT signals. The intermediate phase data may include ultrasound-induced displacement information. At Step 108, for the plurality of stationary beam locations, the intermediate phase data is concatenate to generate displacement data. At Step 110, ultrasound data is derived from time derivatives of the displacement data. At Step 112, a reconstruction algorithm is applied on the ultrasound data to generate the ultrasound image based on the target.

[0046] In other words, the method 100 includes obtaining the ultrasound images from OCT raw data by performing OCT raw data acquisition, followed by US raw data extraction and subsequently US image reconstruction. These processes will be described in more detail later on.

[0047] In various embodiments, emitting the OCT beam sequentially at the plurality of stationary beam locations across the sensing region at Step 102 may include moving the OCT beam laterally from one stationary beam location to another stationary beam location within the sensing region after completing each acquisition cycle until the OCT beam
5 sweeps across the sensing region, thereby scanning the target in a non-contact manner.

[0048] The sensing region may include a three-dimensional volume surrounding the target where the US waves of the target propagate outwardly and radially from the target, reaching the boundaries of the sensing region. The sweeping (or lateral movement) of the OCT beam may perform a non-contact scan. The target may include a vibration source
10 caused by an absorption of laser energy or based on piezoelectric transduction, mechanical loading, Lorentz force, air pulses, or heartbeats. For example, a target may be bones underneath a hand skin, and a laser source may be used to induce vibration of the target. The OCT beam may then be directed at a surface of the hand skin and when scanning, move along the surface.

[0049] Measuring the OCT signals at Step 104 may include capturing at least part of an OCT image.

[0050] For each of the plurality of stationary beam locations, extracting the intermediate phase data from the measured OCT signals at Step 106 may include applying a bandpass filter to the measured OCT signals to determine positions of virtual acoustic detector array (VADA) detectors along a depth axis of the stationary beam location; extracting an OCT
20 instantaneous phase from each VADA detector; and obtaining the intermediate phase data by subtracting the OCT instantaneous phase with a reference phase at T_0 . The depth axis may be extending perpendicularly from a surface plane including the plurality of stationary beam locations, and each VADA detector may be representative of each pixel or each
25 cluster of pixels of the OCT image.

[0051] The bandpass filter applicable to the measured OCT signals may include (or may be implemented) but not limited to a rectangular bandpass filter, a Butterworth filter, or a Morlet wavelet. In other words, other suitable bandpass filters may also be used.

[0052] Extracting the OCT instantaneous phase from each VADA detector may include
30 applying a time-frequency analysis technique on the pixel or the cluster of pixels at each time point from T_0 to T_N . The reference phase at T_0 may be obtainable by applying the

time-frequency analysis technique on the pixel or cluster of pixels at T_0 . The time-frequency analysis technique may include but not limited to a Hilbert transform, a short-time Fourier transform, a wavelet transform, a Gabor transform, a Wigner-Ville distribution, a S-transform, or an empirical mode decomposition. Other suitable methods/techniques providing the similar effect may be alternatively employed.

[0053] The method 100 may further include prior to applying the bandpass filter to the measured OCT signals, removing background noise from the measured OCT signals, and/or adjusting a depth or frequency scale of the measured OCT signals based on a calibration fringe of the OCT beam.

[0054] In various embodiments, for the plurality of stationary beam locations, at least some of the VADA detectors may be positioned in an interlaced manner with the target.

[0055] The method 100 may further include prior to deriving the ultrasound data at Step 110, enhancing a quality of the displacement data with a filter. For example, the filter may include a median filter, a low-pass filter, a high-pass filter or a notch filter.

[0056] In various embodiments, the reconstruction algorithm used at Step 112 may include but not limited to a time reversal algorithm, a delay and sum algorithm, a time-domain algorithm, a model-based algorithm, or a frequency-domain algorithm.

[0057] While the method described above is illustrated and described as a series of steps or events, it will be appreciated that any ordering of such steps or events are not to be interpreted in a limiting sense. For example, some steps may occur in different orders and/or concurrently with other steps or events apart from those illustrated and/or described herein. In addition, not all illustrated steps may be required to implement one or more aspects or embodiments described herein. Also, one or more of the steps depicted herein may be carried out in one or more separate acts and/or phases.

[0058] FIG. 1B shows a schematic cross-sectional view of a system 120 for performing contactless detection of ultrasound waves from a target to generate an ultrasound image based on the target, according to various embodiments. As seen in FIG. 1B, the system 120 includes an optical coherence tomography (OCT) apparatus 122 and a processing unit 124 in communication with the OCT apparatus 122 (as denoted by a line 126).

[0059] The system 120 may be described in analogous context to the method 100 of FIG. 1A, and therefore the corresponding descriptions may be omitted here.

[0060] The OCT apparatus 122 includes a swept-source laser module 128 configured to emit an OCT beam sequentially at a plurality of stationary beam locations across a sensing region of the ultrasound waves (e.g. Step 102), a scanner 130 configured to receive the OCT beam or part thereof reflected from different depths at each of the plurality of stationary beam locations, and an interferometer 132 configured to measure OCT signals, based on the reflected OCT beam or part thereof, periodically for an acquisition cycle at each of the plurality of stationary beam locations (e.g. Step 104). The acquisition cycle starts at T_0 being a first time point when the ultrasound waves are initially emitted from the target and ends at T_N being a N^{th} time point when or after the ultrasound waves are propagated through the sensing region substantially in entirety.

[0061] The processing unit 124 is configured to: for each of the plurality of stationary beam locations, extract intermediate phase data from the measured OCT signals (e.g. Step 106); for the plurality of stationary beam locations, concatenate the intermediate phase data to generate displacement data (e.g. Step 108), and derive ultrasound data from time derivatives of the displacement data (e.g. Step 110); and apply a reconstruction algorithm on the ultrasound data to generate the ultrasound image based on the target (e.g. Step 112). The intermediate phase data may include ultrasound-induced displacement information.

[0062] In other words, the processing unit 124 may be operable with the OCT apparatus 122 to carry out the method 100. More specifically, the processing unit 124 may be configured to carry out at least part of the method 100. The system 120 may provide a compact, non-contact multimodal imaging platform that integrates US imaging, inclusive of PA detection, with OCT.

[0063] Examples of the method 100 and the system 120 will be discussed in more detail below.

[0064] FIG. 2 shows a schematic representative view of a proposed system structure 220, according to an example. FIG. 3 shows a cross-sectional OCT image illustrating a produced Virtual Acoustic Detector Array (VADA) 360 by the proposed system structure 220 of FIG. 2, according to one embodiment.

[0065] The proposed system structure 220 may include the same or like elements or components as those of the system 120 of FIG. 1B, and as such, the same ending numerals

are assigned and the like elements may be as described in the context of the system 120 of FIG. 1B, and therefore the corresponding descriptions are omitted here.

[0066] Prior studies have been conducted to verify the feasibility of this method (e.g. 100) in: high pressure level (MPa) ultrasound imaging applications with piezoelectric transducer emissions, and low pressure level (kPa) photoacoustic (PA) imaging applications with pulsed laser illumination of blood-embedded tissue-mimicking phantoms. The generation of ultrasound (e.g. 240 of FIG. 2) may be achieved through various means such as the absorption of laser energy in techniques such as PA and Laser Ultrasonics, as well as piezoelectric transduction, mechanical loading, Lorentz force, air pulses, heartbeats, among others to provide the US excitation source.

[0067] The proposed system structure 220 primarily utilizes: Swept-Source Optical Coherence Tomography (SS-OCT) 222, adhering to a specialized protocol to acquire raw reflected optical signals, in other words, for optical ultrasound sensing; and a postprocessing unit (e.g. 124 of FIG. 1B) equipped with a tailored algorithm (i.e. the acquisition and processing method 224) to extract ultrasound information and create ultrasound images. Essentially, raw reflected optical signals embedded with US information may be acquired for US images creation.

[0068] In the detection setup, the US detection arm may have various configurations to align with different US applications, e.g. acoustic-resolution PA microscopy 242 which may involve a dichroic mirror, PA tomography 244 which may require expanded excitation, and US imaging and ranging 246.

[0069] *Swept-Source Laser operation in SS-OCT 222*

[0070] Swept-Source Laser operation in SS-OCT 222 performs SS-OCT A-scan acquisition. The SS-OCT subsystem 222 includes a scanner 230 and a swept-source laser module 228. Inset 228a (in FIG. 2) shows an exemplary frequency spectrum 228b illustrating the sweeping of the swept-source laser module 228.

[0071] Like most noncontact optical ultrasound detection methods, the SS-OCT subsystem 222 operates on the principle of interferometry 232, where the phase variation in the OCT fringes reveals US-induced vibrational displacement at the nanometer scale within a sample. In other words, by analysing the interference patterns between a stable reference

beam and a sample beam, which is altered by ultrasound-induced displacements on the sample 248 and obtained via the scanner 230, it reveals the vibrational displacement of the sample 248 over time.

[0072] Among different type of interferometry systems, the SS-OCT 222 may be exclusively selected because the data produced may meet both prerequisites, as follow.

[0073] *Precise spatial sensing localization:* Since OCT (e.g. the SS-OCT 222) is capable of producing depth-resolved images of a target (background seen in FIG. 3), each pixel (or a cluster of surrounding pixels) along the axial (depth) direction 364 may function as a well-defined positional element of a virtual acoustic detector 362 within the VADA 360. The the axial (depth) direction 364 is substantially perpendicular to a lateral direction 368. The lateral direction 368 is substantially parallel to a plane of the target surface. The virtual construction of the VADA 360 is along both lateral and depth directions 368, 364 on the imaging target for non-contact detection of acoustic waves from surrounding US source(s).

[0074] *High temporal resolution (MHz):* The operation of the swept source laser 228 is further explored, where the wavelength of the output beam varies over time. Such correlation of output signal versus time suggests that it is possible to extract an ultrasound signal with MHz temporal resolution from the SS-OCT raw data.

[0075] *Post-processing unit with a tailored algorithm*

[0076] The proposed acquisition and processing method 224 to obtain the ultrasound images from OCT raw data includes the three main steps, namely, OCT raw data acquisition, ultrasound raw data extraction, and ultrasound image reconstruction. This method 224 may be described in similar context to the method 100 of FIG. 1A.

[0077] *OCT raw data acquisition*

[0078] FIGS. 4A to 4D show schematic cross-sectional views 246a, 246b, 246c, 246d illustrating OCT raw data acquisition from a target (e.g. 248) at different times of $t = T_0$, $t = T_1$, $t = T_{N-1}$, and $t = T_N$, respectively, according to an example.

[0079] As seen in FIGS. 4A to 4D, the ultrasound source (e.g. a blood vessel) 448 produces ultrasound waves 482 that propagate through the surrounding medium 484 (e.g. tissue). For example, the sweep period of the high-speed SS-OCT 222, specifically the OCT A-

scan time ($< 1 \mu\text{s}$), may be shorter than the time required for the ultrasound waves 482 to propagate from the source 448 to the sensing region (up to tens of μs). The OCT detection beam 480 is pointing down to the target, and is at a stationary location $x = X_0$. One OCT acquisition cycle is from T_0 to T_N , as shown in FIGS. 4A to 4D. Within each cycle, T_0 marks the moment of ultrasound wave emission (FIG. 4A) and each of T_1 , T_{N-1} , and T_N (FIGS. 4B, 4C and 4D, respectively) represents each moment that the OCT acquires signal (e.g. via the scanner 230 – not shown in FIGS. 4A to 4D). Multiple successive OCT A-scans are required at the stationary beam location $x = X_0$ to cover the entire US propagation. The acquisition process in the detection arm of the SS-OCT 222 continues until the ultrasound waves 482 have propagated through the sensing region (as seen in FIG. 4D) $x = X_0$, where the peak may arrive between time point T_{N-1} and T_N . In this cycle, a total of N OCT A-scans may be performed to capture the complete US waveform. This way, as the beam 480 is stationary, imaging is performed along the depth direction within the cycle.

[0080] Such a cycle may be repeated for the following purposes: enhance signal-to-noise ratio (if the beam position 480 is still at X_0); and for sensing ultrasound waves at different lateral OCT beam locations (if the beam position 480 moves to a different point).

[0081] For the latter, the cycle may be performed at different OCT beam locations to extend the lateral field of view, i.e., the aperture of the VADA 360.

[0082] The acquisition process repeats for all beam positions to scan the target.

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[0083] *Ultrasound raw data extraction*

[0084] FIG. 5A shows a schematic view 501 illustrating ultrasound raw data extraction 505 from the OCT raw data 503' acquired at T_0 , as depicted in FIGS. 4A to 4D.

[0085] The OCT raw data sequence (or OCT A-scans) 503 spans from time point T_0 to T_N within each OCT acquisition cycle e.g. at position X_0 . For example, the OCT A-scan at T_{N-1} may provide OCT raw data (or OCT A-scan fringes) 503', with axes having arbitrary values.

[0086] FIG. 5B shows a flow chart illustrating steps of ultrasound raw data extraction 505 of FIG. 5A to obtain the ultrasound raw data 507.

[0087] The steps 511, 513, 515, 517, 519 in FIG. 5B are applied to datasets (1 to N) collected at each time point (from T_0 to T_N) from the sequence. After processing, the

intermediate phase data is concatenated 521 and filtered 523 to yield the final ultrasound raw data 507. Essentially, US signals are extracted from the phase time evolution of a swept-source OCT's spectral sweep. The detailed steps are described as follows.

[0088] Step 511: Background noise removal is performed by subtracting the background noise from the acquired OCT raw data 503, 503'.

[0089] Step 513: OCT k-linearization is performed by adjusting the depth/frequency scale of the data using the calibration fringe for accurate recalibration.

[0090] Step 515: Determination of detector positions (more specifically, the position of the VADA detector) along the axial/depth axis with bandpass filtering. To facilitate instantaneous phase extraction, the signal ought to remain narrowband. Various bandpass filters may be employed, including rectangular, Morlet wavelet, Butterworth, etc.

[0091] Step 517: Instantaneous phase extraction is performed by using the Hilbert transform or alternative time-frequency analysis methods to extract the OCT instantaneous phase.

[0092] Step 519: Subtraction of the reference phase at T_0 from the OCT instantaneous phase obtained by Step 517 to determine ultrasound-induced displacement information.

[0093] Step 521: Concatenating each phase difference segment (and effectively, all the phase series to produce the complete displacement data.

[0094] Step 523: Applying filters to enhance signal quality and taking time derivative of the displacement data produced by Step 521 to generate the ultrasound raw data 507.

[0095] The concept of the VADA 360 may be described with respect to the following example.

[0096] The OCT raw data (e.g. seen in FIGS. 4A to 4D) may be used to reconstruct image that reveals the internal structure of the target. To illustrate, consider the process of obtaining a cross-sectional OCT image 631 of a finger as shown in FIG. 6A. The OCT beam sweeps laterally from position X_0 633 to the right-side position 633', scanning the target at different lateral positions of the OCT beam. FIG. 6B shows a cross-sectional view 631' of the constructed VADA 662 on the OCT image 631 of FIG. 6A and the corresponding US raw data 635 at X_0 633 along various depths, 637 at the right-side position 633' along various depths. The y-axis label and the x-axis label of the US raw data 635, 637 are amplitude (arbitrary unit) and time point, respectively.

[0097] The steps of OCT raw data acquisition and US raw data extraction, as discussed above, are performed to locate the VADA individual detector 662 location along the axial/depth direction and extract the ultrasound raw data 635, 637 at each scanned location.

[0098] Once the data is collected at one lateral position (e.g. 633), the OCT beam advances to the next, and the process is repeated until the full OCT image 631' is captured, e.g. at 633'. Consequently, each pixel (or a cluster of pixels) in the OCT image 631 effectively becomes one VADA detector 662, from which the ultrasound raw data is extracted. This accumulation of ultrasound raw data 635, 637 from across the scan forms a comprehensive dataset that may be used to create detailed ultrasound images.

[0099] US A-scan extractions at VADA locations may be described in more detail with reference to FIGS. 7A to 7H, which are not to scale.

[0100] FIG. 7A shows a schematic cross-sectional view of OCT raw data acquisition, without US data detected, according to an example. FIGS. 7B to 7D respectively show the time-domain plot, frequency-domain plot and phase plot of the OCT image pixel at (X_0, Z_0) without US data detected, at $t = T_0$.

[0101] FIG. 7E shows a schematic cross-sectional view of OCT raw data acquisition, with US data detected, according to an example. FIGS. 7F to 7H respectively show the time-domain plot, frequency-domain plot and phase plot of the OCT image pixel at (X_0, Z_0) with US data detected, at $t = T_1$.

[0102] As seen in FIGS. 7A and 7E, the OCT beam 780 is stationary and arranged spaced apart from the US source 748, which generates US waves 782.

[0103] VADA may be constructed from the raw OCT data with US A-scans extracted at each detector location. The virtual construction of the VADA may be along both lateral and depth directions on the imaging target for non-contact detection of acoustic waves from surrounding US sources. High-speed scanning (MHz OCT A-scan rate) and ultra-sensitive phase detection (nm displacement sensitivity) allow for the customization of the spatial density of the VADA and the collection of wideband acoustic signals, which are essential for the reconstruction of US images. Among different type of OCT systems (e.g. time-domain OCT, spectral-domain OCT, and SS-OCT), SS-OCT is exclusively selected since it achieves both: (a) depth-resolved VADA detector location, and (b) high temporal resolution US data.

[0104] (a) Depth-resolved VADA detector location

[0105] Since OCT is capable of producing depth-resolved images of the target structure (the background in FIGS. 7A and 7E), each pixel (represented by squares) or a cluster of surrounding pixels along the axial (depth) direction may function as a well-defined positional element within a VADA. The highlighted pixel 781 at (X_0, Z_0) serves as an example. In the time domain (FIG. 7B), the data may be formulated as in Equation 1:

$$x(k) = A \cos(zk) \quad \text{- Equation 1}$$

where A is the amplitude constant, k is the wavenumber of the swept source laser, and z represents the frequency of the fringes. In other words, z indicates the depth of the pixel (e.g. 781), as illustrated in FIGS. 7A and 7C.

[0106] The US data is denoted as $\Phi_n(t)$, which is a time series. Given that the output wavenumber k of the SS-OCT is correlated with time, the US data may be remapped as shown in Equation 2:

$$\Phi_n(t) \rightarrow \Phi_n(k) \quad \text{- Equation 2.}$$

[0107] As the US wave arrives at the detector pixel 781 (as shown in FIG. 7E), it contributes to the original fringe as a phase noise term 783 (FIG. 7F). Consequently, the fringe formula becomes as shown in Equation 3:

$$x(k) = A \cos[zk + \Phi_n(k)] \quad \text{- Equation 3.}$$

[0108] Therefore, power of the fringe signal is dispersed to adjacent frequencies, leading to the creation of noise sidebands. FIG. 7G plots its frequency spectrum, demonstrating that the US spectrum $[Z_{n,min}, Z_{n,max}]$ is shifted and centered at the OCT fringe frequency, corresponding to pixel depth Z_0 . By applying a band-pass filter to the acquired raw OCT data at Z_0 , not only the individual VADA detector may be located, but the received US data is also preserved. Essentially, the sensing locations may be pin-pointed not only in the scanning direction but also extended to the axial/depth direction.

[0109] (b) High temporal resolution US data

[0110] The instantaneous phase of the fringes at each detector location, both without and with the detected US, may be computed via time frequency analysis. The former (illustrated in FIG. 7D) serves as the reference baseline, while the latter (shown in FIG. 7H) may be subtracted from this baseline to obtain the US data $\Phi_n(k)$. This data may then be remapped back to the time domain as shown in Equation 4:

$$\Phi_n(k) \rightarrow \Phi_n(t) \quad - \text{Equation 4.}$$

[0111] The acquisition rate of the time series depends on the acquisition card, ranging from hundredths of MHz to GHz. Generally, this rate is more than sufficient to capture US data up to tens of MHz, thereby extracting high-resolution US raw data. However, due to the uncertainty principle of time-frequency analysis, a careful trade-off may be made between the size of the VADA detector (spectrum width) and the temporal resolution.

[0112] *Ultrasound image reconstruction*

[0113] FIG. 8A shows a representation 831 of a US source (or interchangeably referred to as acoustic/PA source), according to one example.

[0114] FIG. 8B shows a cross-sectional view of the constructed VADA 831' on the representation of FIG. 8A and the corresponding US raw data 835.

[0115] Utilizing the US raw data collected at each detector location (i.e. from each VADA detector 862), various acoustic reconstruction algorithms may be applied to reveal the US source. These algorithms may include time reversal, delay and sum, model-based methods, and frequency domain methods. Although the US source, e.g. the blood vessel, is shown in the representation 831, it should be appreciated that the US source may not be visible in the OCT image.

[0116] The integration of SS-OCT with VADA processing may provide at least one of the following advantages of:

- allowing axial distribution of detectors for enhanced reconstruction quality beyond just the surface of the target; or
- versatility for use in a range of ultrasound sensing technologies such as AR-PAM, OR-PAM, PAT, and additional ultrasound detection method, thereby broadening the realm of all-optical US sensing systems and introducing a new spatial dimension and time discernibility.

[0117] The concept of VADA introduces the possibility of distributing the detector array spatially along the third dimension (axial/depth). Such possibility was not disclosed or considered in existing systems/works. With spatial and temporal resolution, time-resolved acoustic A-scans may be captured at distinct positions in the axial/depth direction. Furthermore, it allows for interlacing with the target - a detector array configuration

previously uncharted and physically unfeasible. It also improves image quality by enabling more efficient construction of high-density detector arrays (concurrently constructing detectors in the axial/depth direction), and providing broader coverage of detection angles (detectors encompassing the source). Resolving the target at depth allows the use of US raw data for effective reconstructions across varied systems, permitting deep tissue imaging.

[0118] The effects of VADA locations on image quality will be exemplified below.

[0119] FIG. 9A shows a flow representation illustrating image quality being enhanced by locating VADA detectors in an axial/depth direction, according to one example.

[0120] In this example, the simulation setup 931 utilizes a reduced number of detectors 962 above the US source 948. The reconstruction process follows, as shown by the sequential snapshots 939a, 939b, 939c, 939d of the reconstruction taken at appropriate time intervals. After the reconstruction process, the reconstructed image 941 reflects poor reconstruction accuracy.

[0121] FIG. 9B shows a flow representation illustrating image quality being enhanced by locating VADA detectors in the axial/depth direction, according to another example.

[0122] In this other example, the simulation setup 931' utilizes an increased number of detectors 962 interlaced with the US source 948. The reconstruction process follows, as shown by the sequential snapshots 939a', 939b', 939c', 939d' of the reconstruction taken at appropriate time intervals. After the reconstruction process, the reconstructed image 941' reflects richer details and enhanced accuracy (compared to 941 of FIG. 9A).

[0123] FIG. 10 shows a schematic view 1001 illustrating the relationship between the OCT signal strength versus time exclusively provided by SS-OCT, arising from the wavenumber variation of the output beam over time, that is thoroughly exploited to extract the high temporal resolution ultrasound raw data.

[0124] This exclusivity provided by the SS-OCT approach is not immediately apparent, as standard OCT applications prioritize the relationship between signal strength and wavenumber in OCT raw data for image creation, often neglecting the signal strength versus time aspect (as shown in the Venn diagram in FIG. 10). This relationship is crucial for the proposed VADA method, as it enables the extraction of high temporal resolution ultrasound raw data, which is essential for producing high-quality ultrasound images. The

VADA is introduced for noncontact sensing and imaging of US and PA, a technique crucial in various industrial and biomedical fields.

[0125] Proof of concept and the experimental evaluations of the system (e.g. 120 of FIG. 1B) / method (e.g. 100 of FIG. 1A) were performed using a scotch tape sample placed under the OCT objective (OCT beam), as shown in the schematic view 1101 of FIG. 11.

[0126] A conventional piezoelectric transducer (with a center frequency of 10 MHz) serves as the US source 1148 emitting US waves 1182. Its focus spot is approximately positioned at the side wall of the tape sample 1184. For example, the transducer may be placed about 2 cm away from the tape sample 1184. As the distance between the tape sample 1184 and the US source 1148 increases, the measured amplitude decreases. Alternatively, a pulse laser source, e.g. generating a laser spot of about 3 mm, with pulse energy of about 0.9 mJ, and pulse width of < 1.8 ns, may be used instead of the piezoelectric transducer to produce the US.

[0127] The OCT beam 1180 sweeps laterally across the tape top surface, forming a 3-dimensional VADA 1162 comprised of 101 x 20 x 20 points. These points are distributed within a volume measuring about 9 mm (x axis) x about 1.7 mm (y axis) x about 1.3 mm (z axis), where the first and second dimensions lie along the lateral plane (x-y plane), and the third dimension is constructed along the depth (z) direction. It is noted that in OCT measurements, the PA amplitude is influenced by the distance between the target (e.g. within the tape sample 1184) and the virtual detector. The sample (e.g. tape sample 1184) may be tilted with respect to the OCT beam 1180 to reduce OCT reflection noise.

[0128] FIG. 12A shows a sequence of OCT images overlaid with the corresponding maximum amplitude projection (MAP) of the acquired US data at each VADA location 1162, specifically the acoustic field distribution inside the tape 1184. Utilizing the raw US data collected from each and every VADA detector location (an exemplary US waveform retrieved from one VADA detector as given in FIG. 12B), various acoustic reconstruction algorithms may be applied to reconstruct the US source 1148. These algorithms may include time reversal, time-domain, model-based, and frequency domain methods. FIG. 12C displays the morphology and position of the piezoelectric layer of the US transducer reconstructed with time reversal (k-wave toolbox). Consequently, 3-dimensional imaging with the data has been shown to be feasible.

[0129] It should be noted that the signals extracted from outside the tape region, which exhibit strong MAP, are system random phase noise across the entire sequence. They possess different temporal and frequency components compared to the normal US data and thus will be eliminated during the reconstruction process.

5 [0130] The sensitivity of the proposed method (e.g. described in similar context to the method 100 of FIG. 1A) is qualified for PA and US sensing, providing a signal-to-noise ratio margin from about 24 dB up to (and potentially exceeding) 36 dB for PA imaging. This may account for differences in sample absorbance (e.g. blood vs tape sample 1184), variations in laser fluence (using a lower power laser, expanding the excitation beam, amongst others), and other influencing factors.

10 [0131] FIGS. 13A to 13C show planar MAP views of the depth-resolved 3-dimensional image of FIG. 12C in the x-y plane 1301a, x-z plane 1301b and y-z plane 1301c, respectively. FIG. 13A shows the cross-sectional view seen from line 1303 of FIG. 13C, while FIG. 13B shows the cross-sectional view seen from line 1305 of FIG. 13C. For comparison purposes, FIG. 14 shows a 2-dimensional image 1401 of the target obtained using an existing method, e.g. similar to OR-PAM.

15 [0132] A high-quality 3-dimensional reconstructed acoustic image (FIG. 12C, FIGS. 13A to 13C) may be observed as compared to the low quality 2-dimensional image (FIG. 14).

20 [0133] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

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CLAIMS

1. A method for performing contactless detection of ultrasound waves from a target to generate an ultrasound image based on the target, the method comprising:
- 5 (a) emitting an optical coherence tomography (OCT) beam sequentially at a plurality of stationary beam locations across a sensing region of the ultrasound waves;
- (b) at each of the plurality of stationary beam locations, measuring OCT signals periodically for an acquisition cycle, wherein the acquisition cycle starts at T_0 being a first time point when the ultrasound waves are initially emitted from the target and ends at T_N
- 10 being a N^{th} time point when or after the ultrasound waves are propagated through the sensing region substantially in entirety;
- (c) for each of the plurality of stationary beam locations, extracting intermediate phase data from the measured OCT signals, wherein the intermediate phase data comprises ultrasound-induced displacement information;
- 15 (d) for the plurality of stationary beam locations, concatenating the intermediate phase data to generate displacement data;
- (e) deriving ultrasound data from time derivatives of the displacement data; and
- (f) applying a reconstruction algorithm on the ultrasound data to generate the ultrasound image based on the target.
- 20
2. The method as claimed in claim 1, wherein emitting the OCT beam sequentially at the plurality of stationary beam locations across the sensing region comprises moving the OCT beam laterally from one stationary beam location to another stationary beam location within the sensing region after completing each acquisition cycle until the OCT beam
- 25 sweeps across the sensing region, thereby scanning the target.
3. The method as claimed in claim 1 or 2, wherein measuring the OCT signals comprises capturing at least part of an OCT image, and
- wherein for each of the plurality of stationary beam locations, extracting the
- 30 intermediate phase data from the measured OCT signals comprises:

applying a bandpass filter to the measured OCT signals to determine positions of virtual acoustic detector array (VADA) detectors along a depth axis of the stationary beam location, wherein the depth axis is extending perpendicularly from a surface plane comprising the plurality of stationary beam locations, and each VADA detector is representative of each pixel or each cluster of pixels of the OCT image;

extracting an OCT instantaneous phase from each VADA detector; and
obtaining the intermediate phase data by subtracting the OCT instantaneous phase with a reference phase at T_0 .

4. The method as claimed in claim 3, wherein the bandpass filter comprises a rectangular bandpass filter, a Butterworth filter, or a Morlet wavelet.

5. The method as claimed in claim 3 or 4, wherein extracting the OCT instantaneous phase from each VADA detector comprises applying a time-frequency analysis technique on the pixel or the cluster of pixels at each time point from T_0 to T_N .

6. The method as claimed in any one of claims 3 to 5, wherein the reference phase at T_0 is obtainable by applying the time-frequency analysis technique on the pixel or cluster of pixels at T_0 .

7. The method as claimed in claims 5 or 6, wherein the time-frequency analysis technique comprises a Hilbert transform, a short-time Fourier transform, a wavelet transform, a Gabor transform, a Wigner–Ville distribution, a S-transform, or an empirical mode decomposition.

8. The method as claimed in any one of claims 3 to 7, further comprising prior to applying the bandpass filter to the measured OCT signals, removing background noise from the measured OCT signals.

9. The method as claimed in any one of claims 3 to 8, further comprising prior to applying the bandpass filter to the measured OCT signals, adjusting a depth or frequency scale of the measured OCT signals based on a calibration fringe of the OCT beam.
- 5 10. The method as claimed in any one of claims 3 to 9, wherein for the plurality of stationary beam locations, at least some of the VADA detectors are positioned in an interlaced manner with the target.
11. The method as claimed in any one of claims 1 to 10, further comprising prior to
10 deriving the ultrasound data, enhancing a quality of the displacement data with a filter.
12. The method as claimed in claim 11, wherein the filter comprises a median filter, a low-pass filter, a high-pass filter or a notch filter.
- 15 13. The method as claimed in any one of claims 1 to 12, wherein the reconstruction algorithm comprises a time reversal algorithm, a delay and sum algorithm, a time-domain algorithm, a model-based algorithm, or a frequency-domain algorithm.
14. The method as claimed in any one of claims 1 to 13, wherein the target comprises
20 a vibration source caused by an absorption of laser energy or based on piezoelectric transduction, mechanical loading, Lorentz force, air pulses, or heartbeats.
15. A system for performing contactless detection of ultrasound waves from a target to generate an ultrasound image based on the target, the system comprising:
25 an optical coherence tomography (OCT) apparatus comprising:
a swept-source laser module configured to emit an OCT beam sequentially at a plurality of stationary beam locations across a sensing region of the ultrasound waves,
a scanner configured to receive the OCT beam or part thereof
30 reflected from different depths at each of the plurality of stationary beam locations, and

an interferometer configured to measure OCT signals, based on the reflected OCT beam or part thereof, periodically for an acquisition cycle at each of the plurality of stationary beam locations, wherein the acquisition cycle starts at T_0 being a first time point when the ultrasound waves are initially emitted from the target and ends at T_N being a N^{th} time point when or after the ultrasound waves are propagated through the sensing region substantially in entirety; and

a processing unit in communication with the OCT apparatus, the processing unit configured to:

for each of the plurality of stationary beam locations, extract intermediate phase data from the measured OCT signals, wherein the intermediate phase data comprises ultrasound-induced displacement information,

for the plurality of stationary beam locations, concatenate the intermediate phase data to generate displacement data, and derive ultrasound data from time derivatives of the displacement data, and

apply a reconstruction algorithm on the ultrasound data to generate the ultrasound image based on the target.

16. The system as claimed in claim 15, wherein the processing unit is configured to carry out a method as claimed in any one of claims 3 to 14.

17. A processing unit operable with an optical coherence tomography (OCT) apparatus to carry out a method as claimed in any one of claims 1 to 14.