

APPARATUS AND METHOD FOR MEASURING AN EMBEDDED OBJECT

Cross Reference to Related Applications

- 5 The present disclosure claims the benefit of Singapore Patent Applications 10202203052W filed on 24 March 2022 and 10202260430S filed on 13 December 2022, each of which is incorporated in its entirety by reference herein.

Technical Field

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The present disclosure generally relates to an apparatus and method for measuring an embedded object. More particularly, the present disclosure describes various embodiments of an apparatus and a method for measuring an object embedded in a structure, such as a rebar embedded in a concrete structure.

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Background

Reinforced concrete is an economical and multipurpose construction material. Corrosion damage in reinforcing steel bars (or rebars) has been a major cause of cracking and spalling of reinforced concrete. For example, reduction in the cross-sectional size of rebars induced by corrosion impacts the durability and sustainability of reinforced concrete structures. Accurate measurement of the rebar size is necessary to assess the corrosion status of the rebar as well as for health examination and safety evaluation of the reinforced concrete structures, so that timely repairs can be conducted.

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Non-destructive measurement methods are used to examine the embedded rebar without destroying the reinforced concrete. Ground-penetrating radar (GPR) is a common non-destructive method that is commercially available to inspect concrete structures and to locate and characterize rebars in concrete structures. However, there are significant challenges to accurately measure the size of the rebar using existing GPR methods, especially for rebars with small diameters.

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Therefore, in order to address or alleviate at least one of the aforementioned problems and/or disadvantages, there is a need to provide an improved apparatus and method for measuring a rebar embedded in concrete.

5 Summary

According to a first aspect of the present disclosure, there is an apparatus for measuring an object embedded in a structure. The apparatus comprises: a plurality of antennas for arranging linearly on the structure; a measurement instrument; and a
10 control system. The measurement instrument is configured for: transmitting, from each antenna sequentially by the linear arrangement of the antennas, radio signals into the structure; and measuring, from all the antennas, the radio signals transmitted from each respective antenna and reflected from the embedded object. The control system is configured for: controlling the measurement instrument to transmit and receive the
15 radio signals for said measurement; reconstructing an image of the embedded object based on the measured radio signals from all the antennas; and measuring a size of the embedded object from the reconstructed image.

According to a second aspect of the present disclosure, there is a method for
20 measuring an object embedded in a structure. The method comprises: arranging a plurality of antennas linearly on the structure; configuring the antennas to transmit and receive radio signals for measurement; transmitting, from each antenna sequentially by the linear arrangement of the antennas, the radio signals into the structure; measuring, from all the antennas, the radio signals transmitted from each respective
25 antenna and reflected from the embedded object; reconstructing an image of the embedded object based on the measured radio signals from all the antennas; and measuring a size of the embedded object from the reconstructed image.

An apparatus and method for measuring an embedded object according to the present
30 disclosure are thus disclosed herein. Various features and advantages of the present disclosure will become more apparent from the following detailed description of the embodiments of the present disclosure, by way of non-limiting examples only, along with the accompanying drawings.

Brief Description of the Drawings

Figure 1 is an illustration of an apparatus for measuring an embedded object.

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Figure 2 is a flowchart illustration of a method for measuring an embedded object.

Figures 3A to 3C are illustrations of measuring an embedded rebar in a concrete structure.

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Figures 4A to 4M are illustrations of numerical simulations for measuring different rebars.

Figures 5A to 5E are illustrations of further numerical simulations for measuring rebars with different misalignments.

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Figures 6A to 6D are illustrations of further numerical simulations for measuring rebars with different spacings.

Figures 7A to 7I are illustrations of real experiments for measuring embedded rebars in concrete structures.

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Detailed Description

For purposes of brevity and clarity, descriptions of embodiments of the present disclosure are directed to an apparatus and method for measuring an embedded object, in accordance with the drawings. While parts of the present disclosure will be described in conjunction with the embodiments provided herein, it will be understood that they are not intended to limit the present disclosure to these embodiments. On the contrary, the present disclosure is intended to cover alternatives, modifications and equivalents to the embodiments described herein, which are included within the scope of the present disclosure as defined by the appended claims. Furthermore, in the following detailed description, specific details are set forth in order to provide a

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thorough understanding of the present disclosure. However, it will be recognized by an individual having ordinary skill in the art, i.e. a skilled person, that the present disclosure may be practiced without specific details, and/or with multiple details arising from combinations of features of particular embodiments. In a number of instances, well-known systems, methods, procedures, and components have not been described in detail so as to not unnecessarily obscure features of the embodiments of the present disclosure.

In embodiments of the present disclosure, depiction of a given element or consideration or use of a particular element number in a particular figure or a reference thereto in corresponding descriptive material can encompass the same, an equivalent, or an analogous element or element number identified in another figure or descriptive material associated therewith.

References to “an embodiment / example”, “another embodiment / example”, “some embodiments / examples”, “some other embodiments / examples”, and so on, indicate that the embodiment(s) / example(s) so described may include a particular feature, structure, characteristic, property, element, or limitation, but that not every embodiment / example necessarily includes that particular feature, structure, characteristic, property, element or limitation. Furthermore, repeated use of the phrase “in an embodiment / example” or “in another embodiment / example” does not necessarily refer to the same embodiment / example.

The terms “comprising”, “including”, “having”, and the like do not exclude the presence of other features / elements / steps than those listed in an embodiment. Recitation of certain features / elements / steps in mutually different embodiments does not indicate that a combination of these features / elements / steps cannot be used in an embodiment.

As used herein, the terms “a” and “an” are defined as one or more than one. The use of “/” in a figure or associated text is understood to mean “and/or” unless otherwise indicated. The term “set” is defined as a non-empty finite organization of elements that mathematically exhibits a cardinality of at least one (e.g. a set as defined herein can

correspond to a unit, singlet, or single-element set, or a multiple-element set), in accordance with known mathematical definitions. The recitation of a particular numerical value or value range herein is understood to include or be a recitation of an approximate numerical value or value range. The terms “first”, “second”, etc. are used
5 merely as labels or identifiers and are not intended to impose numerical requirements on their associated terms.

Representative or exemplary embodiments of the present disclosure describe an apparatus 100 for measuring an object 200 embedded in a structure 210, with
10 reference to Figure 1. The apparatus 100 includes a plurality of antennas 110 for arranging linearly on the structure 210. More specifically, the antennas 110 are arranged in a linear array or arrangement 115 on a surface 220 of the structure 210. For example, the antennas 110 may be manufactured on a thin board which is then assembled in a foam box 112. The foam box 112 includes absorbers surrounding the
15 antennas 110 to reduce coupling between the antennas 110 and ambient noise. The foam box 112 with the antenna array 115 is then placed on the surface 220.

The apparatus 100 further includes a measurement instrument 120 and a control system 130. When the apparatus 100 is in use, the measurement instrument 120 is
20 electrically connected to the antennas 110 and the control system 130 is communicatively connected to the measurement instrument 120. More particularly, the control system 130 is configured for controlling the measurement instrument 120 to configure the antennas 110 to transmit and receive radio signals or waves for measurement. Preferably, the radio signals are radio pulse signals and have a
25 frequency range that preserves high resolution and sensitivity to objects 200 such as reinforcing bars or rebars. For example, the frequency range is about 1.3 GHz to 9 GHz.

The measurement instrument 120 is configured for transmitting, from each antenna
30 110 sequentially by the linear arrangement 115 of the antennas 110, radio signals into the structure 210. The measurement instrument 120 is further configured for measuring, from all the antennas 110, the radio signals transmitted from each respective antenna 110 and reflected from the embedded object 200. In some

embodiments, the measurement instrument 120 is a vector network analyzer which is a test instrument for measuring electrical networks and is configured to generate radio signals for transmission by the antennas 110.

5 As an example, there is a linear array 115 of three antennas 110 located on the structure 210. Firstly, the first antenna 110 transmits the radio signals but the second and third antennas 110 do not. The radio signals transmitted from the first antenna 110 are reflected from the embedded object 200 and detected by all three antennas 110. Secondly, the second antenna 110 transmits the radio signals but the first and
10 third antennas 110 do not. The radio signals transmitted from the second antenna 110 are reflected from the embedded object 200 and detected by all three antennas 110. Thirdly, the third antenna 110 transmits the radio signals but the first and second antennas 110 do not. The radio signals transmitted from the third antenna 110 are reflected from the embedded object 200 and detected by all three antennas 110.

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The control system 130 is configured for reconstructing an image 250 of the embedded object 200 based on the measured radio signals from all the antennas 110. The control system 130 is further configured for measuring a size of the embedded object 200 from the reconstructed image 250. For example, the size of the embedded object 200
20 is measured based on intensity of the reconstructed image 250.

In many embodiments, the control system 130 is a computer device and includes one or more processors configured for executing instructions, codes, computer programs, and/or scripts. The processor includes suitable logic, circuitry, and/or interfaces to
25 execute such operations or steps. Some non-limiting examples of the processor include an application-specific integrated circuit (ASIC) processor, a reduced instruction set computing (RISC) processor, a complex instruction set computing (CISC) processor, a field-programmable gate array (FPGA), and the like. While instructions may be executed by a processor, the instructions may be executed
30 simultaneously, serially, or otherwise executed by one or multiple processors (e.g. in a multi-core configuration).

Representative or exemplary embodiments of the present disclosure also describe a method 300 for measuring an object 200 embedded in a structure 210. The method 300 may be performed by the apparatus 100 or any other suitable apparatus. As shown in Figure 2, the method 300 includes a step 310 of arranging a plurality of
5 antennas 110 linearly on the structure 210. The method 300 includes a step 320 of configuring the antennas 110 to transmit and receive radio signals for measurement. The method 300 includes a step 330 of transmitting, from each antenna 110 sequentially by the linear arrangement 115 of the antennas 110, radio signals into the structure 210. The method 300 includes a step 340 of measuring, from all the antennas
10 110, the radio signals transmitted from each respective antenna 110 and reflected from the embedded object 200. The method 300 includes a step 350 of reconstructing an image 250 of the embedded object 200 based on measured radio signals from all the antennas 110. The method 300 includes a step 360 of measuring a size of the embedded object 200 from the reconstructed image 250.

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In many embodiments such as shown in Figure 1, the object 200 is a cylindrical rebar 200 and the structure 210 is a concrete structure 210, thus resulting in a reinforced concrete structure. It will be appreciated that the rebar 200 may be of other shapes, and the apparatus 100 and method 300 may be used to measure various objects 200
20 embedded in various structures 210.

As the antennas 110 are configured to sequentially transmit the radio signals according to the linear arrangement 115 of the antennas 110, and the reflected radio signals are measured from all the antennas 110, the linear arrangement 115 of the
25 antennas 110 may be referred to as a multiple-input-multiple-output (MIMO) array. Further, the antennas 110 transmit radio signals to measure the rebar 200 embedded below the surface 220 of the concrete structure 210. More specifically, the measurement instrument 120 uses the ground-penetrating radar (GPR) antenna array 115 to transmit the radio signals, such as in pulses, to measure the embedded rebar
30 200. GPR is based on electromagnetic wave propagation and reflection to measure the embedded rebar 200 due to the difference in dielectric permittivity and conductivity of different materials, i.e. the steel rebar 200 and concrete structure 210. The array 115 of antennas 110 may thus be referred to as a MIMO GPR array.

In some embodiments as shown in Figure 3A, there is a linear array 115 of N antennas 110 arranged on the surface 220 of the concrete structure 210 wherein the rebar 200 is embedded. The antennas 110 may be spaced apart at intervals of 10 mm in the linear array 115. The antennas 110 may be ultra-wideband (UWB) antennas 110 such as Vivaldi antennas. The antennas 110 may be polarized along a direction perpendicular to the linear array 115 and perpendicular to the propagation direction of the radio signals from the antennas 110, such as along the y direction. The antennas 110 may be dipole antennas such as Hertzian dipole antennas. Each antenna 110 serves as both transmitter and receiver. The antennas 110 transmit the radio signals sequentially and the reflected radio signals are measured from all the antennas 110 to obtain an N x N matrix of MIMO GPR measurement data.

The control system 130 then reconstructs the image 250 of the embedded rebar 200 based on the N x N matrix data. In many embodiments, the size of the rebar 200 is measured based on intensity of the reconstructed image 250. Various imaging techniques can be used to reconstruct the image 250, as will be readily known to the skilled person. For example, the image 250 may be reconstructed using a diffraction stack migration algorithm.

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The imaging technique sums the measured radio signals at different pixel positions of the reconstructed image 250 based on the travel time of the radio signals to thereby obtain the intensities at these pixel positions. The intensity I at each pixel position (x, z) of the reconstructed image 250 represents the amplitude of the summed signal at the respective pixel position. The intensity I at each pixel position (x, z) can be calculated using the following equations.

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$$I(x, z) = \left| \sum_{i=1}^N \sum_{j=1}^N S_{ij} \left(\frac{d_i + d_j}{v} \right) \right|$$

$$d_i = \sqrt{(x_i - x)^2 + z^2}$$

$$d_j = \sqrt{(x_j - x)^2 + z^2}$$

$$v = \frac{c}{\sqrt{\epsilon_r}}$$

N denotes the number of antennas 110. S_{ij} denotes the complex signal in the time domain that is transmitted by antenna i and received by antenna j. d_i denotes the distance between the transmitter antenna i and the pixel position (x, z). d_j denotes the distance between the receiver antenna j and the pixel position (x, z). x_i denotes the x coordinate of the transmitter antenna i. x_j denotes the x coordinate of the receiver antenna j. z denotes the vertical coordinate relative to the surface 210 of the concrete 200 where $z = 0$. v denotes the propagation velocity of electromagnetic waves in the concrete structure 210. c denotes the speed of light in a vacuum. ϵ_r denotes the relative permittivity of the concrete structure 210.

In some embodiments, the control system 130 pre-processes the acquired $N \times N$ matrix data before reconstructing the image 250. For example, time delay correction is carried out to compensate for time delays through cables 140 connecting the antennas 110 and measurement instrument 120, as well as from the antenna feeding point to the antenna phase centre. For example, background subtraction is performed to eliminate the direct coupling between the antennas 110 and the reflection of the concrete surface 220.

Figure 3B shows an exemplary reconstructed image 250 of the embedded rebar 200. However, it may be challenging to directly measure the size of the rebar 200 from the reconstructed image due to the resolution limit from the radio signals. The pixel positions (x, z) in the reconstructed image 250 have varying intensities. The peak intensity point P is the pixel position (x_P , z_P) in the reconstructed image 250 wherein the calculated intensity I is the maximum. The peak intensity line 260 passes through the peak intensity point P, and the circle corresponds to the actual size and position of the rebar 200.

The width of an antenna beam can generally be determined by the half-power points, which are -3 dB from the peak intensity point P. The half-power points may be referred to as the -3 dB points, which are 3 dB down from the maximum of 0 dB at the peak

intensity point P. Any defect smaller than the width can be assumed to be a radiator, which tends to emit everywhere inside the beam. The size of the defect can be measured as the distance between -3 dB points of the reconstruction image 250. The 3 dB drop technique is used to calculate the length b of the peak intensity line 260 in the reconstructed image 250, wherein the peak intensity line 260 spans between the two -3 dB points relative to the peak intensity point P.

The size of the embedded rebar 200 may be measured based on the peak intensity line 260 and a cover depth h of the embedded rebar 200 in the concrete structure 210. The cover depth h is the distance from the concrete surface 220 (z = 0) to the top of the embedded rebar 200. The cover depth h can be determined using known techniques such as curve fitting techniques (e.g. parabolic curve).

More specifically, as shown in the geometry diagram in Figure 3C, the control system 130 calculates a segment diameter D from a circular segment 270 bounded by the peak intensity line 260 and the cover depth h, wherein the segment diameter D is the measured size of the embedded rebar 200. The segment diameter D can be calculated by the following equations using the length b of the peak intensity line 260, cover depth h, and the height a of the circular segment 270, which is the vertical distance between the peak intensity line 260 (z_P) and the top of the circular segment 270.

$$R^2 = (R - a)^2 + \left(\frac{b}{2}\right)^2$$

$$D = a + \frac{b^2}{4a}$$

$$a = z_P - h$$

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It should be noted that the circular segment 270 is part of a geometrical circle, which represents the actual rebar 200, and the peak intensity line 260 may be referred to as a chord of the geometrical circle. Further, the peak intensity line 260 does not span the horizontal diameter of the geometrical circle as only the upper part of the rebar 200 can be imaged. This is because the antennas 110 are fixed on the concrete surface 220 and have a limited viewing range and the steel rebar 200 acts as a total

reflector. The peak intensity point P in the reconstructed image 250 is thus located in the top part of the geometrical circle.

- A numerical simulation was conducted to evaluate the MIMO GPR array of antennas 110. An electromagnetic simulation software, such as GprMax2D, was used to obtain the matrix data from the MIMO GPR array. As shown in the simulation scenario in Figure 4A, a rebar 200 with a diameter of 8 mm was embedded at a cover depth of 30 mm in concrete structure 210. The concrete structure 210 was in the form of a 500 mm x 100 mm slab. The spatial discretization was 0.1 mm in the x and z directions, and the time step was 0.236 ps. A perfectly matched layer (PML) 230, which is an artificial absorbing layer for wave equations and used in numerical methods, surrounded the concrete structure 210 to avoid reflections from the boundaries. An 80 mm air layer or free space resided between the top side of the PML 230 and the concrete surface 220, a 20 mm air layer or free space resided between the lateral sides of the PML 230 and concrete structure 210, and a 20 mm air layer or free space resided between the bottom sides of the PML 230 and concrete structure 210. The relative permittivity and conductivity of the concrete structure 210 were set as 6 S/m and 0.001 S/m, respectively.
- There were 15 y-polarized Hertzian dipole antennas 110 arranged in a linear array 115 along the x direction on the surface 220 of the concrete structure 210. The antennas 110 were spaced apart at intervals of 10 mm along the x direction. The centre of the linear array 115 was aligned vertically with the centre of the rebar 200. The radio signals transmitted from the antennas 110 were Ricker pulse signals with a central frequency of about 6 GHz. The antennas 110 transmitted the radio signals sequentially according to the linear array 115 and the reflected radio signals were measured from all the antennas 110 to obtain a 15 x 15 matrix of MIMO GPR measurement data.
- Figure 4B shows a process 400 derived from the method 300 for measuring the embedded rebar 200 in the numerical simulation. In a step 410, the 15 x 15 matrix data was obtained as described above. In a step 420, the matrix data was pre-processed to remove the background. In a step 430, the cover depth h of the rebar

200 was determined. In a step 440, the propagation velocity of electromagnetic waves in the concrete structure 210 was determined. In a step 450, the image 250 of the rebar 200 was reconstructed. The reconstructed image 250 is shown in Figure 4C wherein the circle corresponds to the actual size and position of the rebar 200. It can
 5 be seen from the reconstructed image 250 that the rebar 200 can be located accurately.

In a step 460, the peak intensity point P was identified. In a step 470, the chord length of the peak intensity line 260 was measured using the 3 dB drop technique described above. As shown in Figure 4C, the peak intensity point is located at ($x_P = 70$ mm, $z_P =$
 10 31.9 mm) and the chord length is 6.6 mm. In a step 480, given that the cover depth is 30 mm, the height of the circular segment 270 was calculated as 1.9 mm and the segment diameter was calculated as 7.63 mm using the geometrical calculations explained above. The size of the rebar 200 was measured as the calculated segment diameter which was very close to the actual diameter (8 mm).

15 Additional numerical simulations were carried out on various rebars 200 with different diameters ranging from 8 mm to 28 mm and embedded at different cover depths ranging from 30 mm to 50 mm, which are commonly used in reinforced concrete structures. Figures 4D to 4L show the reconstructed images 250 of the rebars 200 with
 20 diameters 12 mm (D12), 20 mm (D20), and 28 mm (D28) and at cover depths 30 mm (H30), 40 mm (H40), and 50 mm (H50). The measured diameters of all the rebars 200 are tabulated in Figure 4M. It can be seen that the measured diameters of the rebars 200 were very close to the actual diameters and the errors were all less than 10%. The results demonstrated that the process 400 is highly accurate in measuring rebars
 25 200 with different diameters and cover depths.

In the above numerical simulations, the centre of the linear array 115 was aligned vertically with the centre of the rebar 200 for optimal measurement of the rebar 200. The horizontal distance l between the centre of the linear array 115 and the centre of
 30 the rebar 200 was zero. The alignment can be achieved experimentally by doing a B-scan imaging and identifying the centre of the hyperbolic signature, but in practice, the alignment may not always be perfect.

Numerical simulations were conducted to evaluate the misalignment of the linear array 115 relative to the rebar 200. The linear array 115 was misaligned at different diameters ranging from 5 mm to 35 mm. The misalignment can be defined by the horizontal distance l and the angle between the line connecting the centre of the linear array 115 to the centre of the rebar 200 and the vertical line perpendicular to the concrete surface 210. Figures 5A to 5D show the reconstructed images 250 of the rebars 200 (8 mm actual diameter at 30 mm cover depth) with the misalignment at horizontal distances l of 5 mm, 10 mm, 15 mm, and 20 mm. The measured diameters D ranged from 7.12 mm to 7.63 mm.

Various rebars 200 with the same 8 mm actual diameter but with various cover depths and misalignments were measured in similar numerical simulations to further evaluate the impact of the misalignment of the linear array 115. The measured diameters of the rebars 200 are tabulated in Figure 5E. It can be seen that the process 400 can tolerate some misalignment of the linear array 115. Particularly, the measured diameters were reasonably accurate for misalignment angles less than 20° as the errors were less than 6%.

The above numerical simulations were conducted for a single rebar 200 embedded in the concrete structure 210. However, as real reinforced concrete structures generally have multiple rebars 200, further numerical simulations were conducted to evaluate how the spacing between the rebars 200 affect the rebar measurements. Models of concrete structures 210 with three embedded rebars 200 (8 mm actual diameter at 30 mm cover depth) were created. For each model, the rebars 200 were equally spaced apart and the spacings varied from 20 mm to 200 mm. The centre of the linear array 115 was aligned to the centre of the middle rebar 200. Figures 6A to 6C show the reconstructed images 250 of the rebars 200 with the spacing at 20 mm, 60 mm, and 100 mm.

Various models with three embedded rebars 200 of the same 8 mm actual diameter and 30 mm cover depth but with different spacings were measured in similar numerical simulations. The measured diameters of the middle rebars 200 are tabulated in Figure 6D. It can be seen that the when the spacing between the rebars 200 was small, the

error was relatively large due to the interference of reflected radio signals from adjacent rebars 200. As the spacing increased, the interference was reduced, leading to improved accuracy in the diameter measurement of the middle rebars 200. It should be noted that the spacing in reinforced concrete structures is usually at least 90 mm, and at such spacings, the measured diameters were reasonably accurate with errors of less than 7%.

Physical experiments were conducted to further evaluate the performance of the apparatus 100 and method 300 in real cases. Four samples (S#1, S#2, S#3, and S#4) of concrete structures 210 were prepared as shown in Figures 7A and 7B. The samples were cast in wood moulds and demoulded after 24 hours. The experiments were conducted after curing the samples for 28 days.

As shown in Figure 7A, the sample S#1 was prepared for evaluating the measurement accuracy for embedded rebars 200 with different diameters. The sample S#1 had a size of 500 mm x 130 mm x 400 mm and had three rebars 200 of different diameters embedded at about the same cover depth of 30 mm with a casting tolerance of 2 mm. More specifically, the first rebar 200 had a 10 mm actual diameter and a cover depth of 32 mm, the second rebar 200 had a 13 mm actual diameter and a cover depth of 30 mm, and the third rebar 200 had a 16 mm actual diameter and a cover depth of 32 mm.

As shown in Figure 7B, the samples S#2 to S#4 were prepared for evaluating the measurement accuracy for embedded rebars 200 at different cover depths. Each of the samples S#2 to S#4 had a size of 200 mm x 130 mm x 400 mm with an embedded rebar 200 of 13 mm actual diameter. The cover depths of the rebars 200 in the samples S#2 to S#4 were 20 mm, 30 mm, and 40 mm, respectively.

In the apparatus 100 that was used to conduct the experiments, the measurement instrument 120 was a vector network analyzer and the linear array 115 consisted of 15 y-polarized Vivaldi antennas 110 spaced apart at intervals of 10 mm. The antennas 110 were assembled in a foam box 112 which included absorbers surrounding the antennas 110 to reduce coupling between the antennas 110 and ambient noise. The

box 112 containing the linear array 115 of antennas 110 was placed on the top surface 220 of the concrete structure 210, such as shown in Figure 1B. The centre of the linear array 115 was aligned vertically, using B-scan imaging, with the centre of each rebar 200 before measuring the respective rebar 200.

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For each rebar measurement, at least 800 measurement points across an ultra-wide frequency band from 2.9 GHz to 9 GHz were recorded to preserve high resolution and sensitivity. A 15 x 15 matrix data for each rebar measurement was then obtained from the measurement points. The 15 x 15 matrix data was then transformed from the frequency domain to the time domain by the inverse Fourier transform. To remove the direct coupling between the antennas 110 and the reflection of the concrete surface 220, background signals were measured by placing the linear array 115 of antennas 110 on the regions of the concrete surfaces 220 that were far from the rebars 200. The measured background signals were then subtracted from the 15 x 15 matrix data.

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Reconstructed images 250 of each rebar 200 were generated from the respective 15 x 15 matrix data by diffraction stacking. The propagation velocity of electromagnetic waves in the concrete structure 210 was estimated based on the backwall reflection. The reconstructed images of the rebars 200 in the samples S#1 to S#4 are shown in Figures 7C to 7H. The 3 dB drop technique was used to measure the chord length of the respective rebar 200 in each reconstructed image 250. The diameters of the rebars 200 were calculated from the chord lengths and cover depths. The measured diameters of the rebars 200 are tabulated in Figure 7I. It can be seen that the errors between the measured and actual diameters of the rebars 200 were less than 6% for all the samples S#1 to S#4.

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Extensive numerical simulations and real experiments have been conducted to examine the performance of the apparatus 100 and method 300 in different scenarios. The results demonstrated that the apparatus 100 and method 300 can be used in real cases to accurately measure embedded rebars 200 with various diameters and cover depths. The diameters of the rebars 200 can be estimated to a measurement accuracy of less than 10%, even when there is misalignment of the antennas 110. The measured diameters of the rebars 200 can be used to assess the deterioration of the

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rebar size, such as the mass loss caused by corrosion. Particularly, the measured rebar diameters can quickly assess the rebar damage so that timely repairs can be conducted to mitigate safety hazards. The apparatus 100 and method 300 thus facilitate non-destructive testing and health inspection of constructions such as reinforced concrete structures and buildings.

Although various embodiments herein describe measurement of rebars 200, particularly cylindrical ones, it will be appreciated that the apparatus 100 and method 300 may be used to measure rebars 200 of other shapes. It will also be appreciated that the apparatus 100 and method 300 may be suitable for measuring other embedded or subsurface objects 200 in various applications.

In the foregoing detailed description, embodiments of the present disclosure in relation to an apparatus and method for measuring an embedded object are described with reference to the provided figures. The description of the various embodiments herein is not intended to call out or be limited only to specific or particular representations of the present disclosure, but merely to illustrate non-limiting examples of the present disclosure. The present disclosure serves to address at least one of the mentioned problems and issues associated with the prior art. Although only some embodiments of the present disclosure are disclosed herein, it will be apparent to a person having ordinary skill in the art in view of this disclosure that a variety of changes and/or modifications can be made to the disclosed embodiments without departing from the scope of the present disclosure. Therefore, the scope of the disclosure as well as the scope of the following claims is not limited to embodiments described herein.

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Claims

1. An apparatus for measuring an object embedded in a structure, the apparatus comprising:
- 5 a plurality of antennas for arranging linearly on the structure;
a measurement instrument configured for:
transmitting, from each antenna sequentially by the linear
arrangement of the antennas, radio signals into the structure; and
measuring, from all the antennas, the radio signals transmitted
10 from each respective antenna and reflected from the embedded object;
and
a control system configured for:
controlling the measurement instrument to configure the
antennas to transmit and receive the radio signals for said measurement;
15 reconstructing an image of the embedded object based on the
measured radio signals from all the antennas; and
measuring a size of the embedded object from the reconstructed
image.
- 20 2. The apparatus according to claim 1, wherein the size of the embedded object
is measured based on intensity of the reconstructed image.
3. The apparatus according to claim 2, wherein the control system is configured
for identifying a peak intensity point in the reconstructed image.
- 25 4. The apparatus according to claim 3, wherein the control system is configured
for measuring a peak intensity line in the reconstructed image, the peak intensity line
passing through the peak intensity point.
- 30 5. The apparatus according to claim 4, wherein the peak intensity line spans
between two -3 dB points in the reconstructed image relative to the peak intensity point.

6. The apparatus according to claim 4 or 5, wherein the size of the embedded object is measured based on the peak intensity line and a cover depth of the embedded object in the structure.
- 5 7. The apparatus according to claim 6, wherein the control system is configured for calculating a segment diameter from a circular segment bounded by the peak intensity line and the cover depth, the segment diameter being the measured size of the embedded object.
- 10 8. The apparatus according to any one of claims 1 to 7, wherein the radio signals are radio pulse signals having a frequency range of about 1.3 GHz to 9 GHz.
9. The apparatus according to any one of claims 1 to 8, wherein the embedded object is a reinforcing bar and the structure is a concrete structure.
- 15 10. A method for measuring an object embedded in a structure, the method comprising:
- arranging a plurality of antennas linearly on the structure;
 - configuring the antennas to transmit and receive radio signals for
 - 20 measurement;
 - transmitting, from each antenna sequentially by the linear arrangement of the antennas, the radio signals into the structure;
 - measuring, from all the antennas, the radio signals transmitted from each respective antenna and reflected from the embedded object;
 - 25 reconstructing an image of the embedded object based on the measured radio signals from all the antennas; and
 - measuring a size of the embedded object from the reconstructed image.
11. The method according to claim 10, comprising measuring the size of the
- 30 embedded object based on intensity of the reconstructed image.
12. The method according to claim 11, comprising identifying a peak intensity point in the reconstructed image.

13. The method according to claim 12, comprising measuring a peak intensity line in the reconstructed image, wherein the peak intensity line passes through the peak intensity point.

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14. The method according to claim 13, wherein the peak intensity line spans between two -3 dB points in the reconstructed image relative to the peak intensity point.

15. The method according to claim 13 or 14, comprising measuring the size of the
10 embedded object based on the peak intensity line and a cover depth of the embedded object in the structure.

16. The method according to claim 15, comprising calculating a segment diameter from a circular segment bounded by the peak intensity line and the cover depth,
15 wherein the segment diameter is the measured size of the embedded object.

17. The method according to any one of claims 10 to 16, wherein the radio signals are radio pulse signals having a frequency range of about 1.3 Ghz to 9 GHz.

20 18. The method according to any one of claims 10 to 17, wherein the embedded object is a reinforcing bar and the structure is a concrete structure.