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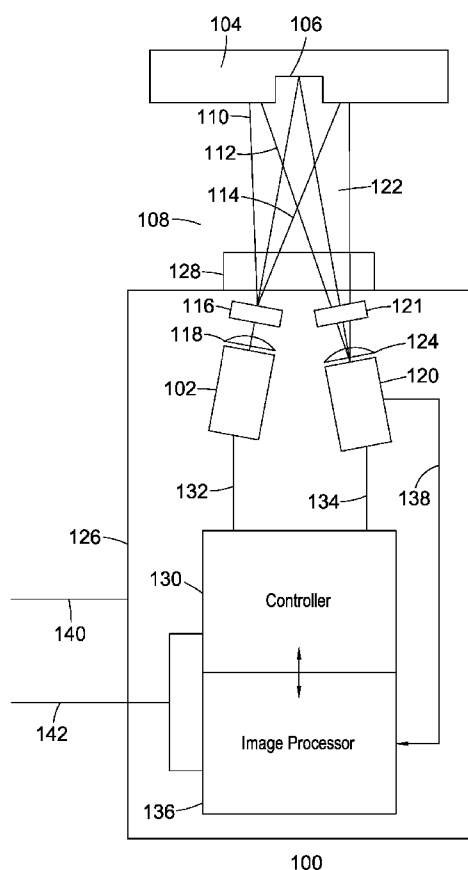


Fig. 1

(57) Abstract: A tread depth measurement module for measuring tread depth of a tyre; the module comprising a housing bearing at least one self-cleaning optical element adapted to cooperate with a tyre surface to clean an upper surface of the optical element, a structured light source for illuminating a tread-bearing surface of the tyre with structured light and, preferably, an analyser for analysing a captured image of the illuminated tread-bearing surface of the tyre to determine the tread depth of the tyre from reflected structured light within the captured image.



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Tyre Assessment

[0001] Embodiments of the invention relate to tyre assessment, and, more particularly, to tyre measurement and, still more particularly, to tread depth measurement.

5 [0002] Various tyre measurement systems are available from, for example, ProContour H3-D, TreadReader, TreadSpecNS and PneuScan. Some of these systems are relatively expensive and can, especially in the case of the ProContour, have significant installation costs, are bulky and complex to manufacture and install.

10 [0003] Embodiments of the present invention at least mitigate one or more problems of the prior art.

[0004] Embodiments provide a tread depth measurement module for measuring tyre condition and more particularly tread depth of a tyre; the module comprising a housing bearing at least one self-cleaning optical element adapted to cooperate with a tyre surface to clean an upper surface of the optical element, a light source for illuminating a tread-bearing surface of the tyre, particularly as structured light source for illuminating the tread-bearing surface of the tyre with structured light and, preferably, an analyser for analysing an image of the illuminated tread-bearing surface of the tyre to determine the tread depth of the tyre from the detected reflected light. Preferably, the light source emits structured light.

20 [0005] Embodiments of the invention are further described hereinafter, by way of example only, with reference to the accompanying drawings, in which:

figure 1 shows an objective feature measurement module;
figure 1A shows an embodiment of a measurement assembly;
figure 2 depicts an operation of a measurement module;
figure 2A shows an operation of a further measurement module;
25 figure 2B depicts an embodiment of a self-cleaning stud;
figure 3 illustrates an exploded view of a measurement module;
figure 4 shows a further view of a measurement module;
figure 5 depicts a measurement module assembly;
figure 5A shows a first arrangement of modules;
30 figure 5B illustrates a second arrangement of modules;
figure 5C depicts a third arrangement of modules;
Figure 5D shows a rake arrangement of modules;
figure 6 illustrates a number of structured light patterns;
figure 7 shows a flowchart of image processing;
35 figures 8 and 9 depict the operations of embodiments;
figures 10 and 11 depict processing according to embodiments;

figure 12 shows reflected structured light;

figure 13 depicts a flowchart of processing according to embodiments;

figure 14 shows a tyre illuminated with structured light.

5 [0006] Referring to figure 1 there is shown a tyre measurement module 100 comprising a light source 102 for illuminating a surface of an objective having a characteristic feature to be determined or measured. The light source can be one of a laser or laser diode. Preferably, the objective is a tyre 104 and the characteristic feature is the tread 106, more particularly, the tread depth. Embodiment use a Thorlabs P650P007 laser diode having an output power of 7mW and
10 a wavelength of 650 nm. However, embodiments are not limited thereto. Embodiments can equally well use laser diodes having other output powers and/or wavelengths or laser diodes provided by other manufacturers.

[0007] Light from the light source is structured. Structured light has a defined illumination pattern 108. Preferably, the defined illumination pattern is non-uniform. The defined
15 illumination pattern is represented using the three patterns 110 to 114 that are incident upon the tyre 104. The foregoing structure carried by the light is spatial. Additionally, or alternatively, the structure can be temporal. Therefore, embodiments provide a light source that has a predetermined temporal pattern. Preferred embodiments use a pattern in which the intensity or power of the light source output is varied. Preferred embodiments use a pulse pattern such as,
20 for example, a 2 millisecond pulse. Using a pulse pattern in essence freezes the image to be captured, which has the advantage of reducing processing overhead in extracting and identifying the reflected structured light. It will be appreciated that a balance can be reached between one or more factors regarding the pulse characteristics, that is, at least one of pulse width, amplitude, wavelength, taken jointly and severally in any and all combinations, based on
25 at least one of the speed of the vehicle, the ambient light, the optical aspects of the system and the camera taken jointly and severally in any and all combinations. Preferred embodiments operate an image sensor 120 and the light source 102 in a manner comparable to a camera and an associated flash. The sensor 120 controls the light source 102 such that the illumination and detection are appropriately timed. Again, such a discontinuous mode of operation as
30 opposed to, for example, continuous illumination and continuous detection reduces the processing overhead needed during at least one of image capture and feature extraction and processing.

[0008] The defined illumination pattern 108 is formed using an optical element 116. The optical element is preferably a diffractive optical element arranged to produce the desired
35 illumination pattern 108.

[0009] The light from the light source 102 preferably is collimated via a collimator 118 such as,

for example, a collimating lens. Preferred embodiments use a collimating lens for small format laser diodes, 4.5mm, f-8001 XL series lenses available from for example Diverse Optics (www.diverseoptics.com/collimating/) part no. 8001-002. It can be appreciated that the collimator has at least one or more of the following characteristics taken jointly or severally in any and all combinations: wavelength range 400 to 1100 nm, numerical aperture of between (and including) 0.4 and 0.6, preferably .05, F-Number 1.0, Exit Pupil Diameter of between 4 mm and 5 mm and preferably 4.5 mm, ELF 4.49 mm, spot size < 1.0 microns, beam diameter 4.5/12.5 mm, Conjugate (nm) 150 to infinity, material acrylic (PMMA), coating MgF₂ anti-reflective single element dual asphere with flange and RoHS & REACH compliant.

[0010] A sensor 120 is used to detect reflected light 122 falling within the field of view of the sensor. The sensor may be a CMOS device. An imaging lens 124 is optionally provided. The reflected light has been illustrated as a patterned reflection associated with the incident structured light, that is, the reflected light is also structured light. Preferably, a filter 121 is used to pass light corresponding to the frequencies emitted by the source 102, which assists in at least one of identifying the reflected structured light and reducing ambient noise. Although preferred embodiments use a filter that passes certain wavelengths, other filters could also be used to filter the light prior to input to the sensor 120. For example, polarised light could be used as the basis of the structured light with a polarisation filter being appropriately aligned relative to the structured light. It can be appreciated that the sensor is substantially upwardly orientated, that is, the field of view of the sensor, and/or the direction of illumination by the light source, is not substantially parallel to the upper surface of the stud 128. Preferred embodiments provide an angle of illumination or direction of field of view that is optionally greater than 15°, optionally less than 45°, and is preferably substantially 30°. Preferred embodiments provide such upward illumination within a predetermined window relative to a normal of the tyre as described below with reference to figure 8.

[0011] Preferred embodiments use a low cost camera for the imaging. For example, cameras such as those found in mobile telephones could be used to implement embodiments of the invention. An example of such a low cost camera is, for example, a Samsung Galaxy Note 2 N7100 Front Camera module, available from <http://rounded.com/samsung-galaxy-note-2-n7100-front-camera-module-flexcable-front-camera-black-spare-part-p2314-torev071236.html>. It will be appreciated that such cameras are small, with a footprint of typically less than 2cm² square and preferably less than 1.5 cm², or, for example, even smaller, such as, for example, less than 30mm³, preferably less than 25mm³ such as available from OmniVision. Additionally, or alternatively, such cameras also have a low power consumption that is of the order of milliwatts. For example, an OVM 7692, available from OmniVision, consumes 120 mW, when active. Additionally, or alternatively, such cameras have a given interface speed and/or a relatively low

quality lens. Additionally, or alternatively, such cameras have a relatively low resolution such as, for example, found in a VGA camera, having pixels of 640 by 480. Preferred embodiments use a resolution or sensor pixel size that is sufficiently small to resolve an intensity profile of the structured light used in embodiments. Embodiments can be realised in which the images captured are preferably at least one of captured and processed as monochrome images even though colour images could be alternatively used.

[0012] The module 100 comprises a housing 126 having an aperture through which the light can pass. The light passes through a self-cleaning stud 128. Preferred embodiments use a glass self-cleaning stud. Preferably, the glass self-cleaning stud will have been annealed or toughened via, for example, chemical toughening or heat treatment.

[0013] Operation of the light source 102 is controlled by a controller 130 via a control connection 132. The light source 102 is switched on and off according to whether or not a tyre 104 is visible through the self-cleaning stud in such a way that the structured light can be reflected from it and detected by the sensor 120. Preferred embodiments use triggering to control the operation; which triggering is described herein with reference to figure 1A for example.

[0014] Operation of the sensor 120 is controlled by the controller 130 via a respective control connection 134. Data output by the sensor 120 is sent to an image processor 136 via a bus 138 for further processing. The further processing comprises detecting or determining a characteristic feature from an image representing the reflected structured light; in particular determining the tread depth from the reflected structured light 122.

[0015] The controller 130 and the image processor 136 can be realized using a digital signal processor (DSP) or another type of processor. A DSP is preferred since it is optimised for mathematical and signal processing operations. Alternatively, or additionally, the further processing can be undertaken by a remote system or remote processor, that is, one external to the module, such as, for example, a computer adapted to receive the data output by the sensor.

[0016] Also shown is a power coupling 140 for coupling power to the electronics of the module and a data coupling/triggering coupling 142 for communicating with at least one of the controller 130 and the image processor 136.

[0017] Referring to figure 2, there is shown a schematic view 200 of various components of the module 100. The light source 102, sensor 120 and processor implementing the controller 130 and the image processor 136 are shown schematically as mounted on a pcb 202. The self-cleaning stud 128 has a profiled upper surface 204. The profiled upper surface 204 is arranged to cooperate with an incident tyre (not shown) such that the cooperation results in relative sliding movement between the tyre and the profiled upper surface 204. The cooperation

thereby polishes the profiled upper surface 204, or at least cleans the profiled upper surface. Optionally, the stud 128 is adapted to bear at least one of optical power and focusing and/or could be adapted to include some of the functions of the collimator lens, thereby acting as a supplementary lens.

5 [0018] It can be appreciated that the structured light illuminating the tyre (not shown) takes the form of a number of light sheets. In the illustrated example, two light sheets 206 and 208 are shown. Also shown is reflected structured light 122. In the illustrated example, the reflected structured light 122 takes the form of a single reflected light sheet 210. The single reflected light sheet 210 is detected by the sensor 120 and processed by the image processor 136. The
10 detected reflected structured light is processed by the image processor 136 to detect or determine an objective characteristic feature such as, for example, tread depth. A preferred embodiment of the stud 128 is elongate and curved, that is, substantially cylindrical, with a radius of curvature of conducive to relative movement between a tyre and the stud 128 to induce at least cleaning thereof and preferably polishing of the stud surface. Embodiments can
15 be realised in which the radius of curvature is between 10 mm and 40 mm, preferably between 20 mm and 35 and still more preferably 28 mm. Although embodiments have been described with reference to a substantially cylindrical surface, variations can use some other form of profiled surface such as, for example, an aspherical surface, a toroidal surface, a trapezoidal surface or some locally curved or protruding surface conducive to being polished or cleaned
20 upon contact with a tyre.

[0019] Also illustrated in figure 2 is pair of, preferably inductive, couplings 212 and 214; first 212 and second 214 inductive couplings. The first inductive coupling 212 is used to provide power for the electronics, that is, the light source 102, the sensor 120, the controller 130 and image processor 136. The second inductive coupling 214 is used to support communication
25 between the processor 136 and an external data processing system (not shown). Although shown as separate inductive couplings 212 and 214, alternative implementations can use the same coupling to receive and supply power to the electronics and to support communications. Furthermore, although the couplings 212 and 214 are shown as being inductive couplings, alternative couplings can be used. The second coupling 214 can be used for either
30 unidirectional exchanges with the external data processing system (not shown) or bidirectional exchanges with the data processing system (not shown).

[0020] In preferred embodiments, the second coupling is also used as a trigger to control image capture. For example, the second coupling can be used to instigate image capture in response to actuation of a corresponding triggering device, such as, for example, a pressure
35 sensor or broken beam indicating the presence of a suitably positioned tyre. Additionally, embodiments can be realised in which the second coupling can be used to terminate image

capture in response to a corresponding trigger. For example, the trigger, in the form of a pressure sensor or a beam to be broken, could be disposed just after the self-cleaning optical element looking in the direction of travel of the tyre. This has the advantage that, firstly, the tyre will have been cleaned or polished the optical element and, secondly, will ensure that the illumination of the tyre with structured light is effected at the correct angle, as can be appreciated from figure 1A, which shows a view 1A00 of a ramp 1A02 comprising a module 100 for illuminating the tyre 104 with structured light 1A04 and for receiving reflected structured light 1A06. The ramp 1A02 comprises at least one of a pressure sensing module 1A08 with a pressure sensor 1A10 in communication with the module 100 or a beam 1A12 to be broken for providing a signal indicating that structured light illumination and image capture of reflected structured light should commence and/or terminate. The ramp 1A02 comprises a leading edge portion 1A14 and a trailing edge portion 1A16. Although the embodiment shown uses a pressure sensor 1A08 to detect the presence of the tyre, other embodiments can be realised that use other technology as a trigger, such as, for example, an ultra-sonic detector or an electromagnetic sensor; both of which would be able to detect the presence of the tyre and act as a trigger. For example, detecting an increase in pressure could operate as a trigger to start image capture and detecting a decrease in pressure could operate as a trigger stop image capture or as a signal to reset the module ready for subsequent measurement runs.

[0021] One skilled in the art will appreciate that image capture can encompass at least one of capturing one or more still images and capturing one or more images as part of a sequence of images.

[0022] Embodiments are arranged so that the triggering occurs at a predetermined distance between the tyre and the module, known as the working distance. Embodiments of the invention use a working distance of between 150 mm and 250 mm and, preferably, 200 mm. Embodiments preferably trigger at least one of the the illumination and image capture after the tyre has passed over the self-cleaning stud 128 so that a wiping or polishing action has occurred prior to at least one of triggered illumination and triggered image capture.

[0023] Referring to figure 2A, there is shown a schematic view 2A00 of various components of a further module 1A00. The light source 102, sensor 120 and processor implementing the controller 130 and the image processor 136 are shown schematically as mounted on a pcb 2A02. The self-cleaning stud 128 has a profiled upper surface 2A04. The profiled upper surface 2A04 is arranged to cooperate with an incident tyre (not shown) such that the cooperation results in relative sliding movement between the tyre and the profiled upper surface 2A04. The cooperation thereby at least cleans and preferably polishes the profiled upper surface 2A04, or at least cleans the profiled upper surface. Optionally, the stud 128 is adapted to bear at least one of optical power and focusing. Again, the stud could include some of the

functions of a collimator/lens and/or act as a supplementary lens.

[0024] It can be appreciated that the structured light illuminating the tyre (not shown) takes the form of a number of light sheets. In the illustrated example, a single light sheet 2A06 is shown. Also shown is reflected structured light 122. In the illustrated example, the reflected structured light 122 takes the form of a single reflected light line or sheet 2A08 or 2A10 from the perspective of the sensor 120. The single reflected light sheet 2A08 or 2A10 is detected by the sensor 120 and processed by the image processor 136. The detected reflected structured light is processed by the image processor 136 to detect or determine an objective characteristic feature such as, for example, tread depth. In the illustrated example, reflected structured light is shown as having been reflected by two different surfaces (not shown) of the tyre (not shown); a first reflection point is indicated as point A and a second reflection point is indicated as being point B. The different points of reflection are temporally and spatially separated and arise due to at least one of rotation of the tyre, which is preferably away from the direction of the incident structured light pattern, and changes in tread depth.

[0025] Also illustrated in figure 2A is pair of, preferably inductive, couplings 2A12 and 2A14; first 2A12 and second 2A14 inductive couplings. The first inductive coupling 2A12 is used to generate power for the electronics, that is, the light source 102, the sensor 120, the controller 130 and image processor 136. The second inductive coupling 2A14 is used to support communication between the processor 136 to an external data processing system (not shown). Although shown as separate inductive couplings 2A12 and 2A14, alternative implementations can use the same coupling to receive and supply power to the electronics and to support communications. Furthermore, although the couplings 2A12 and 2A14 are shown as being inductive couplings, alternative couplings can be used. The second coupling 2A14 can be used for either unidirectional exchanges with the external data processing system (not shown) or bidirectional exchanges with the data processing system (not shown).

[0026] Figure 2B illustrates front 2B02, plan 2B04 and end 2B06 views of an embodiment of a self-cleaning stud 128. It can be appreciated that the stud 128 has an elongate body with a curved upper surface. The radius of the curved upper surface has been described above. The stud has a substantially planar lower, or inner, surface 2B08 and a mounting lip 2B10. Although alternative arrangements can be realised in which the lower surface is profiled such as, for example, concaved.

[0027] Figure 3 shows an exploded view 300 of a measurement module 100 that better illustrates the construction of the above modules. The housing 126 comprises a body 302 and a lid 304. The lid 304 supports or receives the self-cleaning stud 128. Preferably, the self-cleaning stud 128 has a circumferential protrusion 306 that is captured by a complementary formation 308 of the lid 304. It can be appreciated that the complementary formation 308 is a

shoulder. The lid 304 is secured to the body 302 by a number of fasteners such as, for example, the four screws 310 to 316 shown. The screws 310 to 316 are received in corresponding recesses 318 to 324 and are inaccessible once the measurement module 100 is installed. The body 302 and lid 304 have respective corresponding formations 326 to 332. The corresponding formations 326 to 332 are used to couple the module 100 to an adjacent module (not shown). Alternatively, or additionally, the corresponding formations 326 to 332 are used as at least one of extraction points at which a corresponding tool can be used to grip and manipulate the modules and alignment points arranged to cooperate with corresponding formations on a housing 504 described below with reference to figure 5.

[0028] Preferably, at least one of the body 302 and lid 304 is resiliently deformable. Any resilient deformation is responsive to vehicle weight and is elastic. Preferably, at least one of the body 302 and lid 304 is made from polyurethane and is/are elastically deformable. Preferably, the degree of resilience in the deformation can influence contact pressure between the tyre 104 and the self-cleaning stud 128. Furthermore, embodiments can be realised in which selectable or predetermined portions of at least one of the body 302 and the lid 304 have a first level of elastic deformation, and other portions thereof have other degrees of elastic deformation. In some embodiments, the body bears resiliently deformable structures. Alternatively, or additionally, the module can rest upon or be supported by an elastically deformable bed or other form of elastically deformable support or supports. Preferably, the stud 128 is held securely via a polyurethane resin.

[0029] Figure 4 shows a further view 400 of the above measurement modules showing the lid 304 coupled to the body 302 with the self-cleaning stud 128 in place.

[0030] Figure 5 depicts a measurement assembly 500 comprising a number of measurement modules 502 disposed adjacently to one another. The measurement modules 502 are housed in a housing 504. The housing 504 comprises one or more embedded couplings (not shown) arranged to cooperate with the couplings 212 and 214 of the measurement modules 502 to supply power to the measurement modules 502 and to support communications between the measurement modules 502 and the data processing system (not shown) and, preferably, to supply triggering signals. It can be appreciated that the measurement modules 502 are modular. It can also be appreciated that the measurement modules 502 can be readily removed from and replaced in the housing 504.

[0031] Although the realisation shown in figure 5 shows a single row of modules 100, implementations are not limited thereto. Variations include using multiple rows of modules, with each row being immediately adjacent to another row, or spaced apart from another row by a predetermined distance. The modules can be arranged on an n by m basis. The n by m arrangement can be realized with multiple rows and columns being housed within a common

housing such as, for example, housing 504, or with some other number of rows and columns being arranged within respective housings such as, for example, an n by m arrangement could be realised using n single rows of m modules.

[0032] It will be appreciated that the implementation shown in figure 5 illustrates the longitudinal axes of the modules 502 as being perpendicular to the longitudinal axis of the housing 504. Alternatively or additionally, the arrangement of each module within the housing can be such that some other angular relationship prevails, that is, the longitudinal axes of the modules 502 can be arranged at a predetermined angle relative to the longitudinal axis of the housing 504.

[0033] Alternatively, or additionally, the relative orientation of the structured light pattern and the greatest dimension of the sensor, such as, for example, row of pixels in the case of a rectangular or square arrangement of sensor pixels, can be arranged to be aligned.

[0034] In embodiments employing multiple rows of sensors, predetermined axes, such as, for example, the longitudinal axes of the modules of one row can be arranged to be aligned or collinear with respective predetermined axes, such as, for example, longitudinal axes, of another row of modules. Alternatively, or additionally, the predetermined axes of one row can be arranged to have a predetermined off-set relative to the predetermined axes of another row of modules. Such an arrangement could be similar to an arrangement of bricks of a wall.

[0035] Furthermore, a predetermined axis of a module can be arranged to have a predetermined angular relationship with a predetermined axis of the housing 502. Implementations can have a perpendicular relationship between the axes or some other angular, non-perpendicular, relationship, such as, for example, an acute or obtuse angular relationship. In implementations having multiple rows, non-perpendicular relationships of respective rows can vary between acute and obtuse such as, for example, as in a herring bone relationship in which the longitudinal axes of modules of one row are oriented in a given direction relative to the longitudinal axis of the housing 502 whereas the longitudinal axes of another row are oriented in a different direction relative to the longitudinal axis of the housing, or a respective housing where the rows are housed in respective housings 504. Figures 5A to 5C illustrate such embodiments.

[0036] Referring to figure 5A, there is shown a view 5A00 of first 5A02 and second 5A04 rows of modules 100. Also shown is a longitudinal axis 5A06 of a housing 504 (not shown). It can be appreciated that the modules 100 of the first row 5A02 are oriented at an angle θ_1 relative to the longitudinal axis 5A06 of the housing 504. The modules of the second row 5A04 are oriented at an angle θ_2 relative to the longitudinal axis 5A06 of the housing 504. Although the orientations shown in figure 5A show the angles θ_1 and θ_2 as being equal, embodiments are not limited to

such an arrangement. Embodiments can be realised such that $\theta_1 \neq \theta_2$.

[0037] Figure 5B shows an arrangement 5B00 in which a first row 5B02 of modules 100 are aligned with a second row 5B04 of modules 100.

5 [0038] Figure 5C shows an arrangement 5C00 in which a first row 5C02 of modules 100 has a predetermined offset 5C04 relative to a second row 5C06 of modules 100.

10 [0039] Figure 5D shows a still further measurement assembly 5D00 comprising a housing 5D02 containing a number of modules 5D04 to 5D12. Also illustrated in figure 5D00 are a couple of location lugs 5D14 and 5D16, which are embodiments of the above mentioned corresponding formations for correct positioning and/or alignment of the modules within the housing. In use, the longitudinal axis of the modules are arranged to be substantially oriented in an intended direction of travel of a tyre as indicated by, for example, arrow 5D18. Such an arrangement has the advantage that the data from each module is available to be read-out or transmitted at different times, that is, temporally spaced apart or staggered/staged transmit times. This, in turn, influences the capacity, that is, bandwidth, of any communication path
15 needed to carry such data. Clearly, the bandwidth needed to carry simultaneously the data from one or two modules will be less than the bandwidth needed to carry simultaneously the data from all modules. The data paths are schematically illustrated by the respective dashed arrows associated with each module 5D02 to 5D12.

20 [0040] Each measurement module 100 is arranged to at least reduce and preferably prevent moisture condensing on interior surfaces of the measurement module, in particular, on the interior surface of the self-cleaning stud. The foregoing is realized by ensuring that the internal atmosphere is dry. It will be appreciated, therefore, that the measurement modules are preferably sealed to prevent moisture ingress. Any such sealing can be realized using one or more gaskets to provide an effective seal between at least one of the lid 304 and the body 302
25 and the lid 304 and the self-cleaning stud 128. Preferably, the housing 502 comprises a moisture absorbing material to at least reduce and, preferably, prevent condensation issues.

30 [0041] Figure 6 is a view 600 of a number of realisations of structured light. Any of the illustrated structured light patterns shown in figure 6 could be used with the measurement module described in this specification, jointly or severally, spatially and/or temporally, with any other structured light pattern taken in any and all combinations. The patterns are preferably realized using laser diodes and appropriate diffractive optical elements. The dimensions of the features of the structured light patterns are such that they can suitably resolve features of the objective being measured, that is, they can resolve tread features of a tyre of interest. It will be appreciated that tyres of interest can have differing tread pattern dimensions and depths. The
35 variation arises due to at least one of different tyre manufacturers having respective tyre

patterns, differently sized tyres having differently sized tread features and different tyre functions and feature orientations. The structured light patterns are preferably arranged to span an area, for a given working distance, defined by plus and minus predetermined angles relative to a normal of the tyre in both the circumferential and transverse directions, such as, for example
5 $\pm 15^\circ$, and preferably $\pm 10^\circ$. Diffractive optical elements used by embodiments of the present invention are available from, for example, Holoeve Photonics AG. Preferred embodiments use plastic DOEs <http://holoeve.com/diffractive-optics/standard-doe-plastics/>. Still further, a preferred DOE is the DE-R 253. Preferably, the DOE is plastic. Additionally, or alternatively, the DOE has a predetermined angular extent such as, for example, between 35° and 25°
10 degree, preferably 30° .

[0042] A first structured light pattern 602 comprises an ordered array of dots spaced apart from one another by a predetermined horizontal distance and a predetermined vertical distance. For example, at a given working distance, the predetermined circumferential or transverse distance is less than 20mm. For example, at a given working distance, the predetermined
15 circumferential or transverse is less than 80mm.

[0043] A second structured light pattern 604 comprises a cruciform having predetermined arm lengths.

[0044] A third structured light pattern 606 comprises a number of concentric rings, optionally with a central dot, having respective radii.

20 [0045] A fourth structured light pattern 608 comprises a combination of a cruciform together with at least one circle.

[0046] A fifth structured light pattern 610 comprises a plurality of dots arranged to define a cruciform and a circle.

[0047] A sixth structured light pattern 612 comprises a number of similarly, or identically,
25 oriented lines. The sixth structured light pattern 612 is a preferred structured light pattern. In use, the lines are arranged to illuminate the tyre in a transverse orientation. This is particularly advantageous in the case of, for example, steering or trailer tyres that have circumferential features, as opposed to driving tyres that have transverse features. Alternatively, the sixth structured light pattern 612 could, in use, be circumferentially oriented, that is, substantially
30 orthogonal to the transverse orientation of the tyre, which would be preferable to measure a driving tyre as opposed to a steering tyre. Preferred embodiments use a pattern as provided by, for example, a DE R 253, which has 11 thin lines. Embodiments can, however, use some other number of lines such as, for example, 5, 7, 11, 25, 65, fewer lines such as, for example, 2, 4, 6, or 8 lines, or some other number of lines.

35 [0048] A seventh structured light pattern 614 comprises a single line and at least one centrally

disposed dot. Although centrally disposed in the seventh structured light pattern, variations can dispose the dot at any other predetermined position relative to the line, including on or displaced apart from the line.

5 [0049] An eighth structured light pattern 616 comprises a plurality of linearly disposed equally displaced dots.

[0050] Ninth and tenth structured light patterns 618 and 620 comprise a single line, having a predetermined line width and line length. It can be appreciated that the ninth pattern 618 is a relatively long and thin line whereas the tenth pattern 620 is a relatively wider and shorter line.

10 [0051] The structured light patterns described above and herein comprise regularly disposed features, such as, for example, equally spaced lines, dots or curves, equal length lines, substantially identically oriented lines, dots or curves etc. However, variations can, additionally or alternatively, comprise irregularly disposed features such as, for example, unequally spaced lines, dots or curves, unequal line lengths or widths and differently orientated features.

15 [0052] It will be appreciated that the spacing of the structured light features establishes the maximum depth of tread that can be determined without introducing ambiguity.

[0053] Figure 7 shows a flowchart 700 of image processing undertaken on received, reflected, structured light patterns. The presence of a visible tyre is detected at step 702. At steps 704 and 706, at least first and at least second temporally disposed images are captured by the sensor 120. Preferably, just first and second images are captured. However, implementations
20 can capture one or more images at step 704 and/or one or more images at step 706. At step 708, the captured images are processed to identify reflected structured light 122 in at least one of the captured images.

[0054] A determination is made at step 710 regarding whether or not the processing at step 708 indicates the presence of reflected structured light. The presence of reflected structured
25 light can be determined in one or more ways such as, for example, detecting pixel values of the sensor 120 exceeding a predetermined level and/or detecting pixel values of the sensor indicative of a predetermined range of light wavelengths associated with the light source 102. If the determination at step 710 indicates that structured reflected light is not present, image capture resumes at step 706 at least and, optionally, at step 704.

30 [0055] If the determination at step 710 indicates that structured light is present, the captured images are processed at step 712 to identify, extract or isolate the reflected structured light. Identifying, extracting or isolating the structured light can be performed in a number of ways such as, for example, one of the images determined as having structured light can be used as the basis for identifying, extracting or isolating reflected structured light with all subsequent
35 determinations being based thereon. Alternatively, or additionally, multiple images determined

as having reflected structured light can be used as the basis for identifying, extracting or isolating reflected structured light with all subsequent determinations being based thereon. For example, the identified, extracted or isolated reflected structured light can be a function of the reflected structured light of multiple images, such as, for example, an average of values associated with reflected structured light taken from multiple images.

[0056] The identified, extracted or isolated reflected structured light is processed at step 714 to make an assessment of the condition of the objective characteristic, that is, to make an assessment of tyre tread depth. Preferably, the assessment results in the depth of the tread being measured in predetermined units, such as, for example, SI units or empirical units, preferably, millimeters or fractions of an inch.

[0057] At step 716, data associated with the assessment is output. The data output can be a quantitative indication of the measured depth, a quantitative indication of the average tread depth over a corresponding percentage of the measured portion of the tyre or some other quantitative measure or indication. Alternatively, or additionally, the data output can be a qualitative indication of tyre quality such as, pass, that is, the tread is greater than a prescribed minimum depth, fail, that is, the tread is less than a prescribed minimum depth, or some other qualitative indication.

[0058] The processing undertaken by the steps shown in and described with reference to figure 7 can be performed by controller 130 and image processor 136 with the output data being displayed via a connected computer or screen. Alternatively, or additionally, data associated with the output of the sensor can be processed by a connected computer, which has the advantage that the technical aspects of the module 100 are simplified as they are limited to image capture without more, or with only rudimentary image processing, and the image processing to make the qualitative or quantitative determinations described herein are performed using the connected computer. One skilled in the art will appreciate that a balance can be achieved between higher or more extensive local processing performance within the modules, and consequently lower data rate buses to communicate the results, and lower or less extensive local processing performance within the modules, and consequently higher data rate buses to communicate the results. The lower performance local processing results in larger amounts of data needing to be communicated to another processing platform.

[0059] The images are captured over respective predetermined time intervals and are spaced apart by respective predetermined time intervals. The respective predetermined time intervals can be equal or different. Preferably, the respective predetermined time intervals can be established as function of speed of rotation of the tyre to be measured. An indication of the speed of rotation of the tyre to be measured can be determined as a function of the difference between two or more captured images. Preferably, the two or more captured images are

immediately successive images, but do not necessarily need to be immediately successive images. Implementations can be realized in which the two or more captured images are not immediately successive.

5 [0060] As indicated above, preferred embodiments use a form of triggering to at least start, and preferably stop, image capture. The triggering can take the form of, for example, a pressure sensor that is actuated by the tyre as it approaches, leaves or is in contact with the stud. Alternatively, or additionally, the triggering arrangement can comprise optical elements, that is, a beam generator and a beam detector for generating and detecting a beam that is broken by the progress of the tyre relative to the stud.

10 [0061] Referring to figure 8, there is shown a view 800 of the operation of embodiments of the invention. It can be appreciated that a source 802 of structured light, such as the source 102, lens 118 and diffractive element 116 described above, is arranged to illuminate a tyre 104. The tyre 104 comprises an outer tread surface 804 and an inner tread surface 806 such as, for example, tread surface 106 described above. A normal 810 to the tyre 104 is shown for
15 reference. Structured light 812 is incident upon the tyre 104 and is reflected in the form of reflected structured light as described above. Assuming that the incident structured light 812, taking, for example, the form of a line that is transverse to the tyre surface, is incident upon the outer tread surface 804 over one or more portions of the line, reflected structured light 814 associated with the outer tread surface 804 will be detected by the sensor 816. The reflected
20 structured light 814 will fall on respective pixels of the sensor 816. Assuming at least one other portion of the structured light 812 was incident upon the inner tread surface, the associated reflected structured light 816 will be spatially shifted by an amount that is related to the tread depth. Accordingly, the associated reflected structured light 816 will fall on a different portion of the sensor 816. Analysis of the image comprising the first 814 and second 816 reflected
25 structured light will reveal the spatial separation of the two and, following a mapping from pixel coordinates of the sensor to world coordinates, will reveal the tread depth at the point of measurement.

[0062] One skilled in the art will appreciate that a balance has to be reached regarding the angle of incidence and the viewing angle, more particularly, the angle between incident light and
30 the angle of the line of sight of the sensor. The balance is one that seeks a compromise between sensitivity or accuracy of measurement and a need to ensure that the light has a clear view or path to the tread trough or inner tread surface. The greater the angle between line of sight and the incident light, the greater the accuracy of the measurement and visa versa. However, the angle between the two needs to be sufficiently small that, firstly, the structured
35 light can reach the bottom of the tyre tread, that is, the inner tread surface, and, secondly, so that the reflected structured light associated with the inner tread surface and the outer tread

surface can be detected. Preferred embodiments set such an angle at, for example, $\pm 20^\circ$, preferably, at $\pm 10^\circ$ transversely and circumferentially.

[0063] Figure 9 illustrates a view 900 of reflected structured light 902 following reflection from a tyre having a tread pattern due to illumination with a single light sheet, that is, a single line. It can be appreciated that the reflected structured light 902 comprises three portions. First and second portions 904 and 906 represent reflected structured light 814 corresponding to structured light 812 that was incident upon the outer tread surface 804. The third portion of reflected structured light 908 (or 816) corresponds to structured light 812 that was incident upon the inner tread surface 806 of the tyre 104. It can be appreciated that the first 904 and second 906 portions are spatially separated from the third portion 908 due to the tread pattern.

[0064] Figure 10 shows a view 1000 of the variation in intensity of the structured light, in particular, the reflected structured light 814 and 816 separated by the above described shift 1002. Pixels of the sensor, represented by the squares, upon which the reflected structured light 814 and 816 is incident are shown. Each pixel will generate an output value, represented by the horizontal lines, associated with the incident or received reflected structured light 814 and 816. The shift between the two detected portions of reflected structured light 814 and 816 can be determined in a number of ways. For example, a measurement of the distance between local maxima in terms of pixel separation could be performed. Alternatively, or additionally, and preferably, a cross-covariance or cross-correlation is performed using the two intensity distributions; the result of which is associated with the spatial separation and, therefore, the measured or determined tread depth.

[0065] Figure 11 depicts a view 1100 of reflected structured light as described with reference to figure 9, but showing the difference between a schematic ideal representation of the various portions 904 to 908 of the reflected structured light and a schematic representation of a departure from the ideal likely to be encountered in practice due to the shape of the tyre as indicated by corresponding portions 1102 to 1106 of the reflected structured light. Also shown are the schematic representations of the intensity distributions 814 and 816 shown in and described with reference to figure 10.

[0066] Referring to figure 12, there is shown a view 1200 of a reflected structured light pattern. It can be appreciated that the pattern comprises four lines 1202 to 1208 each with respective shifted portions 1210 to 1216 corresponding to tread features. In the illustrated embodiment, the shifted portions are shown aligned, indicating that the corresponding tread features are also aligned. However, it will be appreciated that figure 12 is merely a schematic representation and that the reality will be very different, showing much more complex reflected structured light.

[0067] Figure 13 shows a flowchart 1300 and supporting schematics representing the

processing performed by embodiments of the present invention. At step 1302, preferably in response to triggering, illumination of a tyre 104 with structured light and associated image capture are undertaken together with suppression of noise in the captured image. Noise suppression can be realised in a number of ways such as, for example, the difference or XOR
5 between an image 1304 taken before illumination with the structured light and an image 1306 taken during illumination with the structured light to produce a clean image 1308 having at least reduced noise and preferably no noise. Nevertheless, the captured reflected structured light can still be non-linear and/or distorted due to optical aberrations as described above with reference to figure 11. Again, a balance can be reached between perfect optical elements and
10 no distortion or imperfect optical elements and some distortion, with the concomitant need to address that distortion.

[0068] At step 1310, which is optional, the distorted reflected structured light is aligned to create an aligned image 1312 representing or comprising the reflected structured light 1314 and 1316, that is, processed to compensate for optical aberrations in the optical elements of the
15 module such as, for example, the lenses 118 and 124, the diffractive optical element 116, the self-cleaning stud 128 and the filter 121, taken jointly or severally in any and all combinations.

[0069] The separate instances or elements of the reflected structured light 1314 and 1316 are identified at step 1318 via line segregation, resulting in a segregated image having first 1320 and second 1322 portions each comprising one or more than one element of the overall
20 captured reflected structured light pattern.

[0070] An estimate of the shift is made at step 1324. The estimation can be performed in a number of ways such as, for example, the cross-correlation or cross-covariance techniques described above, or in any other way. In embodiments where the line segregation stage reveals a number of separate instances or elements of the reflected structured light 1314 and
25 1316, an estimate of the shift can be undertaken for each element and output as the result, or an average can be calculated from the shift values associated with all or selectable ones of the processed segments.

[0071] A transformation between pixel co-ordinates to real world co-ordinates is undertaken at step 1326 to provide an indication of the measured tread depth in meaningful units.

30 [0072] It will be appreciated that embodiments of the present invention advantageously operate looking substantially upwardly, or normally, towards the tyre at relatively short working distances such as, for example, 200mm, which is facilitated by using a self-cleaning stud that, in turn, allows a modular approach based upon relatively low cost lenses and sensors to be taken. By using a greater number of lower resolution sensors it is possible to distribute the
35 measurement pixels more effectively. Furthermore, using triggering to control the image capture allows a reduction in camera interface speed to be realised. The benefits of the

modular approach apply equally to the illumination and sensing aspects of embodiments.

[0073] Figure 14 shows a view 1400 of a structured light pattern 1402 illuminating the tyre 104. It can be appreciated that the surface profile of the tyre 104 causes line deviations 1404 (some of which have been identified by the red circles).

5 [0074] Throughout the description and claims of this specification, the words “comprise”, “have” and “contain” and variations of them mean “including but not limited to”, and they are not intended to (and do not) exclude other components, integers or steps. Throughout the description and claims of this specification, the singular encompasses the plural unless the context otherwise requires. In particular, where the indefinite article is used, the specification is
10 to be understood as contemplating plurality as well as singularity, unless the context requires otherwise.

[0075] Features, integers and characteristics described in conjunction with a particular aspect, embodiment or example of the invention are to be understood to be applicable to any other aspect, embodiment or example described herein unless incompatible therewith. All of the
15 features disclosed in this specification (including any accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive. The invention is not restricted to the details of any foregoing embodiments. The invention extends to any novel one, or any novel combination, of the features disclosed in
20 this specification (including any accompanying claims, abstract and drawings), or to any novel one, or any novel combination, of the steps of any method or process so disclosed.

[0076] The reader's attention is directed to all papers and documents which are filed concurrently with or previous to this specification in connection with this application and which are open to public inspection with this specification, and the contents of all such papers and
25 documents are incorporated herein by reference.

CLAIMS

1. A method for measuring tread depth of a tyre, the method comprising
 - a. illuminating a tread-bearing surface of the tyre with structured light, via a self-cleaning optical element adapted to co-operate with a tyre surface to clean an exposed outer surface of the optical element, and
 - b. capturing at least one image comprising reflected structured light associated with the illuminating structured, light, and
 - c. preferably, an analyser for analysing an image of the illuminated tread-bearing surface of the tyre to determine the tread depth of the tyre from the reflected, preferably structured, light.
2. A method as claimed in any preceding claim, wherein the step of illuminating comprises emitting light from an LED, laser or other semiconductor light source.
3. A method as claimed in any preceding claim, wherein the step of illuminating comprises the step of structuring the light from the light source.
4. A method as claimed in any preceding claim, wherein the step of illuminating comprises imparting structure to the light from the light source to produce said structured light.
5. A method as claimed in claim 4, wherein the step of imparting structure to the light comprises at least one of collimating, using a collimator, the light and diffracting, using a diffractive optical element, the light to produce the structured light.
6. A method as claimed in any preceding claim, wherein said structured light comprises at least one of at least one spot, at least one line of light, at least two lines, wherein said line or lines are at least one of linear and non-linear, bounded or unbounded, taken jointly and severally in any and all combinations.
7. A method as claimed in any preceding claim, wherein the structured light comprises an ordered array of structured light elements.
8. A method as claimed in claim 7, wherein the ordered array of structured light elements comprises a plurality of lines, wherein said line or lines are at least one of linear and non-linear.
9. A method as claimed in any preceding claim, wherein the at least one optical element is a self-cleaning optical element.
10. A method as claimed in claim 9, wherein the self-cleaning optical element is responsive to tyre contact to achieve the self-cleaning, preferably via relative movement between a surface of the optical element and a surface of the tyre.
11. A method as claimed in any preceding claim, wherein the step of analysing comprises receiving reflected light associated with said structured light via at least one sensor.

12. A method as claimed in claim 11, wherein the at least one sensor comprises a CMOS sensor.
13. A method as claimed in either of claims 11 and 12, wherein the step of analysing comprises processing, using a processor, said image of the received reflected light to
5 extract said objective feature characteristic.
14. A tread depth measurement module for measuring tread depth of a tyre; the module comprising a housing bearing at least one self-cleaning optical element adapted to cooperate with a tyre surface to clean an upper surface of the optical element, a, preferably structured, light source for illuminating a tread-bearing surface of the tyre with,
10 preferably structured, light and, preferably, an analyser for analysing a captured image of the illuminated tread-bearing surface of the tyre to determine the tread depth of the tyre from reflected, preferably structured, light within the captured image.
15. A module as claimed in claim 14, wherein the structured light source comprises an LED, laser or other semiconductor light source.
16. A module as claimed in any claims 14 to 15, wherein the structured light source
15 comprises means for structuring the light from a light source.
17. A module as claimed in any of claims 14 to 16, wherein the structured light source comprises means for imparting structure to the light from the light source to produce said structured light.
18. A module as claimed in claim 17, wherein the means for imparting structure to the light
20 comprises at least one of a collimator and a diffractive optical element to produce the structured light.
19. A module as claimed in any of claims 14 to 18, wherein said structured light comprises at least one spot, at least one line of light, at least two lines, wherein said line or lines
25 are at least one of linear and non-linear, bounded or unbounded, taken jointly and severally in any and all combinations.
20. A module as claimed in any of claims 14 to 19, wherein the structured light comprises an ordered array of structured light elements.
21. A module as claimed in claim 20, wherein the ordered array of structured light elements
30 comprises a plurality of lines, wherein said line or lines are at least one of linear and non-linear.
22. A module as claimed in any of claims 14 to 21, wherein the at least one optical element is a self-cleaning optical element.
23. A module as claimed in claim 22, wherein the self-cleaning optical element is responsive
35 to tyre contact to achieve the self-cleaning.
24. A module as claimed in any of claims 14 to 23, wherein the analyser for analysing comprises a sensor for receiving reflected light associated with said structured light.

25. A module as claimed in claim 24, wherein the at least one sensor comprises a CMOS sensor.
26. A module as claimed in either of claims 24 and 25, wherein the analyser comprises a processor for processing the image associated with the received reflected light to extract said tread depth.
27. A module as claimed in any of claims 14 to 26, wherein the atmosphere within the housing is substantially moisture free to at least reduce, and preferably prevent, condensation forming on the optical element.
28. A module as claimed in claim 27 wherein the atmosphere is nitrogen.
29. A module as claimed in any of claims 14 to 28, wherein the orientation of a feature of the structured light pattern is arranged to align with a predetermined, preferably greatest, axis or dimension of the sensor.
30. A module as claimed in any of claims 14 to 28, comprising a first coupling arranged to receive power.
31. A module as claimed in claim 30, wherein the first coupling comprises an inductive couple for inductively receiving power for the light source, sensor and analyser.
32. A module as claimed in any of claims 14 to 31, comprising a second coupling arranged to output data from at least one of the sensor and analyser and/or to couple a triggering signal to influence image capture.
33. A module as claimed in claim 32, wherein the second coupling is an inductive coupling.
34. An assembly comprising a housing (502) containing a number of modules as claimed in any of claims 14 to 33.
35. An assembly as claimed in claim 34, wherein the number of modules are arranged in n rows by m columns.
36. An assembly as claimed in claim 35, wherein predetermined axes of one row of modules are collinear with respective predetermined axes modules of another row.
37. An assembly as claimed in claim 35, wherein predetermined axes of one row of modules have a predetermined offset relative to respective predetermined axes modules of another row.
38. An assembly as claimed in any of claims 34 to 37, wherein a predetermined axis of at least one module has a predetermined orientation relative to a predetermined axis of the housing (502) containing the number of modules.
39. An optical element for as assembly, preferably an assembly as claimed in any of claims 34 to 38, the optical element comprising a profiled upper surface adapted to cooperate with a tyre on contact to induce relative motion between the profiled upper surface and the tyre.

40. A housing of an objective feature measurement assembly comprising a lid adapted to receive a self-cleaning optical element and a body adapted to house a structured light source and a respective sensor.
- 5 41. A housing as claimed in claim 40, further comprising an optical element as claimed in claim 39.
42. A method substantially as described herein with reference to and/or as illustrated in the accompanying drawings.
43. A module, system or assembly substantially as described herein with reference to and/or as illustrated in the accompanying drawings.
- 10 44. An optical element substantially as described herein with reference to and/or as illustrated in the accompanying drawings.
45. A housing substantially as described herein with reference to and/or as illustrated in the accompanying drawings.
- 15 46. A housing as claimed in either of claims 40 and 41, wherein at least one of the body and lid comprise resiliently deformable portions.
47. A housing as claimed in claim 46, wherein the resiliently deformable portions comprise at least one of resiliently deformable structures and resiliently deformable walls or other portions.
- 20 48. An assembly comprising a housing as claimed in any of claims 40, 41, 46 and 47 and a resiliently deformable support for supporting the housing.

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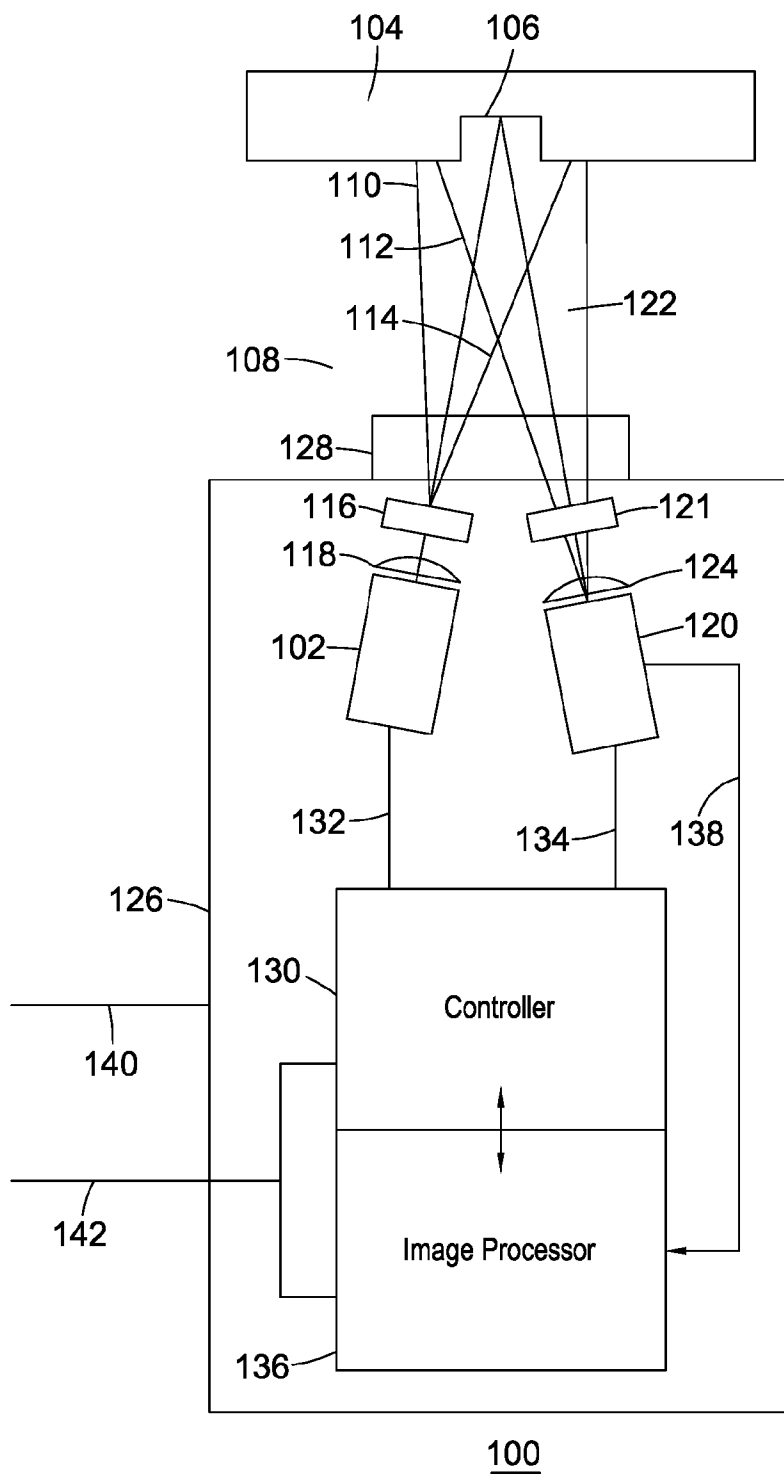


Fig. 1

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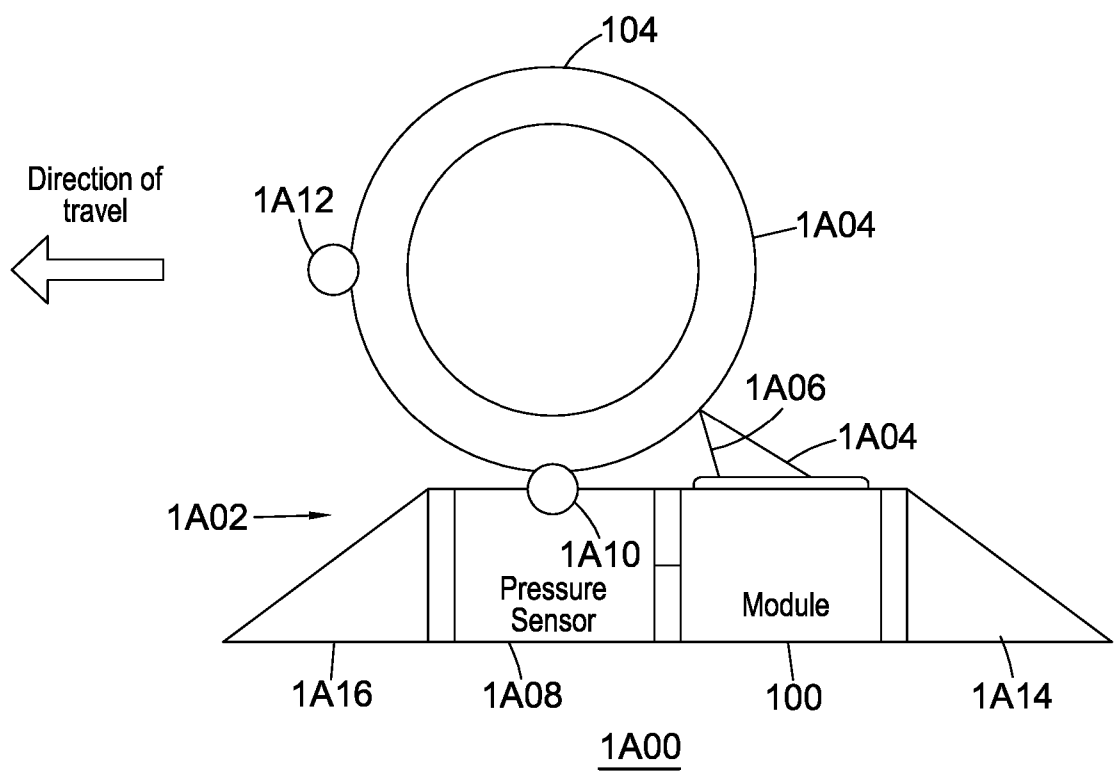


Fig. 1A

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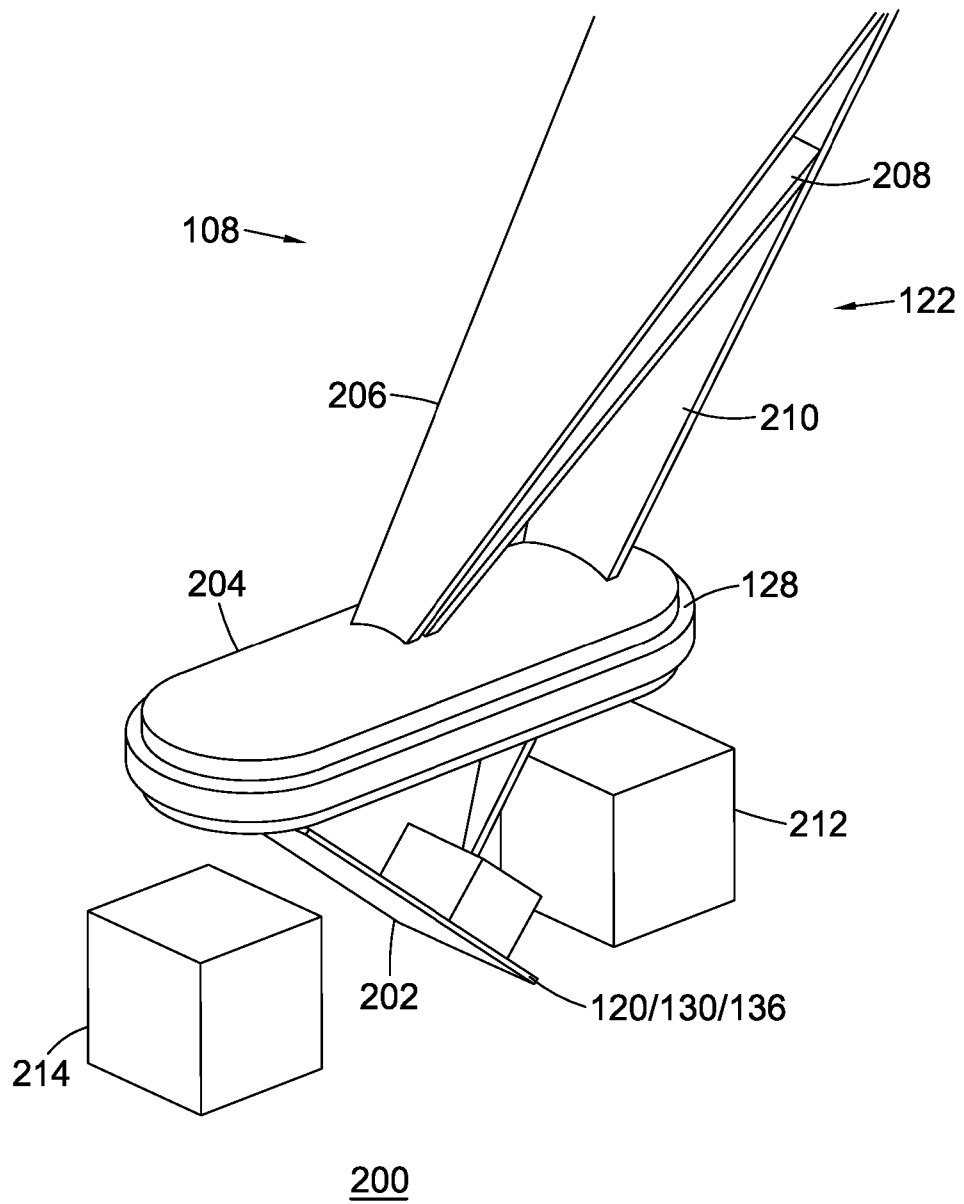


Fig. 2

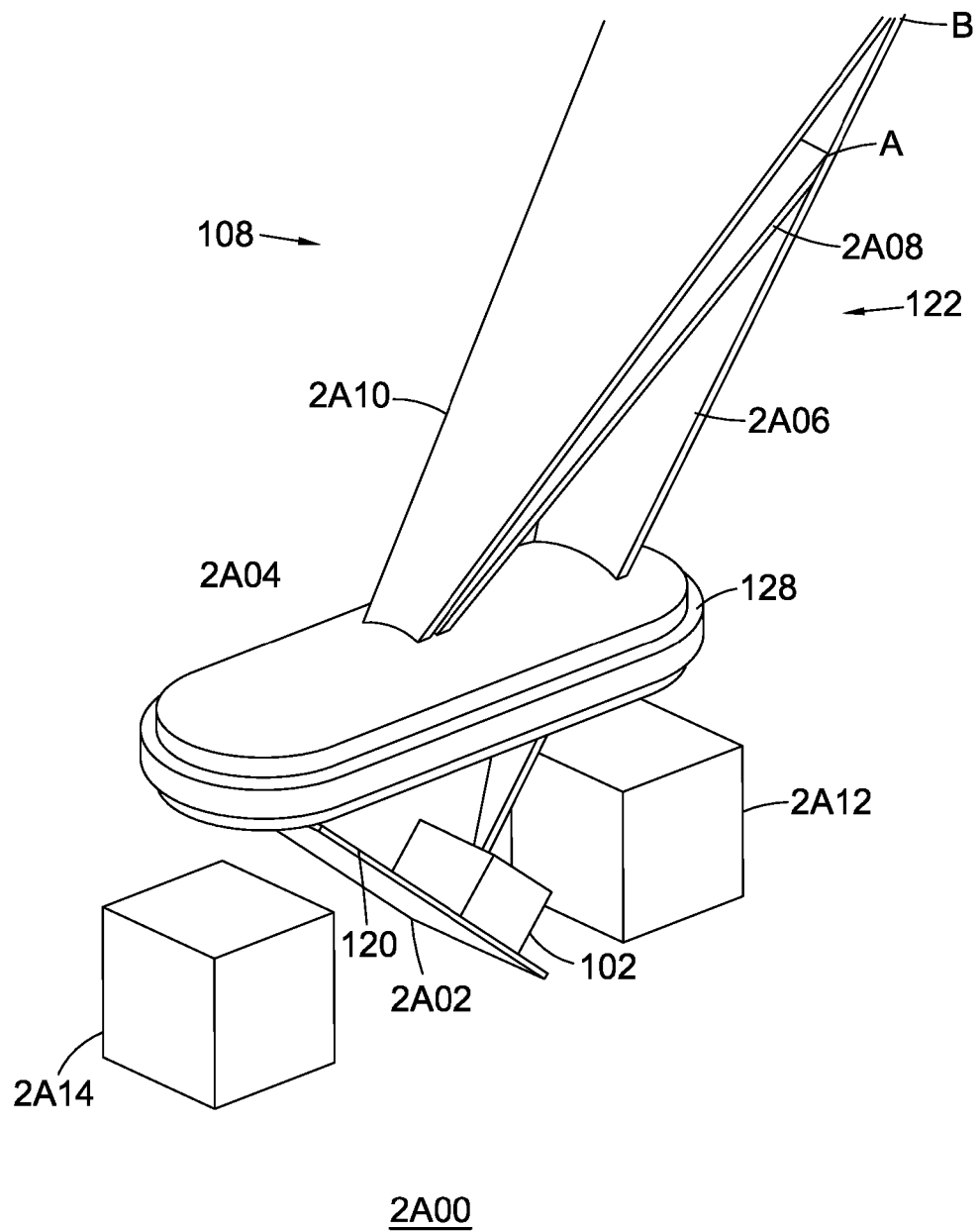


Fig. 2A

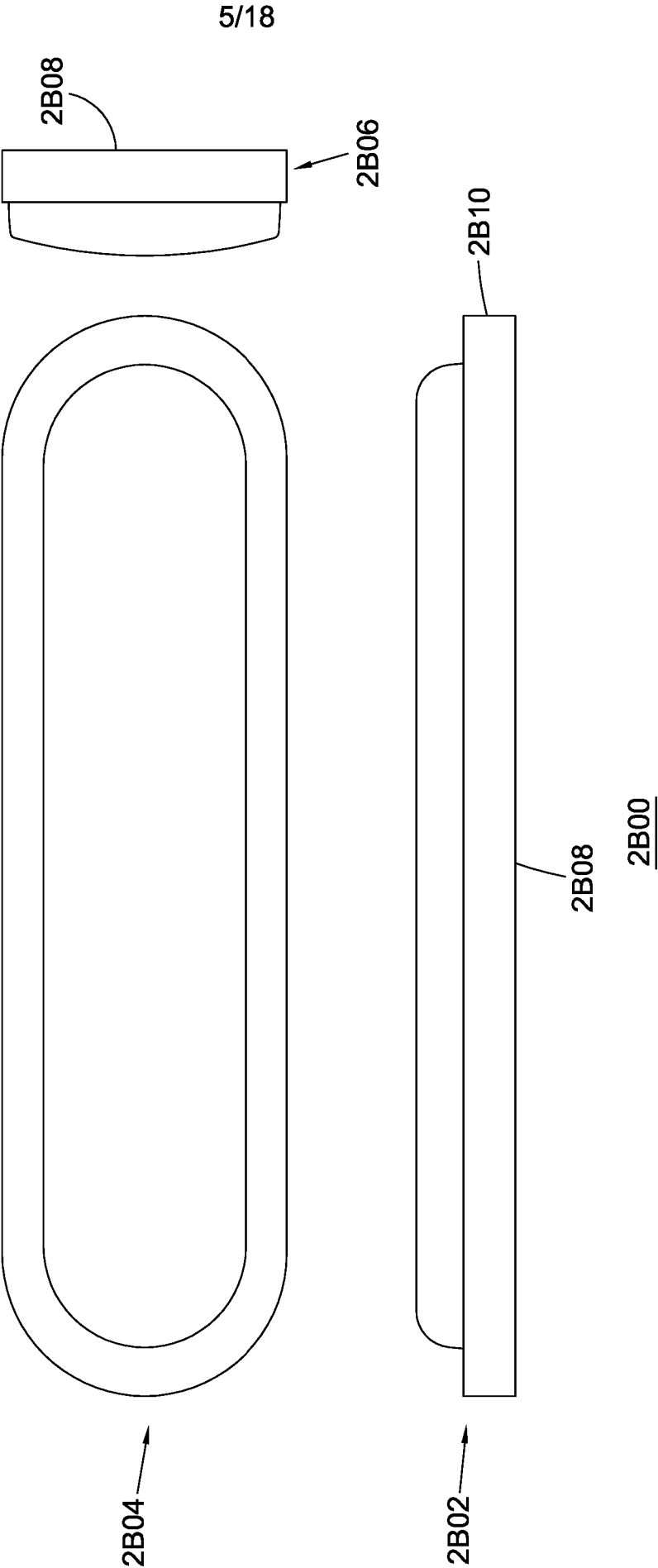


Fig. 2B

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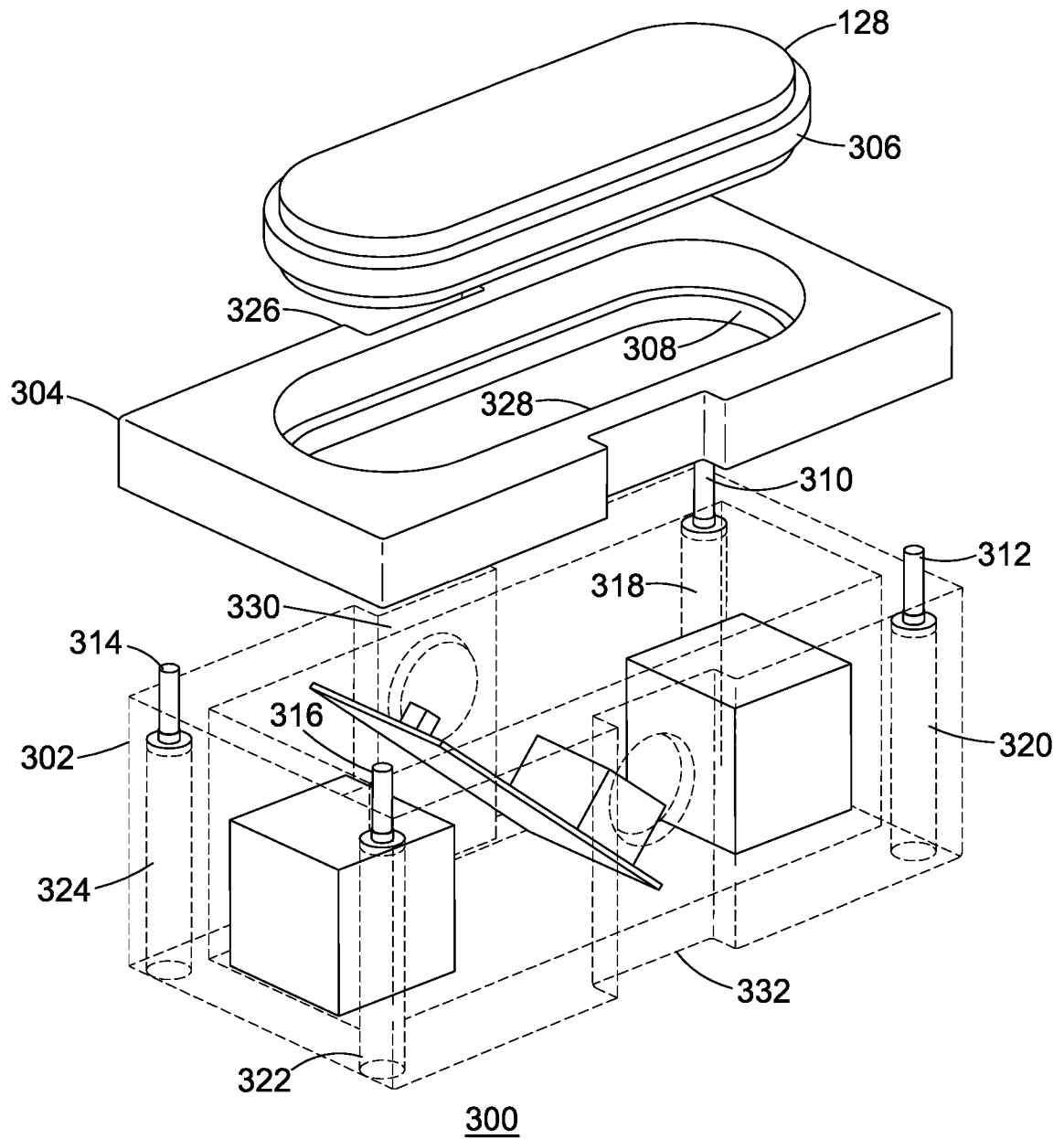


Fig. 3

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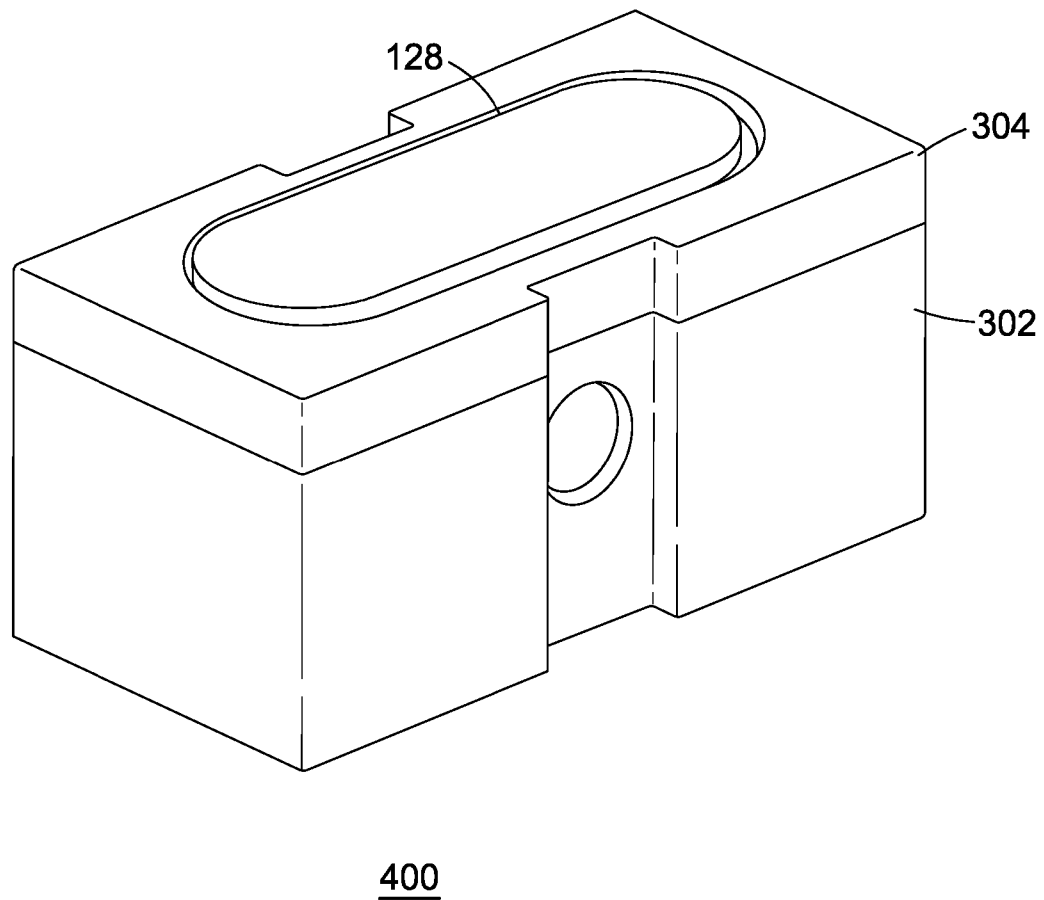


Fig. 4

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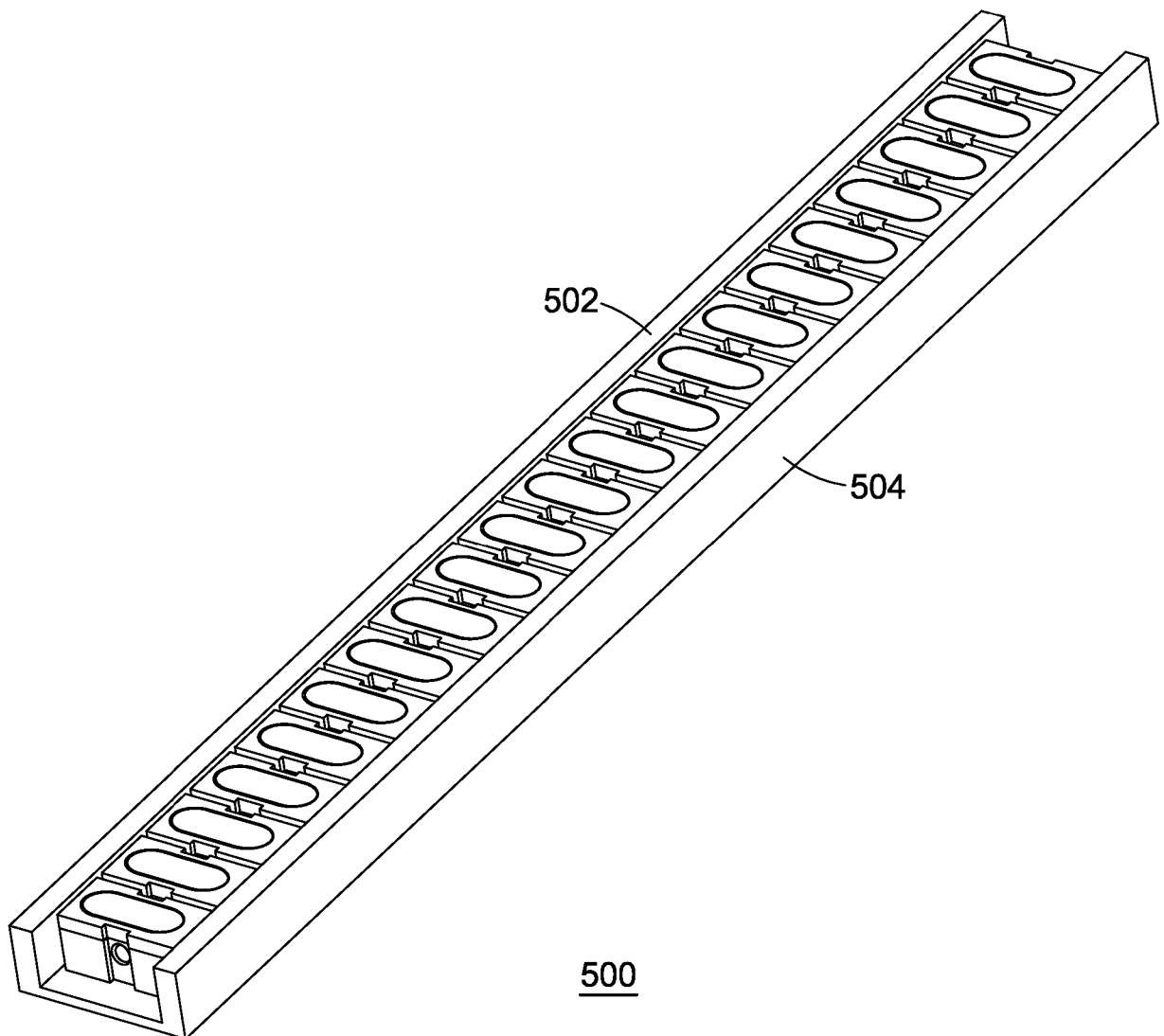
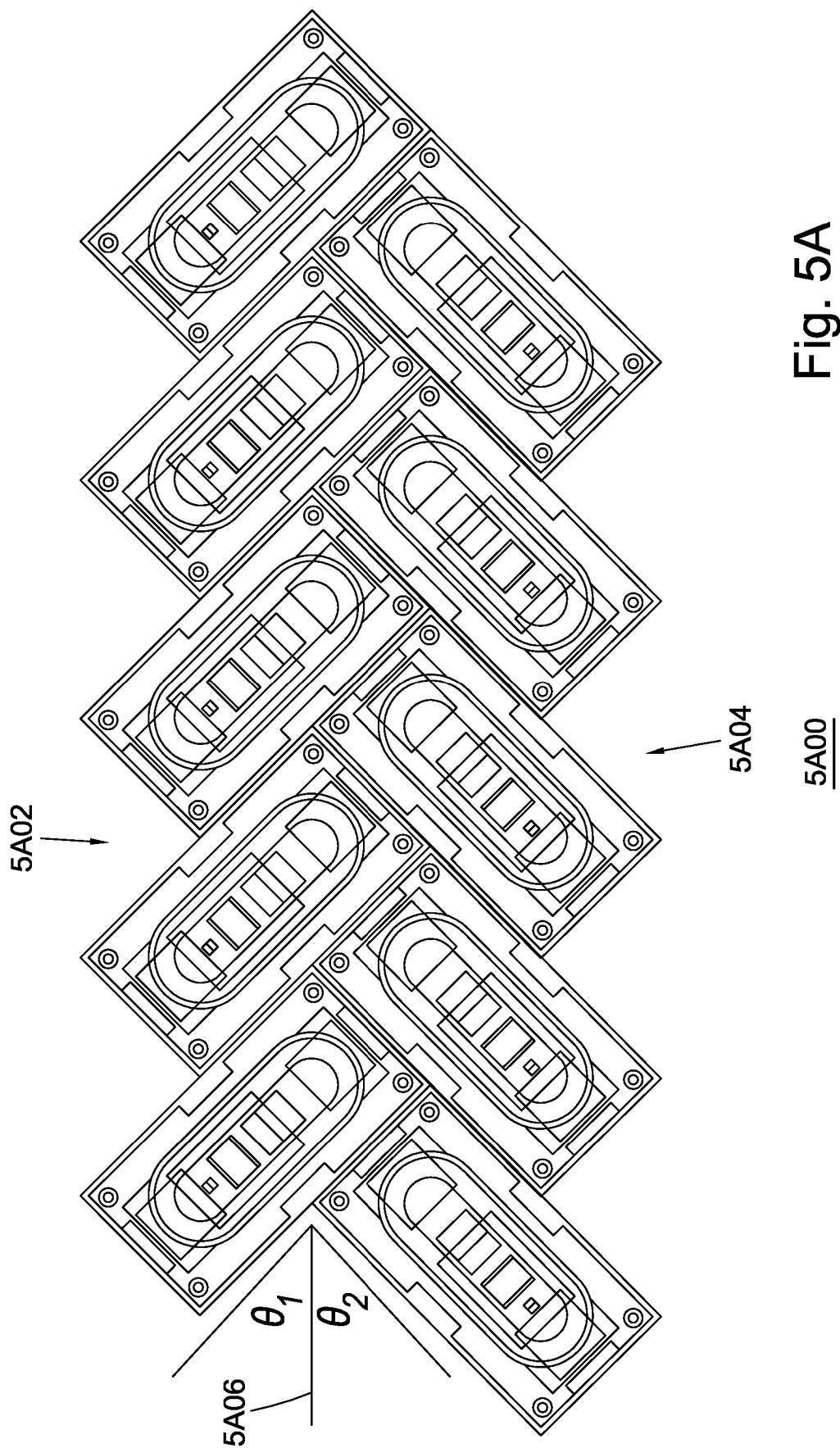


Fig. 5

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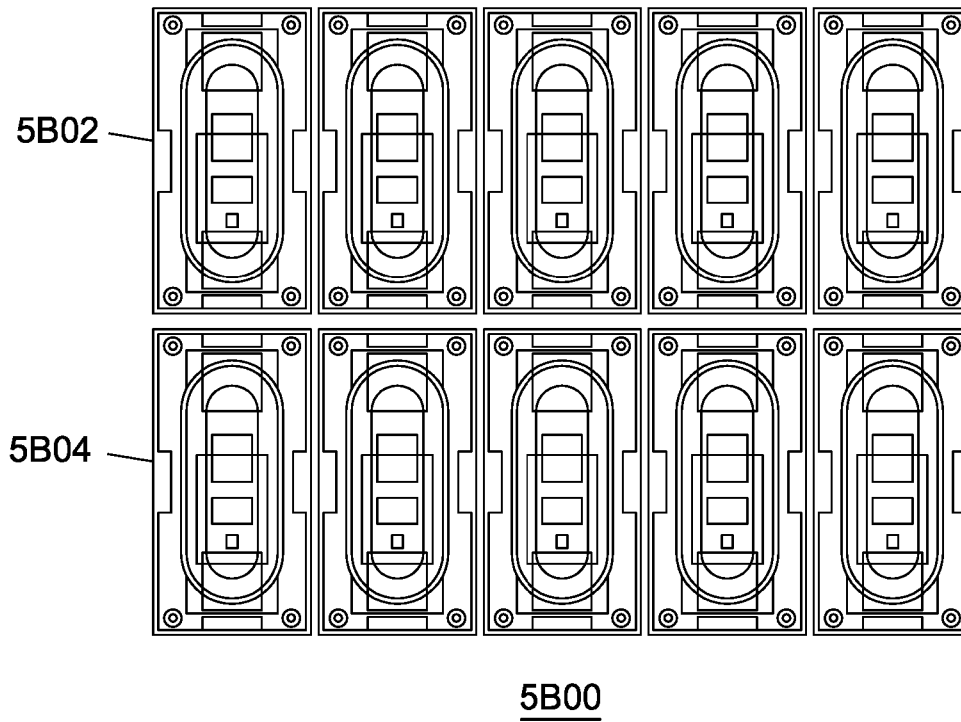


Fig. 5B

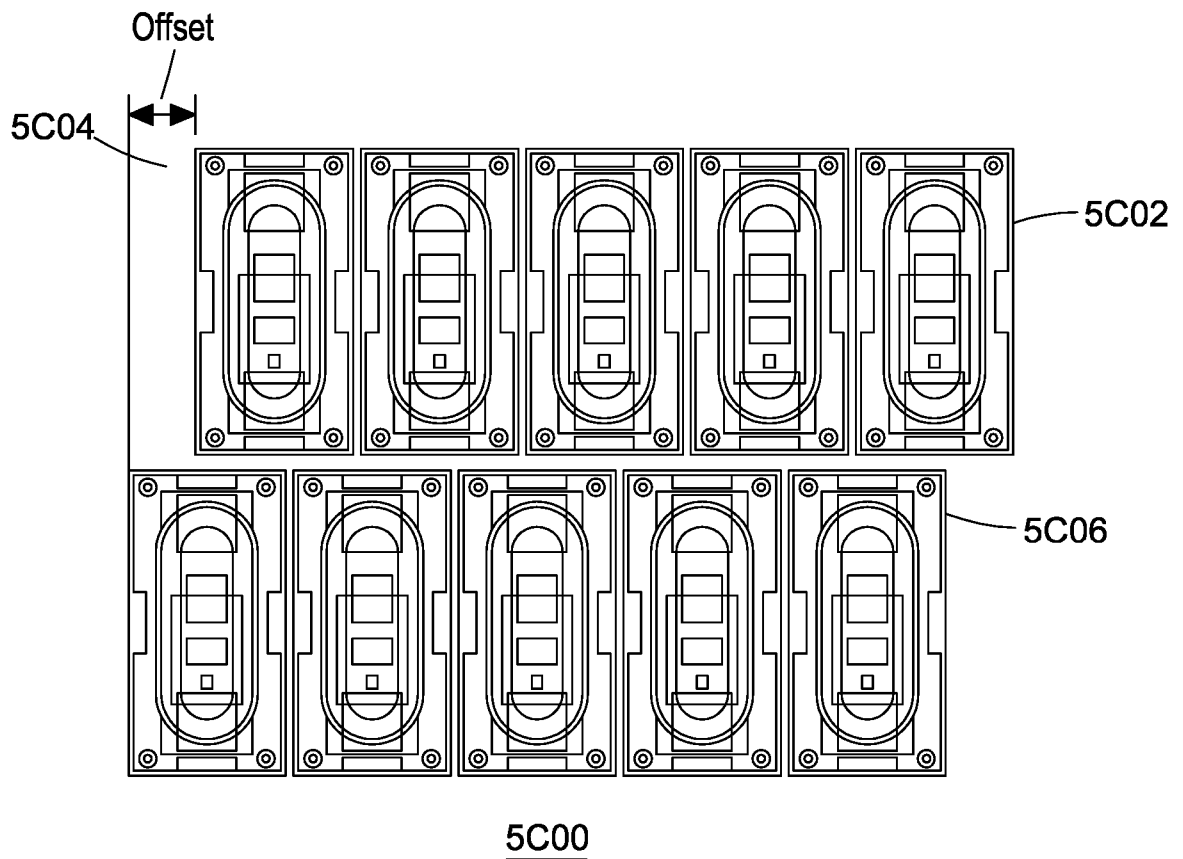


Fig. 5C

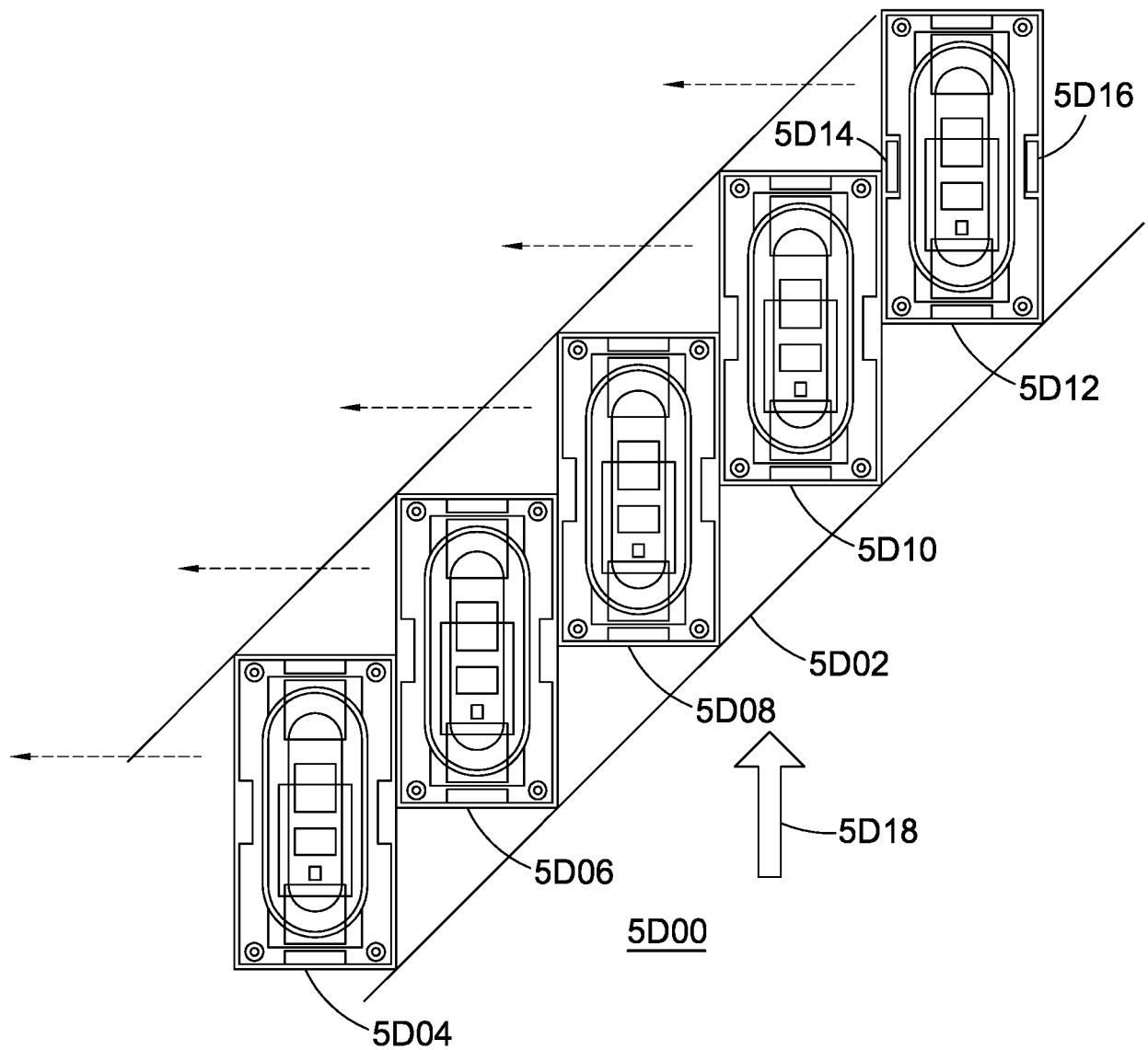


Fig. 5D

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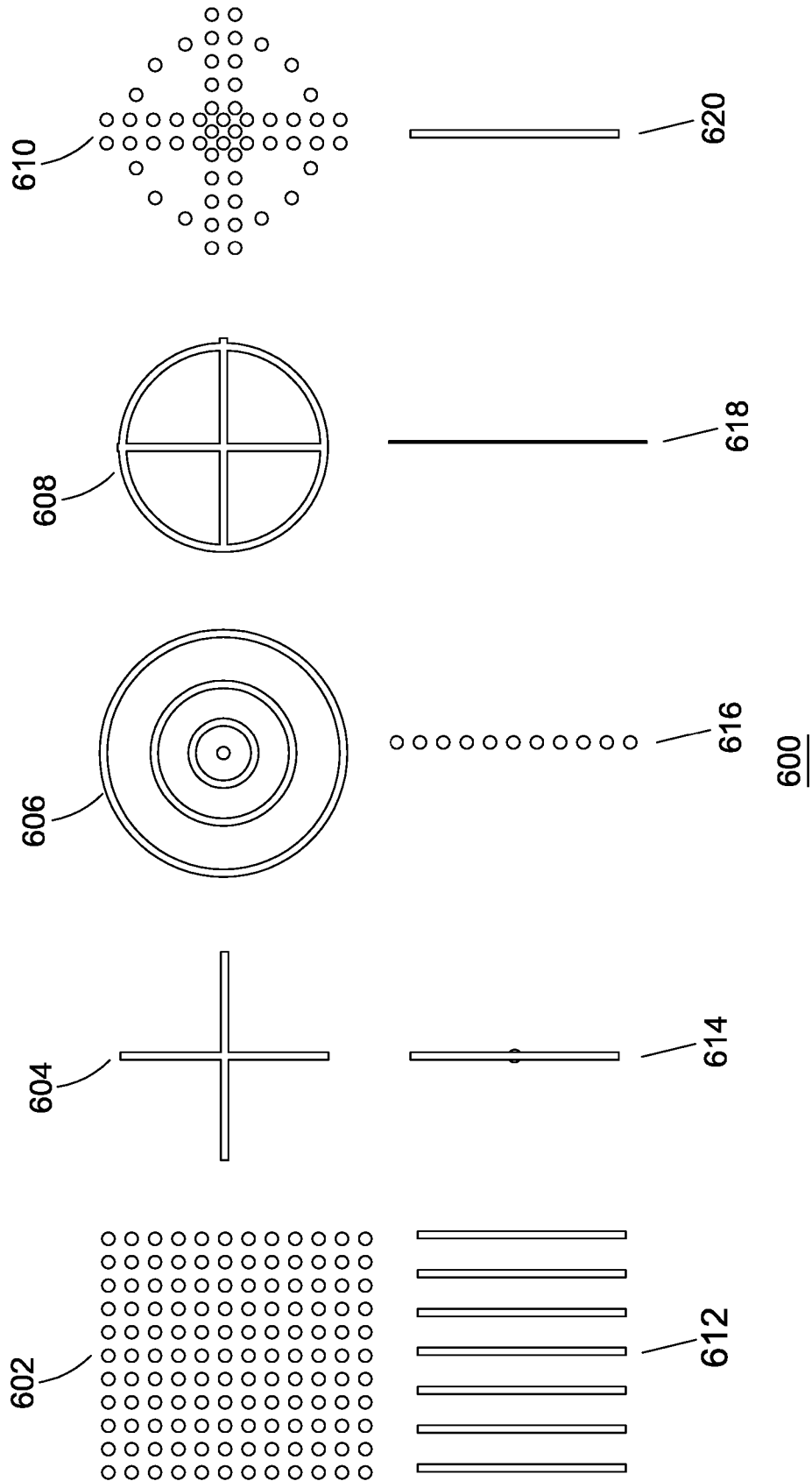


Fig. 6

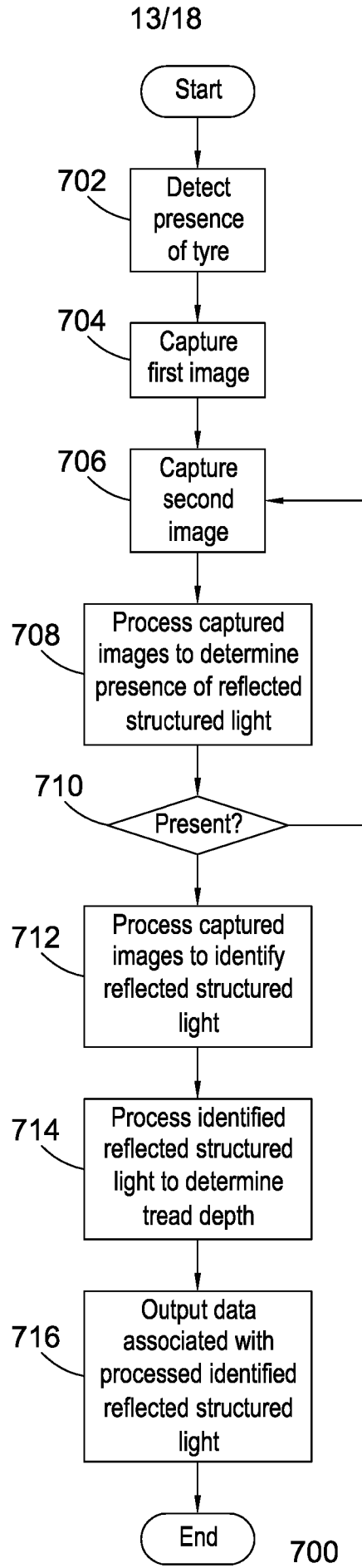


Fig. 7

14/18

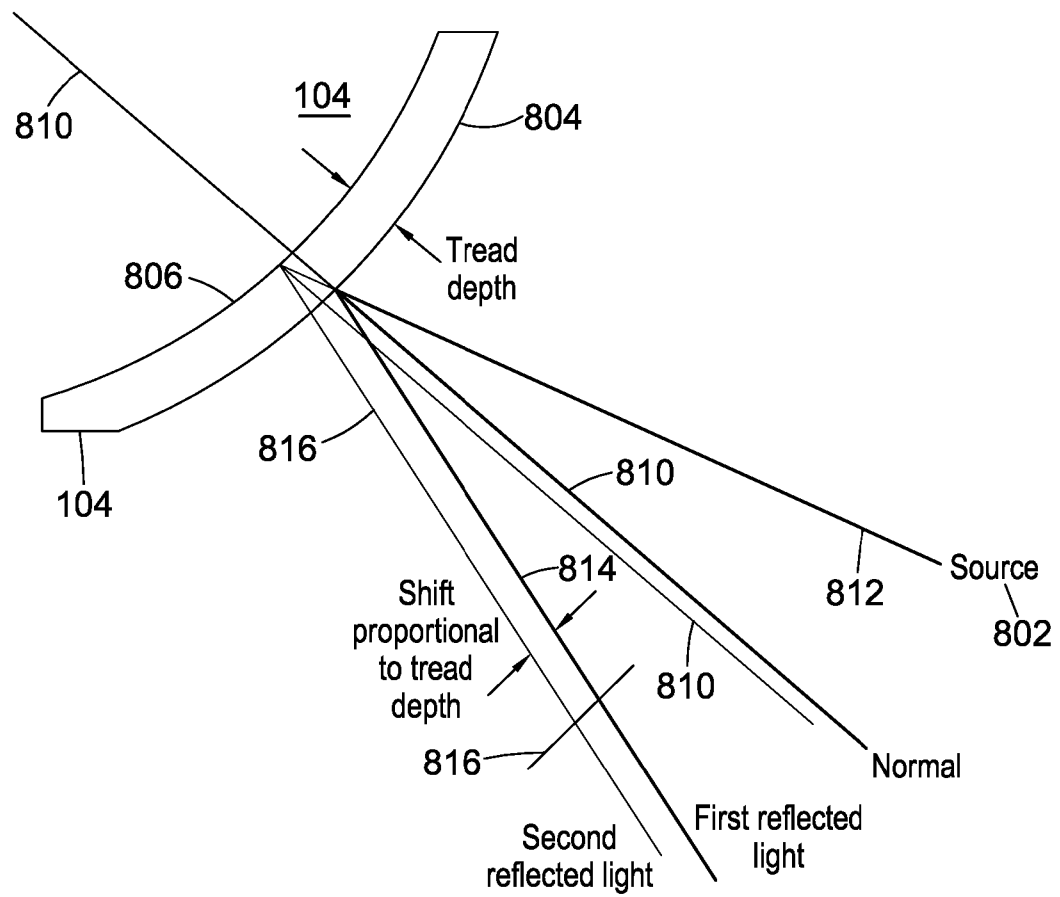
800

Fig. 8

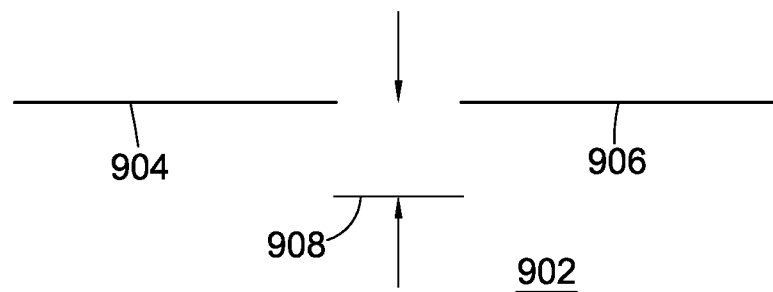
900

Fig. 9

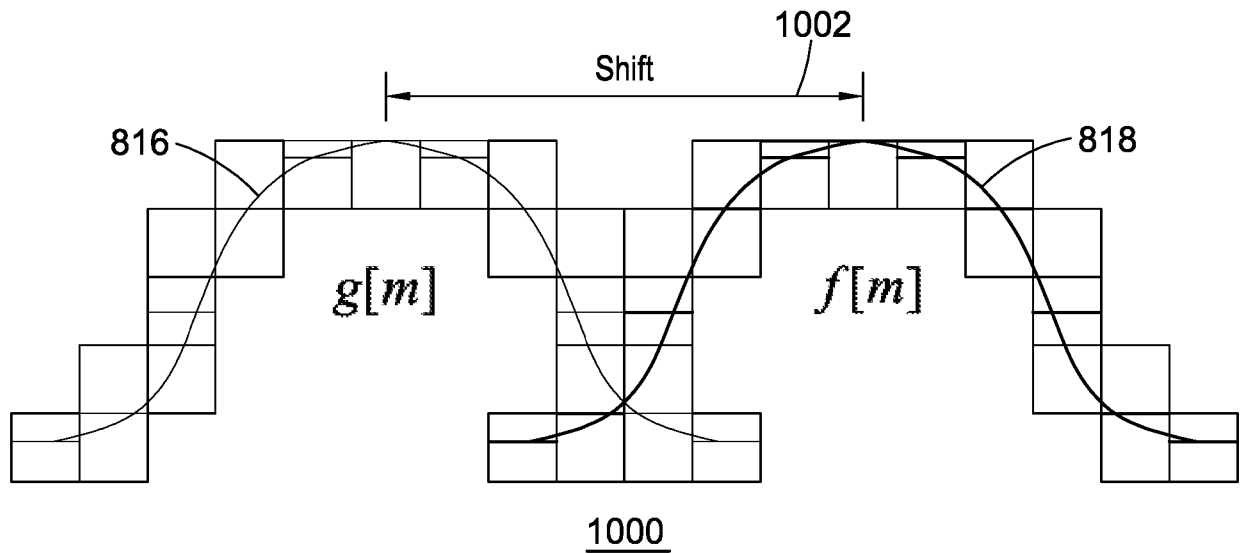


Fig. 10

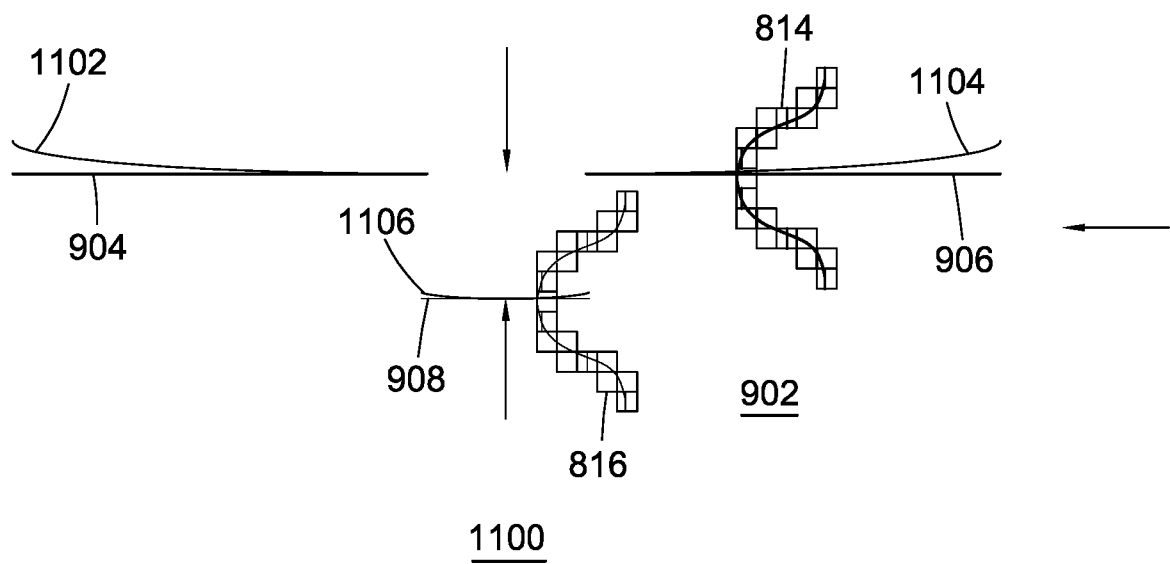


Fig. 11

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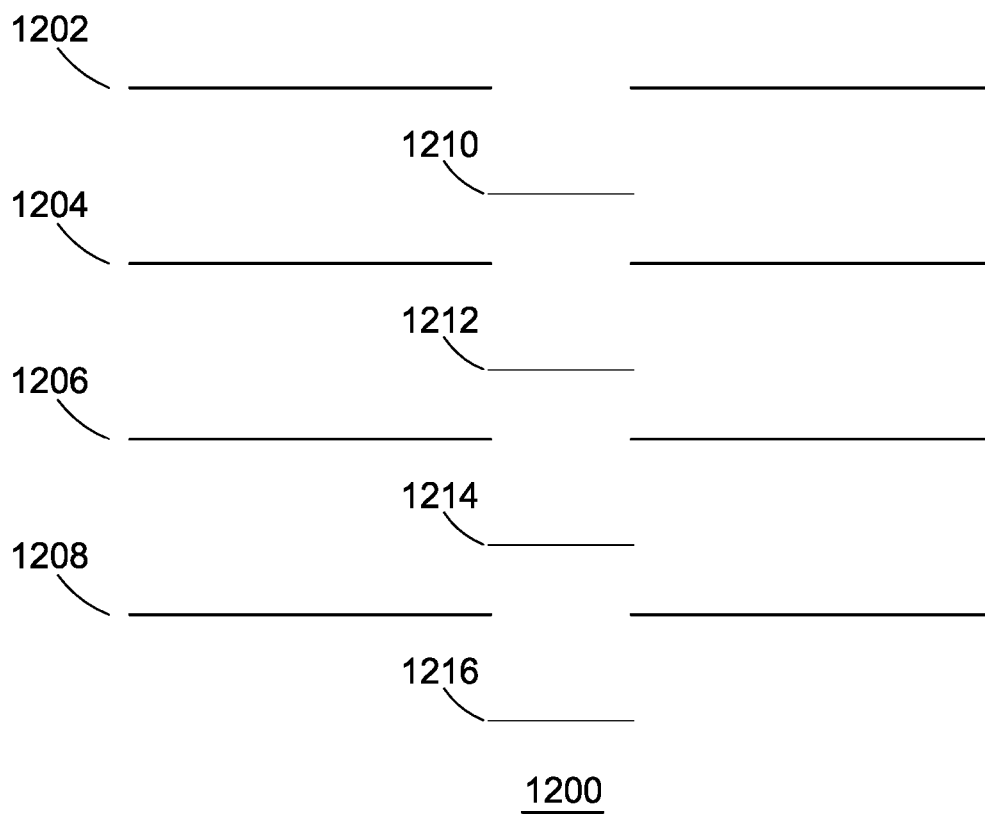


Fig. 12

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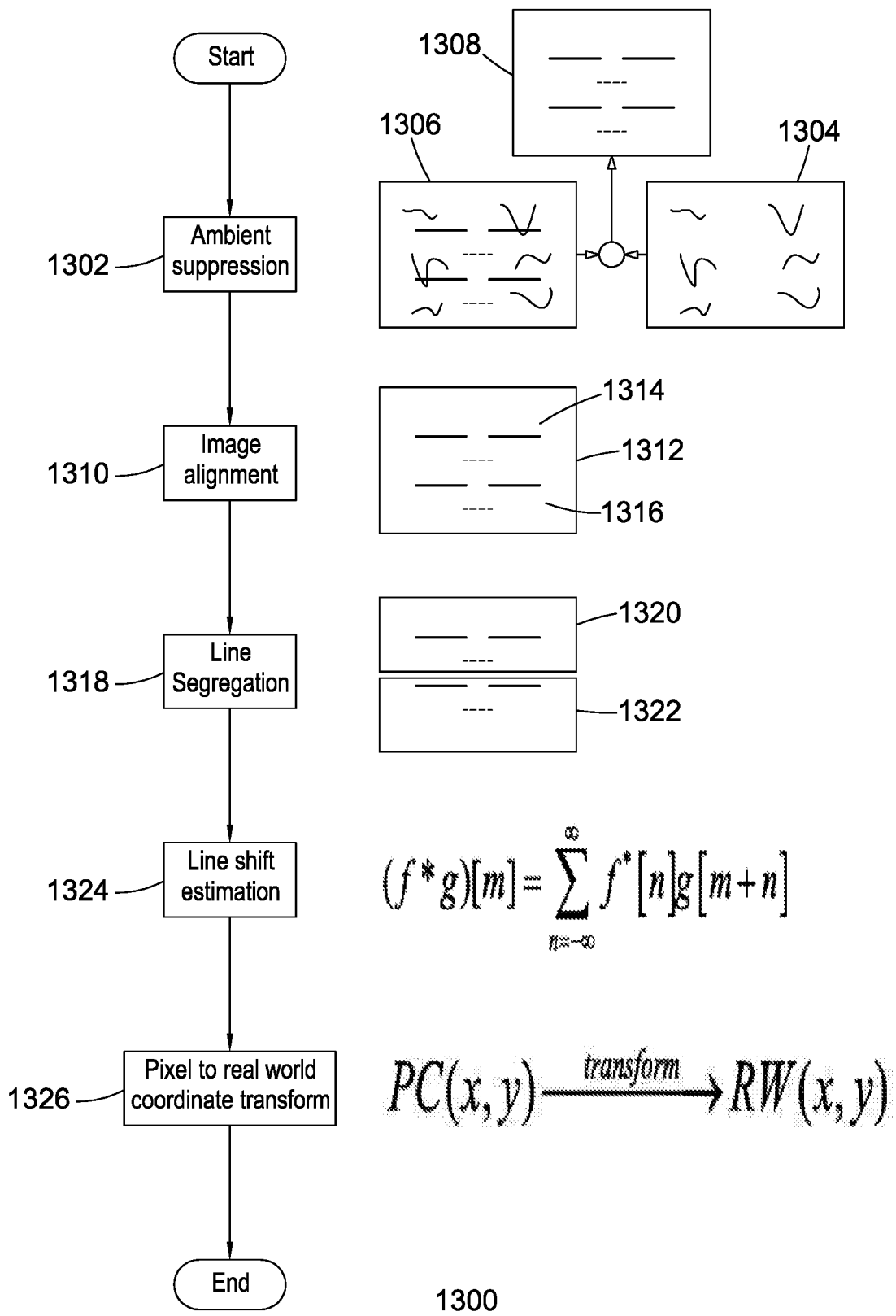


Fig. 13

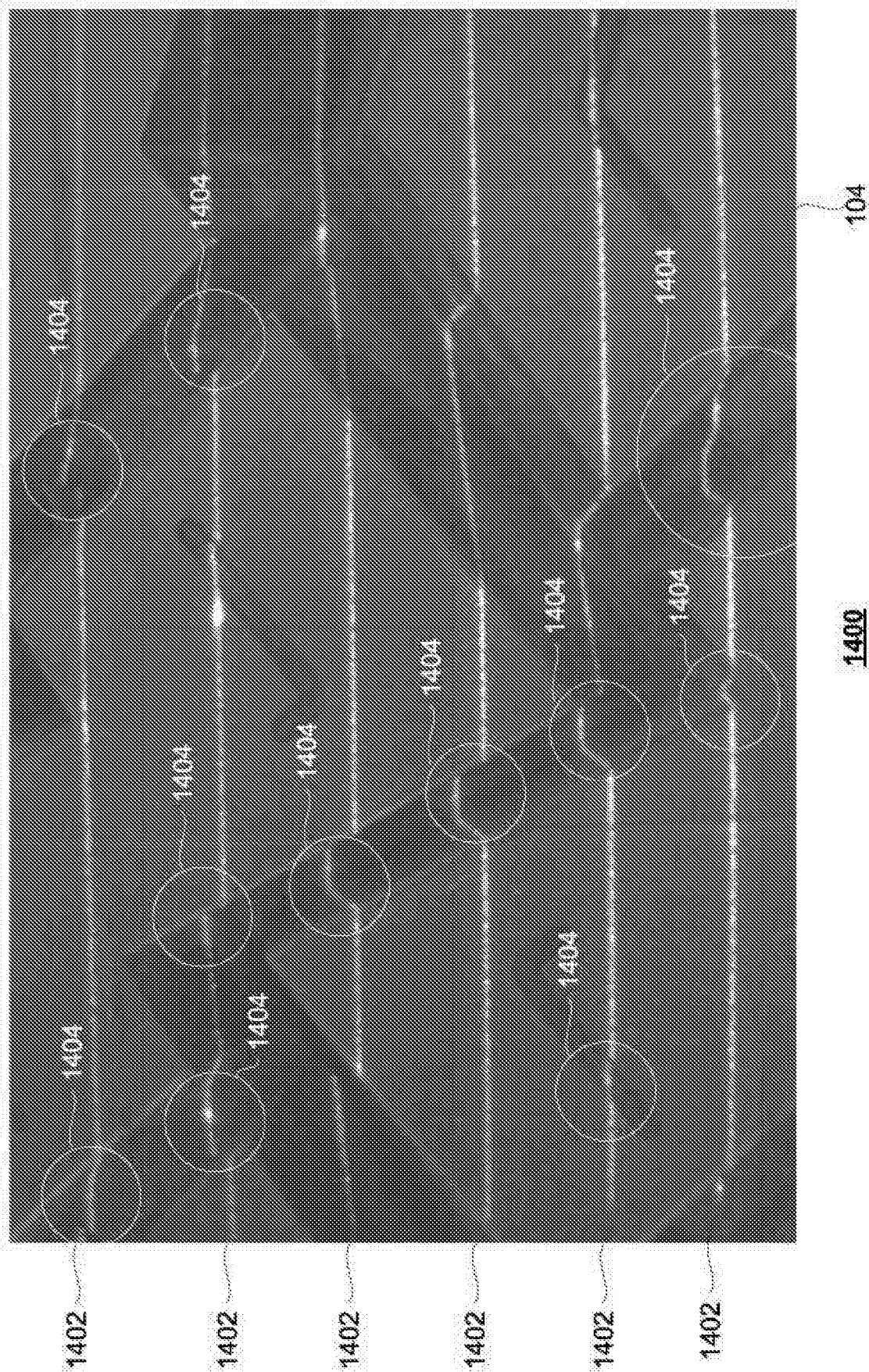


Fig. 14