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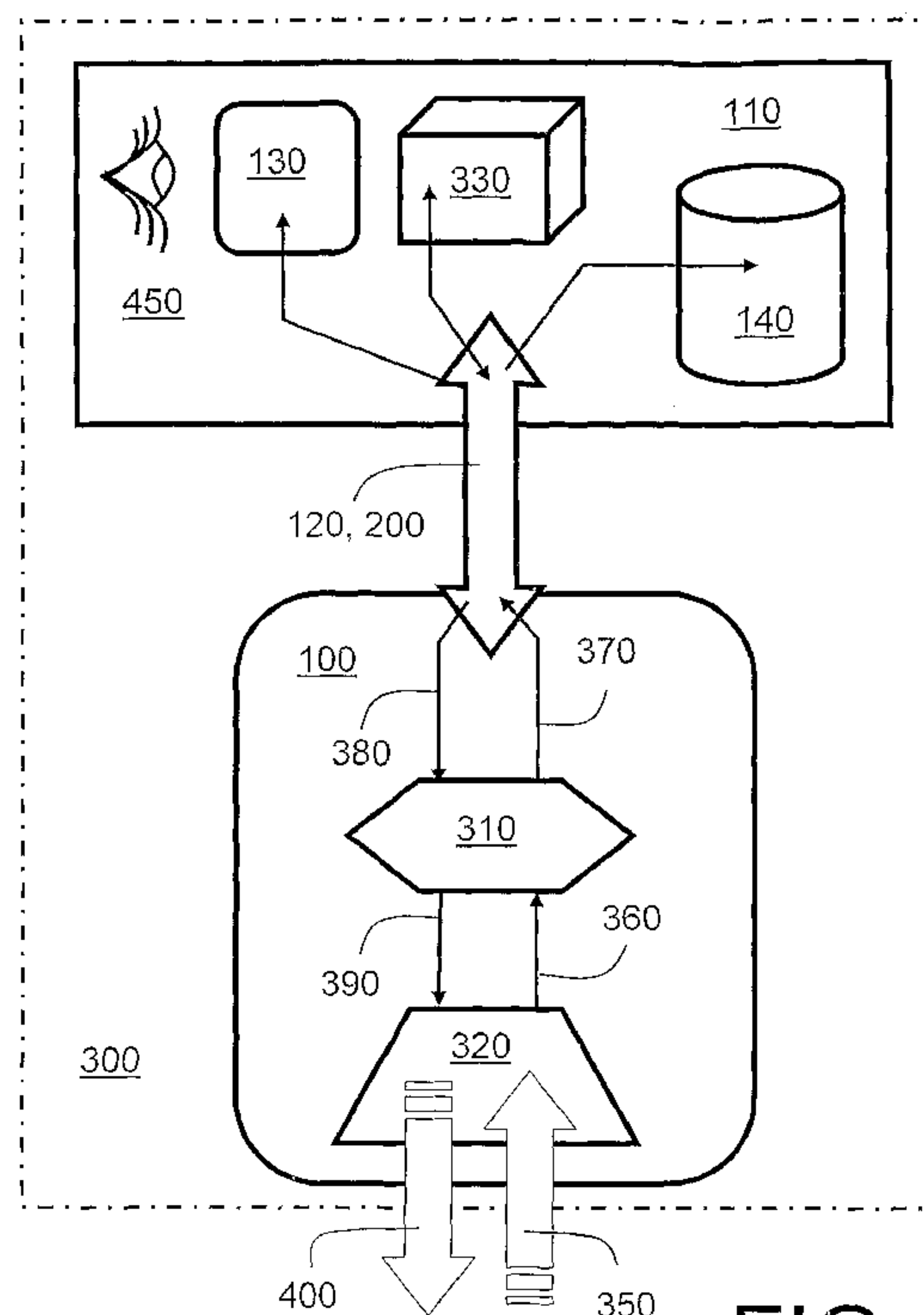
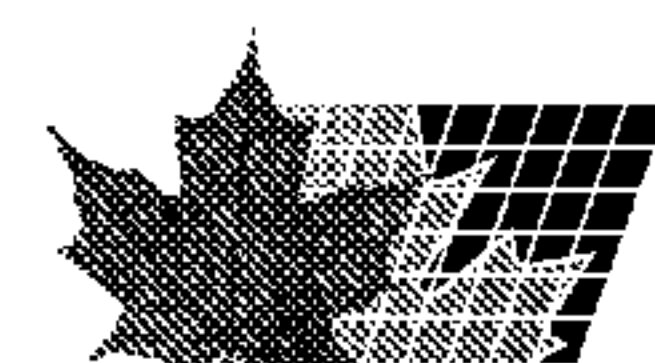


**FIG. 4**

(57) **Abrégé/Abstract:**

There is provided a monitoring system (300) for monitoring within a borehole (10). The system (300) comprises a probe assembly (100) operable to be moved within the borehole (10) for sensing one or more physical parameters therein, a data processing arrangement (110) located outside the borehole (10), and a data communication link (120) operable to convey sensor data indicative of the one or more physical parameters from the probe assembly (100) to the data processing arrangement (110) for subsequent processing and display and/or recording in data memory (140). The probe assembly (100) includes one or more



(57) **Abrégé(suite)/Abstract(continued):**

sensors (320) for spatially monitoring within the borehole (10) and generating corresponding sensor signals (360). Moreover, the probe assembly (100) includes a digital signal processor (310) for executing preliminary processing of the sensor signals (360) to generate corresponding intermediately processed signals (370) for communication via the data communication link (120) to the data processing arrangement (110). Furthermore, the data processing arrangement (110) is operable to receive the intermediately processed signals (370) and to perform further processing on the intermediately processed signals (370) to generate output data for presentation (130) and/or for recording in a data memory arrangement (140). The system (300) is of benefit in that it enables real-time spatial monitoring of the borehole (10) to be achieved.

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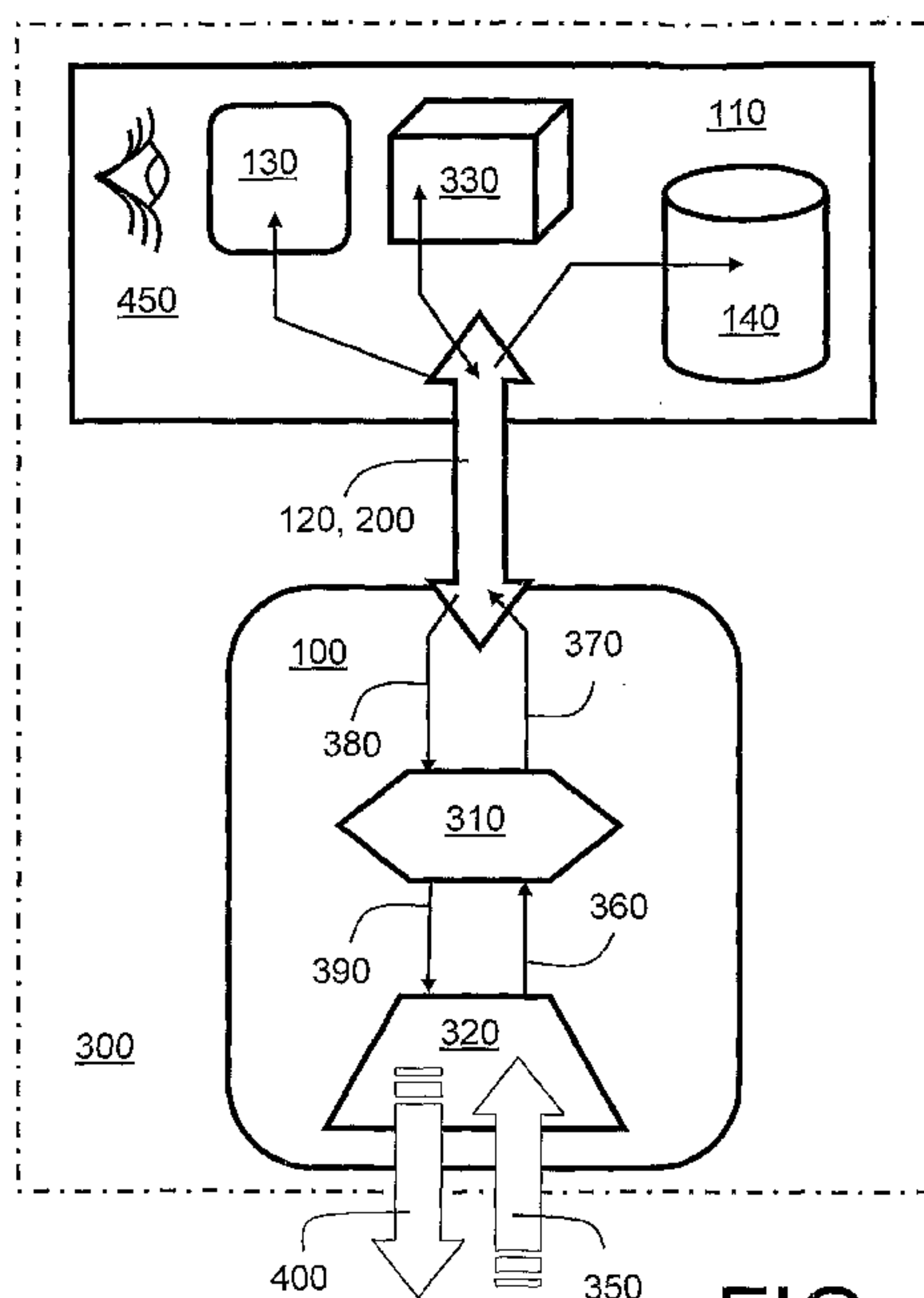


FIG. 4

(57) Abstract: There is provided a monitoring system (300) for monitoring within a borehole (10). The system (300) comprises a probe assembly (100) operable to be moved within the borehole (10) for sensing one or more physical parameters therein, a data processing arrangement (110) located outside the borehole (10), and a data communication link (120) operable to convey sensor data indicative of the one or more physical parameters from the probe assembly (100) to the data processing arrangement (110) for subsequent processing and display and/or recording in data memory (140). The probe assembly (100) includes one or more sensors (320) for spatially monitoring within the borehole (10) and generating corresponding sensor signals (360). Moreover, the probe assembly (100) includes a digital signal processor (310) for executing preliminary processing of the sensor signals (360) to generate corresponding intermediately processed signals (370) for communication via the data communication link (120) to the data processing arrangement (110). Furthermore, the data processing arrangement (110) is operable to receive the intermediately processed signals (370) and to perform further processing on the intermediately processed signals (370) to generate output data for presentation (130) and/or for recording in a data memory arrangement (140). The system (300) is of benefit in that it enables real-time spatial monitoring of the borehole (10) to be achieved.

## SYSTEM FOR SPATIALLY MONITORING A BOREHOLE IN REAL-TIME

5 **Field of the invention**

The present invention relates to monitoring systems, for example to monitoring systems for monitoring boreholes in connection with oil and/or gas exploration and/or extraction. Moreover, the present invention is concerned with methods of monitoring boreholes in connection with oil and/or gas exploration and/or extraction. Furthermore, the present invention also relates to software products for use in implementing these aforesaid methods.

**Background of the invention**

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Referring to Figure 1, a borehole indicated generally by **10** is formed in a region of ground **20** during gas and/or oil exploration. In an event that deposits of oil and/or gas are found substantially at an end of the borehole **10**, the borehole **10** provides a route by which the oil and/or gas deposits can be subsequently extracted. The borehole **10** is often several kilometres in depth and filled with liquid, for example:

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- (a) with drilling mud when executing boring operations during oil and/or gas exploration; and
- (b) with a multiphase mixture of oil, water and sand particles during subsequent oil extraction, namely during production.

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In such circumstances, a relatively elevated pressure is often encountered at the end of the borehole **10**, for example in an order approaching 1000 Bar. Moreover, on account of geothermal heating in lower strata of the region of ground **20**, an ambient temperature within the borehole **10** is susceptible to approaching 150 °C for more. Furthermore, the region of ground **20** is potentially porous and susceptible to fragmenting into quantities of gravel and similar types of sand particles.

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In order to successfully drill the borehole **10**, it is conventional practice to line the borehole **10** along at least part of its depth with one or more liner tubes **30a**, **30b**, **30c**, **30d**. The liner tubes **30a** to **30d** are operable, for example, to prevent water and other contaminants penetrating into the borehole **10** at upper regions of the ground **20**. Moreover, the liner tubes **30a**, **30b**, **30c**, **30d** are also operable to reduce leakage of oil and/or gas from the borehole **10**. For reasons of economy, the borehole **10** is drilled to have a diameter sufficient for

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accommodating drilling and/or extraction apparatus **50** as well as providing for gas and/or oil extraction; the borehole **10** is not made to be unnecessarily large because drilling time to form the borehole **10** and associated costs would thereby be unnecessarily increased. In practice, the liner tube **30a** is conveniently in an order of 200 mm in diameter.

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Many practical problems are often encountered when drilling the borehole **10**; moreover, subsequent problems can arise when extracting oil and/or gas via the borehole **10**. An example of such problems is that the liner tube **30a** develops one or more leakage holes. The one or more leakage holes are susceptible to enabling water and sand present in the  
10 region of ground **20** to penetrate into a central region of the liner tube **30a**; alternatively, the one or more leakage holes are susceptible to resulting in a loss for oil and/or gas from the liner tube **30a** into the ground **20**, thereby reducing yield of oil and/or gas from the borehole **10**. Moreover, the liner tube **30a** itself is potentially susceptible to becoming obstructed with deposits transported up the liner tube **30a**, for example sand/oil/tar deposits. Furthermore, a  
15 flow of liquid and/or gas in an external region between the liner tube **30a** and the ground **20** is also susceptible to occurring which can result in potential pollution, combustion risk and/or a loss of pressure within the borehole **10**; maintaining a high pressure in the borehole **10** is, for example, desirable for achieving an enhanced rate of oil and/or gas delivery from the borehole **10**. When aforementioned one or more leakage holes and/or obstructions occur  
20 many kilometres underground, it is often very difficult to know at an above-ground region **40** what precisely is happening in the ground **20** in respect of the borehole **10**. In view of the borehole **10** potentially costing many millions of dollars (US dollars) to drill and prepare for subsequent oil and/or gas extraction, reliable and efficient detection of defects arising in the borehole **10** is of considerable commercial importance. However, physical conditions within  
25 the borehole **10**, for example in lower regions thereof, are very hostile on account of abrasive particles present, high ambient temperatures in an order of 150 °C or more, high pressure approaching 1000 Bar and corrosive and/or penetrative fluids present in the borehole **10**.

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Various types of down-borehole tools are known, for example for measuring multiphase fluid composition within boreholes. Referring to Figure 2, certain implementations of these tools each comprise a probe assembly **100** operatively inserted into the borehole **10** to be monitored, a data processing arrangement **110** in the above-ground region **40**, and a flexible communication link **120** mutually coupling together the data processing arrangement **110** and the probe assembly **100**. In operation, the probe assembly **100** senses one or more  
35 parameters within the borehole **10**, for example temperature and/or pressure therein, using one or more sensors to generate one or more sensor signals which are then communicated via the communication link **120** to the data processing arrangement **110**. At the data

processing arrangement **110**, the one or more sensor signals are at least one of: displayed on a display **130** in real-time, recorded in a data memory or data base **140** for subsequent analysis. Implementations of the tools, for example as illustrated in Figure 2, optionally enable real-time monitoring of boreholes to be achieved. A sliding fluid seal (not shown in  
5 Figure 2) is formed at the top of borehole **10** around a cable implementing the communication link **120** so as to seal the borehole **10** in an event that the borehole **10** is operating under excess pressure, for example as a result the borehole **10** intercepting a gas deposit in the ground region **20**.

10 Alternatively, as illustrated in Figure 3, other implementations of these tools each comprise the probe assembly **100** which additionally includes a semiconductor data memory **150** locally therein for recording signals generated by one or more sensors of the probe assembly **100** in a first step S1 when the probe assembly **100** is employed to characterize the borehole **10**. In such an implementation, the probe assembly **100** is operable to function as an  
15 autonomous apparatus which is moved substantially blindly within a borehole **10** to collect data therefrom. In a step S2, the probe assembly **100** is then subsequently extracted from the borehole **10** to the above-ground region **40**, whereat the probe assembly **100** is coupled to its associated data processing arrangement **110** for downloading monitoring data thereto, as denoted by **160**, namely from the data memory **150** of the probe assembly **100** to the data  
20 processing arrangement **110**.

A technical problem is encountered when the probe assembly **100** in Figure 2 is employed to spatially inspect, for example by employing one or more optical cameras, an inside of a borehole **10** on account of a considerable amount of corresponding data which is generated.

25 Measurements such as one or more temperatures within the borehole **10**, one or more pressures within the borehole **10**, and phase composition of fluid within the borehole **10** generally generate significantly less corresponding amounts of data in comparison to executing three-dimensional spatial inspection, for example 360° two-dimensional imaging and imaging resulting in perspective images of an inside of the borehole **10** being generated.  
30 In consequence, when spatial inspection is to be performed, severe technical demands are placed upon communication performance of the aforesaid communication link **120** in respect of data bandwidth, or upon data memory capacity which must be provided robustly within the probe assembly **100** when operated in an autonomous manner.

35 It is thus desirable to be able to spatially inspect, in real-time, an inside of a borehole by using a probe assembly. On detection of a defect such as a leakage hole or obstruction, it is desirable for the probe assembly to be maintained in a locality of the defect for a longer

period to sample an enhanced amount of data, thereby enabling the defect to be identified and characterized to a greater degree of certainty. By identifying and characterizing one or more defects to a greater degree of certainty, repair or mitigation of the one or more defects are susceptible to being implemented in a more efficient and selective manner.

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A technical problem which the present invention therefore addresses is at least partially resolving conflicting constraints of, firstly, real-time monitoring of a borehole and, secondly, providing spatial inspection of the borehole which have hitherto seemed impossible to adequately resolve.

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### Summary of the invention

An object of the present invention is to provide an improved monitoring system which is operable to enable real-time monitoring of boreholes whilst also enabling spatial inspection of boreholes to be achieved.

According to a first aspect of the invention, there is provided a monitoring system as claimed in appended claim 1: there is provided a monitoring system for monitoring within a borehole, the system comprising a probe assembly operable to be moved within the borehole for sensing one or more physical parameters therein, a data processing arrangement being located outside the borehole, and a data communication link operable to convey sensor data indicative of the one or more physical parameters from the probe assembly to the data processing arrangement for subsequent processing and display and/or recording in data memory,

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characterized in that

- (a) the probe assembly includes one or more sensors for spatially monitoring within the borehole and generating corresponding sensor signals;
- (b) the probe assembly includes a digital signal processor for executing preliminary processing of the sensor signals to generate corresponding intermediately processed signals for communication via the data communication link to the data processing arrangement; and
- (c) the data processing arrangement is operable to receive the intermediately processed signals and to perform further processing on the intermediately processed signals to

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generate output data for presentation and/or for recording in a data memory arrangement.

5 The invention is of advantage in that preliminary processing executed within the digital signal processor is capable of reducing a quantity of measurement data to be communicated, thereby rendering possible real-time spatial monitoring of the borehole.

Thus, beneficially, the system is operable to generate the output data for presentation in real-time when the probe assembly is moved within the borehole.

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Optionally, the system is implemented to be operable in at least one of first and second modes, wherein:

- (a) the first mode results in the system passively sensing noise sources present in the borehole generating radiation for sensing at the one or more sensors; and
- 15 (b) the second mode results in the system actively emitting radiation into the borehole and receiving at the one or more sensors corresponding reflected radiation from a region in and/or around the borehole for generating the sensor signals.

20 The first mode is of benefit in that it enables sources of noise, for example leakage holes, failed seals, cracks and other types of defect through which fluids are capable of flowing and generating acoustic noise, to be detected.

25 More optionally, the system is operable to be dynamically reconfigurable between the first and second modes when the probe assembly is being moved in operation within the borehole. Such a feature to be able to dynamic reconfigure the system enables the system to detect in real-time a greater range of types of features and defects. However, the system is optionally adapted for operating specifically solely in the first mode or in the second mode.

30 Optionally, the system is operable to communicate data bi-directionally between the data processing arrangement and the probe assembly, wherein the digital signal processor of the probe assembly is operable to be reconfigured between a first function of generally sensing around in a region of the borehole in a vicinity of the probe assembly, and a second function of specific sensing in a sub-region of the region of the borehole in a vicinity of the probe assembly. Bi-directional communication enables the probe assembly to be reconfigured to occasionally concentrating on sensing certain sub-regions of the borehole of special interest, thereby using finite communication bandwidth provided by the communication link in an efficient manner.

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Optionally, the system is implemented such that the one or more sensors are implemented as one or more ultrasonic transducer arrays disposed at one or more positions on the probe assembly including:

- 5 (a) as an array at a bottom surface of the probe assembly facing down the borehole when the probe assembly is inserted into the borehole in operation;
- (b) one or more ring formations at one or more ends of the probe assembly, or radially around an radial side wall of the probe assembly; and
- (c) in one or more rows or one or more spiral formations around a peripheral surface of  
10 the probe assembly in a substantially longitudinal direction along the probe assembly.

Optionally, the system is operable to process the sensor signals and compare the processed signals with one or more signal templates for automatically detecting features present in the borehole which are encountered in operation by the probe assembly. Such comparison is  
15 optionally based upon correlation and/or neural network analysis techniques.

Optionally, the system is implemented such that the data communication link comprises one or more twisted-wire pairs including plastics material insulation and copper electrical conductors embedded within the plastics material, the data communication link being clad by  
20 cladding susceptible to bearing a weight of the probe assembly when the assembly is moved in operation within the borehole. Use of twisted pairs is of benefit in providing a reliable and stable line impedance for electrical signals and thereby substantially avoiding end reflections of electrical signals when appropriately-matched line drivers and receivers are employed, whilst providing a mechanically robust implementation when the probe assembly is  
25 manoeuvred in the borehole.

Optionally, the system is implemented such that the data communication link comprises one or more twisted-wire pairs including plastics material insulation and copper electric conductors embedded within the plastics material, the data communication link being  
30 provided with an associated mechanical element susceptible to bearing a weight of the probe assembly when the assembly is moved in operation within the borehole.

Optionally, the monitoring system is implemented such that the data processing arrangement is located in operation remotely from the probe assembly, the data processing arrangement  
35 providing an interface for one or more users to control in real-time operation of the probe assembly, and for generating graphical images for presenting on one or more displays to the

one or more users, the graphical images being representative of spatial features present within and/or around the borehole in a vicinity of the probe assembly.

According to a second aspect of the invention, there is provided a method of monitoring  
5 within a borehole as claimed in appended claim 11: there is provided a method of monitoring within a borehole by using a monitoring system, the system comprising a probe assembly operable to be moved within the borehole for sensing one or more physical parameters therein, a data processing arrangement located outside the borehole, and a data communication link operable to convey sensor data indicative of the one or more physical  
10 parameters from the probe assembly to the data processing arrangement for subsequent processing and display and/or recording in data memory,

characterized in that the method includes steps of:

- 15 (a) spatially monitoring using one or more sensors of the probe assembly within the borehole and generating corresponding sensor signals;
- (b) using a digital signal processor included in the probe assembly, executing preliminary processing of the sensor signals for generating corresponding intermediately processed signals;
- 20 (c) communicating via the data communication link the intermediately processed signals to the data processing arrangement; and
- (d) receiving the intermediately processed signals at the data processing arrangement for performing further processing on the intermediately processed signals for generating output data for presentation and/or for recording in a data memory  
25 arrangement.

Optionally, the method includes a further step of:

- (e) generating using the system the output data for presentation in real-time when the probe assembly is moved within the borehole.

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Optionally, the method is implemented such that the monitoring system is operable in at least one of first and second modes, wherein:

- (a) the first mode results in the system passively sensing noise sources present in the borehole generating radiation for sensing at the one or more sensors; and
- 35 (b) the second mode results in the system actively emitting radiation into the borehole and receiving at the one or more sensors corresponding reflected radiation from a region in and/or around the borehole for generating the sensor signals.

More optionally, the method includes a further step of dynamically reconfiguring the system between the first and second modes when the probe assembly is being moved in operation within the borehole. Such dynamic reconfiguring enables more diverse types of features to be monitored substantially simultaneously using the system in real-time.

Optionally, the method includes a step of:

(f) communicating data bi-directionally between the data processing arrangement and the probe assembly, wherein the digital signal processor of the probe assembly is operable to being reconfigured between a first function of generally sensing around in a region of the borehole in a vicinity of the probe assembly, and a second function of specific sensing in a sub-region of the region of the borehole in a vicinity of the probe assembly.

Optionally, when implementing the method, the one or more sensors are implemented as one or more ultrasonic transducer arrays disposed at one or more positions on the probe assembly including:

- (a) as an array at a bottom surface of the probe assembly facing down the borehole when the probe assembly is inserted into the borehole in operation;
- (b) one or more ring formations at one or more ends of the probe assembly, or radially around an radial side wall of the probe assembly;
- (c) in one or more rows or one or more spiral formations around a peripheral surface of the probe assembly in a substantially longitudinal direction along the probe assembly.

Optionally, the method includes a further step of:

- (g) processing the sensor signals to generate corresponding processed signals; and then
- (h) comparing the processed signals with one or more signal templates for automatically detecting features present in the borehole which are encountered in operation by the probe assembly.

Optionally, when employing the method, the data communication link is beneficially implemented using one or more twisted-wire pairs including plastics material insulation and copper electric conductors embedded within the plastics material, the data communication link being clad by cladding susceptible to bearing a weight of the probe assembly when the assembly is moved in operation within the borehole. Such an implementation of the data communication link is susceptible to providing a suitable compromise between data communication rate, robustness and acceptable manufacturing cost, especially bearing in

mind that the communication link and its associated cladding is potentially many kilometres long and has to be able to bear its own weight.

Optionally, when employing the method, the data communication link is beneficially implemented using one or more twisted-wire pairs including plastics material insulation and copper electric conductors embedded within the plastics material, the data communication link being provided with a mechanical element susceptible to bearing a weight of the probe assembly when the assembly is moved in operation within the borehole.

10 Optionally, the method includes a step of:

- (i) locating the data processing arrangement in operation remotely from the probe assembly, the data processing arrangement providing an interface for one or more users to control in real-time operation of the probe assembly, and for generating graphical images for presentation on one or more displays to the one or more users, the graphical images being representative of spatial features present within and/or around the borehole in a vicinity of the probe assembly.

According to a third aspect of the invention, there is provided a computer software product recorded on a data carrier, the computer software product being executable on computing hardware for implementing a method pursuant to the second aspect of the invention.

According to a fourth aspect of the invention, there is provided a probe assembly for monitoring in a borehole, the probe assembly being adapted for use in the system pursuant to the first aspect of the invention.

Features of the invention are susceptible to being combined in any combination without departing from the scope of the invention as defined by the appended claims.

### 30 **Description of the diagrams**

Embodiments of the present invention will now be described, by way of example only, with reference to the following diagrams wherein:

35 **Figure 1** is an illustration of a borehole furnished with a liner tube arrangement;

Figure 2 is a schematic illustration of a down-borehole probe arrangement for sensing physical parameters within a borehole and generating corresponding signals for communicating in real-time to a data processing arrangement remote from the borehole;

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Figure 3 is a schematic illustration of a down-borehole probe arrangement for sensing physical parameters within a borehole and generating corresponding signals for data-logging locally within a probe assembly, for subsequent down-loading to a data processing arrangement when the probe assembly has been extracted from the borehole;

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Figure 4 is a schematic illustration of a monitoring system pursuant to the present invention for monitoring down boreholes;

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Figure 5 is a more detailed illustration of component parts of the system in Figure 4, the components including a transducer array for receiving ultrasonic radiation from boreholes, and optionally for also interrogating such boreholes;

Figure 6 is an illustration of polar sensing angles of the transducer array of Figure 5;

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Figures 7a and 7b are illustrations of signals present in the system of Figure 4 when in operation;

Figure 8 is a flow diagram of signal processing operations executed within the system of Figure 4; and

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Figure 9 is an illustration of a probe assembly of the system of Figure 4 providing examples of configurations of transducer array which are optionally included in the probe assembly.

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### Description of embodiments of the invention

In overview, embodiments of the present invention include principal features akin to Figure 2, namely:

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(a) a probe assembly **100** for spatially sensing within a borehole **10**;

(b) a communication link **120** whose associated cladding or mechanical structural core is operable to mechanically support the probe assembly **100** when deployed within the borehole **10**, and whose signal guiding components are operable to convey signals transmitted from the probe assembly **100**, and to convey control signals to the probe assembly **100**;

(c) a data processing arrangement **110** coupled via the communication link **120** to the probe assembly **100**, the data processing arrangement **110** being operable to receive signals from the probe assembly **100** and to send instruction signals to the probe assembly **100**.

The probe assembly **100**, the communication link **120** and the data processing arrangement **110** constitute a system as denoted by **300** in Figure 4; the system **300** constitutes an embodiment of the present invention.

The system **300** is distinguished from subject matter presented and described in respect of Figure 2 in that:

(a) the probe assembly **100** includes a transducer array **320** comprising one or more sensors coupled via a digital signal processor (DSP) **310** and then via the communication link **120** to the data processing arrangement **110**; and

(b) the data processing arrangement **110** includes a data processor **330** which is operable to receive data from the probe assembly **100** via the communication link **120**; the data processor **330** is also operable to send control commands via the communication link **120** to reconfigure the digital signal processor (DSP) **310**, for example in response to one or more signals generated in operation by the transducer array **320**.

The system **300** is optionally susceptible to operating in at least one of a first passive mode and a second active mode.

In the first passive mode, one or more physical signals **350** that are generated in an environment of the borehole **10** propagate within the borehole **10** and are eventually received by the transducer array **320**. The transducer array **320** generates one or more corresponding electrical signals **360** which are conveyed to the digital signal processor (DSP) **310**. Thereafter, the digital signal processor **310** performs primary processing of the one or more electrical signals **360** to generate corresponding intermediate processed signals **370** which are communicated via the communication link **120** to the data processor **330**. The data processor **330** then performs secondary processing on the intermediate processed signals **370** to generate corresponding output data. Moreover, the data processor **330** is optionally operable to store at least part of the intermediate processed signals **370** in the

data memory **140**. Moreover, the data processor **330** is optionally operable to store at least part of the output data in the data memory **140**. Moreover, the data processor **330** is operable to present the output data on the display **130**.

5 In the second active mode, the data processor **330** is operable to send control signals **380** to the digital signal processor (DSP) **310** to drive the transducer array **320** with one or more drive signals **390** to cause the transducer array **320** to emit radiation **400** into the borehole **10**. Optionally, the emitted radiation **400** is pulsed radiation comprising pulses punctuated by quiet periods; portions of the radiation **400** reflected from structures within and in near  
10 proximity to the borehole **10** are received back at the transducer array **320** as the one or more physical signals **350** to generate the corresponding one or more electrical signals **360** which are subsequently processed in the digital signal processor **310** to subsequently generate the intermediate processed signals **370**. The data processor **330** then performs secondary processing of the intermediate processed signals **370** to generate corresponding  
15 output data. Moreover, the data processor **330** is optionally operable to store at least part of the intermediate processed signals **370** in the data memory **140**. Moreover, the data processor **330** is optionally operable to store at least part of the output data in the data memory **140**. Moreover, the data processor **330** is operable to present the output data on the display **130**.

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The system **300** is optionally designed to be able to switch dynamically between the aforementioned first passive mode and second active mode. Alternatively, the system **300** is optionally designed to function only in the first passive mode, for example optimized to function in the first passive mode. Yet alternatively, the system **300** is optionally designed to  
25 function only in the second active mode, for example optimized to function in the second active mode.

It will be appreciated from the foregoing that the system **300** is operable to distribute data processing activities between the digital signal processor **310** and the data processor **330**.  
30 Such a distribution of data processing activities is of benefit in that data reduction within the probe assembly **100** is feasible to achieve so that available bandwidth of the communication link **120** is not occupied by data which bears relatively irrelevant information. By such data reduction, for example achieved by various data compression techniques which will be described in more detail later, it becomes feasible to provide real-time images of the  
35 borehole **10** on the display **130** at a sampling rate which is practical for the probe assembly **100** to be moved at an acceptably fast velocity up or down the borehole **10** for investigating defects therein or in a vicinity thereof. When the borehole **10** is many kilometres in length,

an inspection rate when using the system **300** beneficially corresponds to several metres per second along the borehole **10**. It is desirable that the system **300** is operable to perform metrology on the borehole **10** within a time period of 1 to 20 hours when the borehole **10** has a length in an order of kilometres. When the borehole **10** is implemented for gas extraction, the system **300** is susceptible to being used concurrently with gas extraction being performed.

The system **300** has been described in overview in the foregoing. However, before describing component parts of the system **300** in greater detail, other issues regarding the probe assembly **100** will next be elucidated. The borehole **10** is often at a pressure  $P$  which, in certain circumstances, can approach 1000 Bar. For example, the borehole **10** can often be many kilometres deep and filled with water, or with an abrasive multiphase mixture including oil, water and rock particles. When the probe assembly **100** is lowered into the borehole **10** filled with liquid to a depth of a kilometre or more, the pressure  $P$  acting upon the probe assembly **100** is potentially enormous. In such circumstances, a leakage hole in the liner tube **30a** with many Bar differential pressure between a first region outside the liner tube **30a** to a second region inside the liner tube **30a** potentially results in a considerable flow of fluid between the first and second regions causing turbulent generation of acoustic radiation from a vicinity of the leakage hole. It is also feasible in certain situations that the borehole **10** is filled with gas at a high pressure approaching 1000 Bar on account of the borehole **10** intercepting a gas reservoir. Such high pressures in the borehole **10** risk forcing gas or liquid to ingress into an inside region of the probe assembly **100** and can also force gas into a polymeric material from which the cladding **200** is fabricated. For example, if the cladding is fabricated from polymeric material and is suddenly depressurized from a high pressure of 1000 Bar pressure to nominal atmospheric pressure of 1 Bar (760 mm Hg), gas forced by such a high pressure to earlier ingress into interstitial spaces within the polymeric material is susceptible to cause the polymeric material to expand to form a foam-like material with microvoids therein, potentially resulting in permanent damage to the polymeric material. Optionally, as illustrated in Figure 1, the inner liner tube **30a** includes a seal around a top region thereof as illustrated in Figure 1 when the borehole **10** is required in operation to exhibit an elevated pressure relative to ambient atmospheric pressure of nominally substantially 1 Bar (760 mm Hg). The seal is beneficially adapted to be capable of sealing around the cladding **200**, for example in a sliding manner, when the probe assembly **100** is deployed within the borehole **10**. Although a use of a polymeric material to form the cladding **200** to clad the communication link **120** is virtually unavoidable, a casing of the probe assembly **100** is beneficially fabricated from a robust material which is resistant to abrasion and corrosion, for example fabricated from machined solid stainless steel material or

seamless stainless steel tubing. Alternatively, or additionally, at least a portion of the probe assembly **100** can be fabricated from more exotic materials, for example advanced rigid polymer materials, silicon nitride material, and/or ceramic material for example.

5 The transducer array **320** is beneficially implemented as an array of one or more piezo-electric elements, for example fabricated from lead zirconate titanate (PZT) or similar strongly piezo-electric material. In operation, the transducer array **320** is susceptible to being excited by the one or more drive signals **390** applied thereto to generate the radiation **400** as ultrasonic radiation, and also susceptible to receive the radiation **350** as reflected ultrasonic  
10 radiation for generating aforesaid one or more electrical signals **360**. Piezo electric material of the transducer array **320** is optionally directly in physical contact with fluid present within the borehole **10** in order to obtain most efficient coupling of ultrasonic radiation. Alternatively, the transducer **320** is operable to communicate with the interior region of the borehole **10** via one or more interfacing windows.

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On account of the borehole **10** being potentially heated up to a temperature  $T$  approaching  $150\text{ }^{\circ}\text{C}$  by geothermal energy in rock formations surrounding the borehole **10**, there is a potentially severe limitation regarding power dissipation which can occur within the probe assembly **100** when in operation. When the probe assembly **100** is operating pursuant to the  
20 aforesaid second active mode, generating the one or more drive signals **390** in drive amplifiers is susceptible to resulting in electrical power dissipation within the probe assembly **100**. Moreover, data processing occurring in operation in the digital signal processor (DSP) **310** is susceptible to causing additional dissipation in both the first passive mode and in the second active mode.

25

Optionally, the digital signal processor (DSP) **310** is provided with one or more Peltier cooling elements for optionally cooling the signal processor **310**; however, use of the one or more Peltier cooling element is susceptible to adding to a total dissipation occurring within the probe assembly **100** and is therefore only employed selectively where effective cooling of the  
30 processor **310** is susceptible to being thereby achieved.

The digital signal processor (DSP) **310** is beneficially implemented using semiconductor devices based upon CMOS technology which are not vulnerable to thermal runaway as a result of increase in minority-carrier currents therein during operation. Similarly, the drive  
35 amplifiers employed within the probe assembly **100** to provide the one or more drive signals **390** are beneficially also based upon MOSFET devices which are capable of operating at elevated temperatures approaching  $200\text{ }^{\circ}\text{C}$  without suffering thermal runaway.

Alternatively, or additionally to employing the one or more Peltier cooling elements, the signal processor **310** is implemented using several integrated circuits to spread power dissipation and therefore try to avoid hot-spots wherein a silicon die of an integrated circuit is at an elevated temperature relative to its local environment on account of dissipation occurring within the die during operation. Optionally, the several integrated circuits are fabricated as a hybrid module, for example including a ceramic substrate providing a low thermal resistance path to an ambient environment within the probe assembly **100**.

On account of the liner tube **30a** having an inside diameter in an order of 200 mm, the probe assembly **100** is manufactured to have a diameter in a range of 100 mm to 180 mm, more preferably to have a diameter of substantially 150 mm. Moreover, the cladding **200** of the communication link **120** is optionally required to be strong enough to bear a weight of the probe assembly **100** when lowered kilometres down the borehole **10** including a weight of the cladding itself; alternatively, or additionally, one or more mechanical supporting elements, for example one or more high-tensile steel ropes, are optionally employed to bear a weight of the probe assembly **100** when deployed in the borehole **10**. If the cladding **200** is relatively larger in diameter, for example 25 mm or greater in diameter, it becomes too massive and is difficult to bend around pulleys of feed hoists above the borehole **10**. Conversely, if the cladding **200** is relatively small in diameter, for example 4 mm or smaller in diameter, the cladding **200** is susceptible to becoming snarled on projections forming in operation on an inside-facing surface of the borehole **10** and is potentially unable to reliably bear its own weight and also the weight of the probe assembly **100**. In practice, with modern advanced cladding materials, for example by using one or more of carbon fibres, Kevlar and advanced nano-material fibres, it is feasible to provide sufficient robustness for the cladding **200** when the cladding has a diameter in a range 5 mm to 15 mm, more preferable a diameter in a range of 6 mm to 10 mm, and most preferably a diameter of substantially 8 mm.

In operation, the cladding **200** is susceptible to exhibiting strain when a stress arising from weight is applied thereto. Optical fibres are not robust to stretching and can potentially be fractured when undergoing even modest longitudinal strain. In consequence, the communication link **120** is implemented as one or more electrical twisted pairs of wires. Optionally, the one or more electrical twisted pairs of wires are included within one or more overall electrically-conductive braided screens or similar. The wires each include plastics material insulation which is capable of stretching under stress. Moreover, each wire includes copper conductors therein; copper is a ductile metal of relatively low weight, of high electrical conductivity, of relatively high resistance to oxidative corrosion, and is less prone to work

hardening when subjected to repeated bending cycles in comparison to other metals. At each end of the communication link **120** is included Ethernet line drivers matched to a transmission-line impedance of the one or more twisted-wire pairs of the communication link **120**; data is thereby bi-directionally communicated in operation along the communication link **120** which is capable of enabling a data flow of several hundred kbytes per second to be supported. It is however to be bourn in mind that conventional real-time streaming of two-dimensional video images often requires a communication bandwidth in the order of MHz.

The data processing arrangement **110** is implemented as a configuration of proprietary components and is susceptible to being installed: on-land, on a sea-going vessel, in a submarine, on an oil exploration platform, or on an air-borne vehicle via an additional wireless link. The data processor **330** and the display **130** are beneficially implemented using proprietary computing hardware; the data processor **330** beneficially has a data entry device, for example a keyboard and a computer tracker-ball mouse, for enabling one or more users **450** to control operation of the system **300** in real-time. The data processor **330** is coupled in communication with the data memory **140** which is conveniently implemented by using at least one of: semiconductor memory, optical data memory, magnetic data memory.

Operation of the system **300** will now be described in greater detail.

During exploratory drilling activities for gas and/or oil, expensive and complex equipment is used under the supervision of experienced technical staff. In consequence, drilling and lining the borehole **10** with the liner tubes **30** is an extremely expensive activity, for example often costing in a region of a million United States dollars per day. When such high costs are encountered, problems occurring within the borehole **10** need to be identified quickly and resolved promptly. Even an operation of removing a drill bit and its associated string from the borehole **10** is a major undertaking, in some cases corresponding to several days of expensive work. When applied to monitor the borehole **10**, for example after removal of a drill bit and associated drive string therefrom, the system **300** needs to be highly reliable, susceptible to being rapidly deployed into the borehole **10**, and to provide flexibility in use by way of real-time monitor to avoid a need to repeatedly reinsert the probe assembly **100** into the borehole **10** when performing metrology thereon and monitoring thereof.

Referring to Figure 5, the transducer array **320** comprises an array of one or more piezo-electric transducer elements **460** operable to at least receive ultrasonic radiation denoted by the radiation **350** from the borehole **10**; there are  $n$  transducer elements in the transducer array **320**, wherein a number  $n$  is beneficially in a range of one to several thousand, more

preferable a plurality of transducer elements. As elucidated in the foregoing, the radiation **350** is generated by one or more processes occurring in the borehole **10** when the system **300** is operating in the first passive mode, and is generated by reflection of the radiation **400** when the system **300** is operating in the aforesaid second active mode. As described earlier,  
 5 the array of transducer elements **460** optionally ultrasonically communicate via an interfacing member **452** which transmits ultrasonic radiation therethrough as well as protects the transducer elements **460** from a harsh environment within the borehole **10**.

The one or more transducer elements **460** in the transducer array **320** are operable to  
 10 generate signals  $S_i e^{j\omega t}$  wherein  $i$  is in a range of 1 to  $n$ ; the signals  $S_i$  correspond to the electrical signals **360** described earlier. Beneficially, one or more of the transducer elements **460** are operable to emit and/or receive ultrasonic radiation having a frequency in a range of 100 kHz to 10 MHz when the system is operating pursuant to the second active mode, and more preferably in a range of 500 kHz to 5 MHz. Such a frequency range is of benefit it that  
 15 individual transducer elements are susceptible to being implemented in a compact manner and that ultrasound at such frequency has a relatively short wavelength in an order of 1 mm. Conversely, one or more of the transducer elements **460** are operable to receive ultrasonic radiation having a frequency in a range of a few hundred Hz to several hundred kHz when the system **300** is functioning in the first passive mode, depending on which type of  
 20 monitoring is to be performed within the borehole **10**. The digital signal processor **310** is operable to condition one or more of the signals  $S_i$  in a manner of a phased array algorithm to steer a direction of greatest sensitivity of the transducer array **320**. Such steering is achieved by performing two principal steps in the digital signal processor **310**.

25 The first step of beam forming involves selectively phase shifting and scaling the signals  $S_i$  under control of various control parameters. Moreover, the first step is performed in computing hardware of the digital signal processor **310** operable to execute a software product stored on a data carrier, for example the data carrier being a non-volatile semiconductor data memory associated with the digital signal processor **310**. In the first  
 30 step, the signals  $S_i$  are subject to scaling and phase shifting operations as defined by Equation 1 (Eq. 1) to generate corresponding intermediate processed signals  $H_i$ :

$$H_i = A_i S_i e^{j\omega t} e^{\cos \theta_i + j \sin \theta_i} \quad \text{Eq. 1}$$

35 wherein

$j =$  square route of -1;

$\omega$  = angular frequency of signal component of interest;  
 $t$  = time;  
 $\theta_i$  = phase shift applied for beam forming purposes;  
 $A_i$  = scaling coefficient for beam forming purposes.

5

The second step of beam forming selectively summing one or more of the intermediate processed signals  $H_i$  as defined by Equation 2 (Eq. 2) to generate corresponding signals  $B_{\alpha, \beta}$  representative of a component of radiation received at the transducer array **320** from a specific direction as follows:

10

$$B_{\alpha, \beta} = \sum_{i=r}^s H_i \quad \text{Eq. 2}$$

wherein

$\alpha, \beta$  = angles define the specific direction relative to an orientation of the transducer array **320** in which the transducer array **320** is preferentially sensitive for generating the signal  $B_{\alpha, \beta}$ ; and

15

$r, s$  = index values defining which intermediate signals  $H_i$  to be selectively summed to generate the signal  $B_{\alpha, \beta}$ .

The signals  $H_i$  to be summed optionally do not necessarily need to lie consecutively in series of index value  $i$ ; for example appropriate scaled and phase-shifted signals  $S_i$  for  $i = 1, 10, 12, 15$  can be selectively combined to generate the signal  $B_{\alpha, \beta}$ . The angles  $\alpha$  and  $\beta$  are susceptible to being defined, for example, as illustrated in Figure 6. A mathematic mapping relates the angles  $\alpha, \beta$  to corresponding phase shift  $\theta_i$  and scaling coefficient  $A_i$  are denoted by function  $G$  in Equation 3 (Eq. 3):

20

25

$$(\theta, A) = G(\alpha, \beta) \quad \text{Eq. 3}$$

wherein the function  $G$  is determined by a geometry and configuration of the transducer array **320**. The function  $G$  is optionally pre-computed and stored as a mapping in data memory, for example in a form of a look-up table; the look-up table is beneficially stored in at least one of the data processing arrangement **110** and the digital signal processor **310**. Alternatively, the function  $G$  can be computed in real-time from parameters in at least one of the data processing arrangement **110** and the digital signal processor **310**.

30

The signals  $B_{\alpha, \beta}$  are computed using at least Equations 1 and 2 (Eq. 1 and 2) in real-time and then communicated from the digital signal processor **310** via the communication link **120**

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to the data processor arrangement **110** for further processing there. Optionally, for example under control from the data processing arrangement **110** communicated via the communication link **120** to the probe assembly **100**, the signals  $S_i$  are communicated directly in real-time, namely directly streamed, in a substantially unprocessed state via the communication link **120** to the data processing arrangement **110** and a majority of data processing then performed in the data processing arrangement **110**.

As elucidated in the foregoing, the system **300** is designed to economize on a way in which an available bandwidth of the communication link **120** is utilized in operation. Data flow reduction is susceptible to being achieved by one or more of following approaches:

- (a) by dynamically instructing the probe assembly **100** only to send the signals  $S_i$  or the signals  $B_{\alpha, \beta}$  corresponding to radially directions defined by  $B_{\alpha, \beta}$  of special interest, thereby avoiding to process and send data for directions which are not of interest;
- (b) by dynamically instructing the digital signal processor **310** only to process signals from a subset of the transducers **460**, corresponding to a reduction in angular and spatial resolution, for example by dynamically adjusting values for limit indexes  $r, s$ ; this saves computing effort and power dissipation within the probe assembly **100**;
- (c) by dynamically instructing the digital signal processor **310** to send the signals corresponding to  $B_{\alpha, \beta}$  or  $S_i$  at a reduced resolution, for example by only sending more significant bits of data bytes whilst maintaining computational accuracy within the digital signal processor **310**; and
- (d) by performing a fast Fourier transform (FFT) at the digital signal processor **310** of the signal  $B_{\alpha, \beta}$  to generate corresponding Fourier spectrum coefficients  $F_{\alpha, \beta}$  and then by communicating the spectrum coefficients  $F_{\alpha, \beta}$  via the communication link **120** to the data processing arrangement **110**, namely by adopting a parameterized data compression process.

Optionally, in approach (d), the digital signal processor **310** is operable to compare, for example by a correlation-type technique or using a neural network approach, the Fourier spectrum coefficients  $F_{\alpha, \beta}$  with templates of frequency spectra of specific types of known defects occurring within boreholes, for example leakage holes, obstructions, cracks and so forth. In an event of the computer frequency spectrum  $F_{\alpha, \beta}$  being sufficiently similar, within a threshold limit, to one or more of the frequency spectra of the one or more templates, a defect in the borehole **10** is deemed to have been found; in such case of finding a defect for the angles  $\alpha, \beta$ , the digital signal processor **310** is operable to simply send an identification that one or more defects have been detected and a nature of the one or more defects. Such

an extension of the approach (d) represents considerable data processing in the probe assembly 100 but also provides a very high degree of data compression which potentially enables, for a given bandwidth available in the communication link 120, the probe assembly 100 to be advanced at a greater longitudinal velocity along the borehole 10 whilst simultaneously providing real-time monitoring. In an event that the borehole 10 is mostly free of defects along its length, such an approach as in (d) results in a relatively smaller amount of data exchange along the communication link 120 until a defect is found; in such an event that a defect is found, the system 300 is, for example, capable of dynamically switching from the approach as in (d) to comprehensive sampling of the signal  $B_{\alpha,\beta}$  when the probe assembly 100 is in close proximity to the detected defect and whilst the probe assembly 100 is manoeuvred more slowly relative to the detected defect.

When the system 300 is operated in the first passive mode, a signal  $B_{\alpha,\beta}$  as illustrated in Figure 7a is often obtained. In Figure 7a, there is an absence of any drive signal  $S_d$ , 390 applied to the transducer array 320; such absence is denoted by a horizontal line in Figure 7a. Noise generated within the borehole 10 is received at the transducer array 320 and gives rise to a resolved noise-like chaotic signal as illustrated in Figure 7a.

Conversely, when the system 300 is operated in the second active mode, the transducer array 320 is driven with the one or more drive signals  $S_d$  390 which are optionally phase shifted and amplitude adjusted so that the transducer array 320 emits a beam of ultrasonic radiation in a preferred direction. Alternatively, the transducer array 320 is driven with the one or more signals  $S_d$  390 to emit ultrasonic radiation more omni-directionally from the transducer array 320. The one or more drive signals  $S_d$  390 optionally include a temporal sequence of single excitation pulses mutually separated by a time duration  $\Delta t$ ; such excitation single pulses approximate to pseudo-Dirac pulses and excite a natural mode of resonance of the transducer array 320 such that the radiation 400 is emitted at a frequency of this natural mode of resonance. Conversely, when the drive signal  $S_d$  390 is a periodically repeated sequence of a burst of pulses 600 as illustrated in Figure 7b, the frequency of the radiation 400 is susceptible to being at least partially defined by a pulse repetition frequency within the burst of pulses 600.

When operating in the second active mode, the burst of pulses 600 results in instantaneous direct signal breakthrough coupling, for example by way of direct electrostatic and/or electromagnetic coupling, giving rise to an initial detected pulse 610 which, optionally, can be gated out without the digital signal processor 310. A pulse wavefront in the radiation 400 propagates from the transducer array 320 to an inside facing surface of the liner tube 30a

wherefrom a portion of the radiation **400** is reflected and propagates as a component of the radiation **350** back to the transducer array **320** to give rise to a reflected pulse **620** as shown in Figure 7b in the resolved signal  $B_{\alpha, \beta}$ . A proportion of the radiation **400** is further coupled into the liner tube **30a** and is reflected from an exterior facing surface of the liner tube **30a** back through the liner tube **30a** and further as another component of the radiation **350** back to the transducer array **320** to give rise after resolving to a weaker pulse **630** as shown in Figure 7b in the resolved signal  $B_{\alpha, \beta}$ . In an event that an obstruction is present on an inside surface of the liner tube **30a**, a pulse corresponding to the obstruction will be observed before the pulse **620**. Moreover, in an event that the liner tube **30a** is cracked or fractured, reflections forming the pulses **620**, **630** will be confused, namely a convoluted and attenuated mixture of signal components. A portion of the radiation **400** is susceptible to propagating through the liner tube **30a** and propagating further into a region, for example a cavity, between an external surface of the liner tube **30a** and the ground **20**; the region represents an abrupt spatial acoustic impedance variation and results in a portion of the radiation thereat being reflected back to the probe assembly **100**. The system **300** is thereby capable of performing metrology on such a region between the external surface of the line tube **30a** and the ground **20**. Such a region is susceptible, for example, to providing a path for leakage of oil and/or gas up the borehole **10** externally to the line tube **30a**.

In the first passive mode of operation of the system **300**, spectral analysis, for example executed using a form of fast Fourier transform, of acoustic radiation generated by fluid flow through leakage holes and around an exterior of the liner tube **30a** enables certain categories of defects to be detected. Conversely, when fluid flow is not occurring within the borehole **10**, the second active mode of operation enables other types of defects to be identified. As elucidated in the foregoing, the system **300** is capable of being optimized for operating solely in either the first passive mode or solely in the second active mode. Alternatively, the system **300** is capable of being implemented to be able to function in both the first passive mode and the second active mode; for example, the system **300** is capable of being implemented to dynamically switch between the first and second modes in real-time when making measurements within the borehole **10**.

Optionally, in order to reduce a quantity of data to be communicated via the communication link **120** when the system **300** is operating in the second active mode, the digital signal processor **310** is optionally configurable from the data processing arrangement **110** to analyze the signal  $B_{\alpha, \beta}$  to identify times  $t_p$  when reflection pulses, for example the pulse **620**, **630**, occur after their corresponding excitation burst of pulses **600** or single excitation pulse, and to determine their corresponding amplitudes  $U$ , and then communicate time of reflected

pulse information  $t_n$  and corresponding amplitude  $U$  as descriptive parameters via the communication link **120** to the data processing arrangement **110**, thereby achieving potentially considerable data compression in comparison to communicating the signal  $B_{\alpha, \beta}$  directly to the data processing arrangement **110**; a rate at which the probe assembly **100** is  
5 capable of being advanced along the borehole is thereby potentially considerably enhanced in real-time when data compression is utilized.

Operation of the data processing arrangement **110** will now be further elucidated. When data is communicated from the probe assembly **100** via the communication link **120** to the  
10 data processing arrangement **110**, the processing arrangement **110** is optionally operable to record the received data from the probe assembly **100** as a data log in the data memory **140**. Such a record enables, for example, subsequent analysis to be performed after the probe assembly **100** has been extracted from the borehole **10**, for example to perform noise reduction operations for increasing a certainty of detection of various types of defects in the  
15 borehole **10**. The data processor **330** is operable to execute one or more software products which apply further analysis and conditioning of data received via the communication link **120** from the probe assembly **100**.

In real-time, when the system **300** is functioning in the second mode of operation, the data  
20 processor **330** presents on the display **130** a local 3-dimensional view of an interior of the borehole **10** substantially at a depth  $z$  at which the probe assembly **100** is positioned within the borehole **10**, for example refer to Figures 2, 3 and 5 for a definition of the depth  $z$ ; in Figure 5, increasing depth  $z$  is in an upward direction in the drawing. Such representation on the display **130** in the second active mode of operation enables the one or more users **450** to  
25 visually spatially inspect the inside surface of the liner tube **30a** in real-time. Time instances of receipt, for example, of the reflected pulses **620**, **630** at the transducer array **320** provides an indication of the spatial location of the inside and outside surfaces of the liner tube **30a** and also potentially an ultrasonic radiation view of material surrounding an exterior of the liner tube **30a**.

Alternatively, in the first passive mode of operation of the system **300**, there is provided an indication of potential defects or ultrasonic noise sources as a function of the depth  $z$  and the angles  $\alpha, \beta$ , see Figure 6. A different type of presentation is then optionally provided on the display **130** illustrating identified defect and/or noise type as a function of radial position as  
35 defined by the angles  $\alpha, \beta$ , and the depth  $z$ .

When the system **300** is configured to function in the second active mode, the data processor **330** employs one or more software products which operate to map the signal  $B_{\alpha, \beta}$  by a mapping function  $M$  to a Cartesian or a polar coordinate data array, namely  $w(x, y, z)$  or  $w(\alpha, \beta, z)$ , as denoted as a mapping step **700** in Figure 8 and described by Equation 4 (Eq. 4):

$$w(x, y, z) = M(B_{\alpha, \beta}, z)$$

$$w(\alpha, \beta, z) = M(B_{\alpha, \beta}, z)$$

Eq. 4

Values stored in elements  $w$  of the data array correspond to strength of reflected ultrasonic radiation, namely aforementioned  $U$ , as determined from reflection pulse peak amplitude in the signal  $B_{\alpha, \beta}$ .

The signal  $B_{\alpha, \beta}$ , for example as illustrated in Figure 7b, is optionally communicated to the data processing arrangement **110** in data-compressed in a parameterized form as elucidated earlier. By action of the mapping function  $M$ , the data array  $w$  thereby has stored therein a spatial crude 3-dimensional image of an inside view of the borehole **10** wherein an array element  $w$  position is equivalent to a corresponding spatial position within the borehole **10**.

Thereafter, in a gradient computation step **710**, the data processor **330** is operable to apply a gradient-determining function to determine 3-dimensional gradients in element  $w$  signal amplitude values stored in the data array  $w(x, y, z)$  or  $w(\alpha, \beta, z)$ , namely to determine whereat spatial boundaries between features are present in the ultrasonic image of the borehole **10** recorded in the data array  $w$ . Identification of spatial boundaries is also known as "iso-surface extraction" in the technical art of image processing and involves computation of partial differentials of the array elements  $w$  as provided in Equation 5 (Eq. 5):

$$\frac{\partial w}{\partial x}, \frac{\partial w}{\partial y}, \frac{\partial w}{\partial z} \quad \text{or} \quad \frac{\partial w}{\partial \alpha}, \frac{\partial w}{\partial \beta}, \frac{\partial w}{\partial z} \quad \text{Eq. 5}$$

depending upon whether Cartesian or polar coordinate systems are employed.

In a step **720**, the one or more software products are then operable to enhance values in the data array  $w$ , for example by curve fitting techniques, to show more clearly whereat continuous boundaries occur in the elements  $w(x, y, z)$  or  $w(\alpha, \beta, z)$  stored image data store in the data memory of the data processor **330**. Such curve fitting operations offer a

smoothing function so that images presented on the display **130** are not cluttered with irrelevant surface texture details, but nevertheless show relevant features regarding integrity and operation of the borehole **10**. Optionally, a step of smoothing is alternatively performed before a step of extracting iso-surfaces is performed.

5

Thereafter, in a step **730**, the data processor **330** is operable to read data from the element  $w$  of the data array and then write corresponding presentation values, after geometrical transformation when necessary, into a memory buffer serving the display **130**.

10 Optionally, in an event that the one or more software products executing on the data processor **330** identify when extrapolating one or more boundaries in the image stored in the elements  $w$  of the data memory to be unclear, the data processor **330** is then operable in real-time to instruct, as denoted by **740**, the digital signal processor **310** for specific values of the angles  $\alpha, \beta$  to repeat measurements within the borehole **10** for resolving such lack of  
15 clarity in the image stored at the data processor **330**. Such instruction to the digital signal processor **310** optionally includes one or more of:

(a) causing the probe assembly **100** to employ its digital signal processor **310** to appropriately phase shift and scale pursuant to Equations 1 and 2 (Eqs. 1 and 2) more of its electrical signals  $S_i$  to generate corresponding values of the signal  $B_{\alpha, \beta}$   
20 thereby having greater directional definition and resolution, the signals  $B_{\alpha, \beta}$  being subsequently communicated to the data processing arrangement **110** for further data processing and subsequent presentation on the display **130**;

(b) averaging, namely filtering, over numerous samples of the signal  $S_i$  to reduce noise for a limited range of specified angular sensing directions defined by the angles  $\alpha, \beta$ ,  
25 and then computing corresponding signals  $B_{\alpha, \beta}$  for communicating via the communication link **120** to the data processing arrangement **110** for subsequent further data processing thereat and thereafter presentation on the display **130**;

(c) driving the transducer array **320** in the manner of a phased array so that more of its ultrasonic radiation **400** is delivered into a particular direction in which metrology and monitoring was previously unclear, acquiring further values of the signal  $S_i$  and  
30 subsequently computing corresponding signals  $B_{\alpha, \beta}$  for communication to the data processing arrangement **110** for further data processing at the data processing arrangement **110** and thereafter presentation on the display **130**; and

(d) acquiring a larger set of measurements over a given defined limited range of angles  
35  $\alpha, \beta$  so as to map out finer details of a feature present in the borehole **10**, processing corresponding acquired signals  $S_i$  to generate corresponding signals  $B_{\alpha, \beta}$ ,

communicating the signals  $B_{\alpha, \beta}$  via the communication link **120** to the data processing arrangement **110** for further data processing and eventual presentation on the display **130**.

- 5 Beneficially, one or more of the users **450** as well as the data processing steps as illustrated in Figure 8 are able to invoke a reconfiguration of the probe assembly **100** to acquire enhanced information from one or more regions of the borehole **10**. After the enhanced information is acquired by the system **300**, the system **300** is beneficially operable to revert back to its previous configuration state to continue monitoring the borehole **10**. Thus, during
- 10 monitoring operations involving manoeuvring the probe assembly **100** of the system **300** along the borehole **10**, the system **300** is optionally set to perform a method comprising steps of:
- (a) performing a series of spatially coarse measurements along the borehole **10** whilst monitoring in real-time for any trace of one or more defects or other unusual features
  - 15 in the borehole **10**;
  - (b) detecting one or more potential defects or other unusual features at a location along the borehole **10** in real-time;
  - (c) reconfiguring the probe assembly **100** to perform a selective more detailed series of measurements of the one or more defects or other unusual features; and
  - 20 (d) after executing the more detailed series of measurements in step (c), resuming the series of spatially coarse measurements along the borehole **10** as in step (a).

This method is capable of being employed when the system **300** is operating in its first passive mode or in its second active mode. Optionally, the system **300** is beneficially

25 operable to dynamically switch in real-time between the first and second modes when performing the series of spatially coarse measurements along the borehole **10**.

It will be appreciated that the system **300** is operable to provide 2-D images of an inside of the liner tube **30a**, and also information of a region between an outside of the liner tube **30a**

30 and the ground **20**, for example an existence of voids or cavities. Moreover, the system **300** is capable of generating 3-D views, for example perspective views on planar screens such as liquid crystal pixel display screens, which are most readily interpreted by human visual viewing.

35 It will be appreciated that embodiments of the invention as described in the foregoing are susceptible to being modified without departing from the scope of the invention as defined by the appended claims.

Beneficially, the probe assembly **100** is furnished with one or more pressure sensors for measuring a pressure  $P$  present within the borehole **10** as the probe assembly **100** is manoeuvred in operation along the borehole **10**. In an event that the probe assembly **100** detects that the pressure  $P$  in the borehole **10** becoming excessive, for example in excess of 500 Bar, the probe assembly **100** is operable to transmit a warning message to the one or more users **450**.

Beneficially, the probe assembly **100** is furnished with a temperature sensor for measuring an operating temperature  $T$  within the probe assembly **100**. In an event that the operating temperature  $T$  exceeds a predefined threshold temperature  $Th$ , the probe assembly **100** is operable to send a request to the data processing arrangement **110** to enable the probe assembly **100** to assume intermittent operation, wherein the digital signal processor **310** is permitted intermittently to enter a hibernating low-power state in order to provide the digital signal processor **310** with an opportunity to cool slightly by reducing electrical power dissipation therein. When in the hibernating state, advance of the probe assembly **100** along the borehole **10** is optionally temporarily halted. Optionally, such intermittent operation of the signal processor **310** is progressively more adopted as the operating temperature  $T$  exceeds above the threshold temperature  $Th$ . Beneficially, the data processing arrangement **110** is susceptible to being instructed to temporarily assume a hibernating state during which its power dissipation is reduced in comparison to its normal non-hibernating operation.

The transducer array **320** is described briefly in the foregoing. In Figure 9, there is shown an illustration of the probe assembly **100**, wherein the array **320** is susceptible to being implemented in various configurations, for example at least one of:

- (a) a rectangular matrix **800** of mutually perpendicular rows and columns of individual transducer elements, for example cut from a single slab of polarized piezo-electric material, for example by using a fine diamond saw; peripheral edges of the matrix **800** are optionally straight or curved; the rectangular matrix is beneficially mounted at a bottom surface of the probe assembly **100** facing down the borehole **10** when the probe assembly **100** is in operation;
- (b) a series of individual transducer elements arranged in one or more ring formations **810**; the ring formation is beneficially mounted at one or more ends of the probe assembly **100**, or radially around an radial side wall of the probe assembly **100**; and
- (c) in one or more rows **830** or a spiral formation **840** around a peripheral surface of the probe assembly **100** in a substantially longitudinal direction along the probe assembly **100**.

Optionally, the probe assembly **100** further includes an electronic compass for measuring a direction of the Earth's north and south magnetic poles at the probe assembly **100** in order to provide a corresponding orientation signal for communicating via the communication link **120** to the data processing arrangement **110**; receipt of such an orientation signal enables the data processor **330** to correct for the angle  $\beta$  as shown in Figure 6 when the probe assembly **100** is lowered into the borehole **10** and revolves during its descent into or during subsequent extraction from the borehole **10**. The probe assembly **100** is thus beneficially fabricated from non-ferromagnetic materials, for example non-magnetic stainless steel.

The probe assembly **100** beneficially has an exterior diameter "d" in a range of 100 mm to 180 mm, more beneficially a diameter in a range of 120 mm to 160 mm, and most beneficially substantially a diameter of substantially 150 mm. Moreover, the probe assembly **100** beneficially has a longitudinal length "L", disregarding attachment of the cladding **200** and its associated communication link **120**, in a range of 0.5 metres to 5 metres, more beneficially in a range of 1 metre to 3 metres and beneficially substantially 1.5 metres.

The system **300** is capable of being adapted to perform one or more of the following functions:

- (a) Well leak detection, wherein the system **300** is operable to function as a Well Leak Detector (WLD). Leak depth accuracy to within an order of a centimetre is feasible. Moreover, leak rates in a range of 0.02 litres/minute to 300 litres/minute are susceptible to being detected and monitored by using the system **300**; leak detection in production packers, expansion joints, tubing, down-borehole **10** safety valves, one or more casings in a well associated with the borehole **10**, and in a wellhead associated with the borehole **10** are susceptible to being monitored using the system **300**; in operation, it is often not necessary when using the system **300** in the borehole **10** to pull drill-string tubing up for identifying and monitoring a failing barrier in a well;
- (b) Well sand detection, wherein the system **300** is operable to function as a Well Sand Detector (WSD). Sand is probably a biggest challenge to operators in the oil industry. Sand fills up the borehole **10** and chokes back productivity of the borehole **10** when used for oil extraction. Sand erodes well equipment and facilities, causing breakdown and sometimes causing blowouts. The system **300** is susceptible to being used to identify sand-producing regions of geological strata, namely sand-producing intervals, and is also susceptible to being used to identify failures in sand control devices employed in conjunction with sand control for the borehole **10** when used to extract oil. Beneficially, the probe assembly **100** is implemented such that its housing has a

relatively smaller diameter, for example in a range of 40 mm to 80 mm, when adapted specifically for well sand detection. Acoustic energy is generated in the housing when sand particles impact upon the casing when the probe assembly **100** is in use, wherein the acoustic energy has a characteristic frequency spectrum by which the sand can be identified; at least a portion of the transducer array **320** is then specifically adapted for sensing such acoustic radiation resulting from sand impact on the probe assembly **100**;

(c) Well flow detection, wherein the system **300** is operable to function as a Well Flow Detector (WFD); the system **300** configured to function as a well flow detector is susceptible in operation to providing detailed information about an inflow profile from the borehole **10** when used for oil extraction, for example for providing relative velocity profiles between different producing or injecting intervals of the borehole **10**, for example those intervals which are not contributing at all to oil extraction; and

(d) Well annular flow detection, wherein the system **300** is operable to function as a Well Annular Flow monitor (WAF); the system **300** operable as the Well Annular Flow monitor is capable of detecting and locating flow behind a pipe in an annulus between a liner tube, namely casing, and a geological formation; the system **300** is thereby operable to detect contamination of groundwater, one or more underground blowouts, sustaining liner tube pressure, one or more undesirable water cuts, and one or more undesirable gas cuts when drilling the borehole **10**.

The system **300** is optionally optimized to perform one of functions (a) to (d). Alternatively, the system **300** can be optimally designed to perform several of these functions and to dynamically switch between such functions when in use. Certain of the functions (a) to (d) are serviced in the aforementioned first passive mode, whereas other of the functions (a) to (d) are addressed by the system **300** operating in its second active mode. In general, a cost and complexity of the system **300** increases as it is required to be more versatile in dynamically performing diverse functions.

Expressions such as "including", "comprising", "incorporating", "consisting of", "have", "is" used to describe and claim the present invention are intended to be construed in a non-exclusive manner, namely allowing for items, components or elements not explicitly described also to be present. Reference to the singular is also to be construed to relate to the plural.

Numerals included within parentheses in the accompanying claims are intended to assist understanding of the claims and should not be construed in any way to limit subject matter claimed by these claims.

**CLAIMS**

5 1. A monitoring system (300) for monitoring within a borehole (10), said system (300) comprising a probe assembly (100) operable to be moved within said borehole (10) for sensing one or more physical parameters therein, a data processing arrangement (110) being located outside the borehole (10), and a data communication link (120) operable to convey sensor data indicative of said one or more physical parameters from the probe  
10 assembly (100) to the data processing arrangement (110) for subsequent processing and display and/or recording in data memory (140),

characterized in that

15 (a) said probe assembly (100) includes one or more sensors (320) for spatially monitoring within the borehole (10) and generating corresponding sensor signals (360);  
(b) said probe assembly (100) includes a digital signal processor (310) for executing preliminary processing of the sensor signals (360) to generate corresponding  
20 intermediately processed signals (370) for communication via said data communication link (120) to the data processing arrangement (110);  
(c) said data processing arrangement (110) is operable to receive said intermediately processed signals (370) and to perform further processing on said intermediately processed signals (370) to generate output data for presentation (130) and/or for  
25 recording in a data memory arrangement (140).

2. A monitoring system (300) as claimed in claim 1, said system (300) being operable to generate said output data for presentation (130) in real-time when said probe assembly (100) is moved within the borehole (10).

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3. A monitoring system (300) as claimed in claim 1 or 2, wherein said system (300) is operable in at least one of first and second modes, wherein:

(a) said first mode results in said system (300) passively sensing noise sources present in the borehole (30) generating radiation (350) for sensing at the one or more sensors  
35 (320); and  
(b) said second mode results in said system (300) actively emitting radiation into the borehole (10) and receiving at said one or more sensors (320) corresponding

reflected radiation from a region in and/or around the borehole (10) for generating said sensor signals (360).

4. A monitoring system (300) as claimed in claim 3, wherein said system (300) is operable to be dynamically reconfigurable between said first and second modes when said probe assembly (100) is being moved in operation within said borehole (10).

5. A monitoring system (300) as claimed in any one of the preceding claims, wherein said system (300) is operable to communicate data bi-directionally between said data processing arrangement (110) and said probe assembly (100), wherein said digital signal processor (310) of said probe assembly (100) is operable to being reconfigured between a first function of general sensing around in a region of the borehole (10) in a vicinity of the probe assembly (100), and a second function of specific sensing in a sub-region of said region of the borehole (10) in a vicinity of the probe assembly (100).

6. A monitoring system (300) as claimed in any one of the preceding claims, wherein said one or more sensors (320) are implemented as one or more ultrasonic transducer arrays disposed at one or more positions on the probe assembly (100) including:

- (a) as an array at a bottom surface of the probe assembly (100) facing down the borehole (10) when the probe assembly (100) is inserted into the borehole (10) in operation;
- (b) one or more ring formations (810) at one or more ends of the probe assembly (100), or radially around an radial side wall of the probe assembly (100);
- (c) in one or more rows (830) or one or more spiral formations (840) around a peripheral surface of the probe assembly (100) in a substantially longitudinal direction along the probe assembly (100).

7. A monitoring system (300) as claimed in any one of the preceding claims, wherein said system (300) is operable to process the sensor signals (360) and compare the processed signals with one or more signal templates for automatically detecting features present in the borehole (10) which are encountered in operation by the probe assembly (100).

8. A monitoring system (300) as claimed in any one of the preceding claims, wherein said data communication link (120) is implemented using one or more twisted-wire pairs including plastics material insulation and copper electric conductors embedded within said plastics material, the data communication link (120) being clad by cladding (200) susceptible

to bearing a weight of the probe assembly (100) when said assembly (100) is moved in operation within the borehole (10).

9. A monitoring system (300) as claimed in any one of claims 1 to 7, wherein said data communication link (120) is implemented using one or more twisted-wire pairs including plastics material insulation and copper electric conductors embedded within said plastics material, the data communication link (120) being provided with an associated mechanical element susceptible to bearing a weight of the probe assembly (100) when said assembly (100) is moved in operation within the borehole (10).

10. A monitoring system (300) as claimed in any one of the preceding claims, wherein said data processing arrangement (110) is located in operation remotely from the probe assembly (100), said data processing arrangement (110) providing an interface for one or more users (450) to control in real-time operation of the probe assembly, and for generating graphical images for presentation on one or more displays (130) to the one or more users (450), said graphical images being representative of spatial features present within and/or around said borehole (10) in a vicinity of said probe assembly (100).

11. A method of monitoring within a borehole (10) by using a monitoring system (300), said system (300) comprising a probe assembly (100) operable to be moved within said borehole (10) for sensing one or more physical parameters therein, a data processing arrangement (110) located outside the borehole (10), and a data communication link (120) operable to convey sensor data indicative of said one or more physical parameters from the probe assembly (100) to the data processing arrangement (110) for subsequent processing and display and/or recording in data memory,

characterized in that said method includes steps of:

- (a) spatially monitoring using one or more sensors (320) of said probe assembly (100) within the borehole (10) and generating corresponding sensor signals (360);
- (b) using a digital signal processor (310) included in said probe assembly (100), executing preliminary processing of the sensor signals (360) for generating corresponding intermediately processed signals (370);
- (c) communicating via said data communication link (120) said intermediately processed signals (370) to the data processing arrangement (110); and
- (d) receiving said intermediately processed signals (370) at said data processing arrangement (110) for performing further processing on said intermediately

processed signals (370) for generating output data for presentation (130) and/or for recording in a data memory arrangement (140).

12. A method as claimed in claim 11, including a further step of:

- 5 (e) generating using said system (300) said output data for presentation (130) in real-time when said probe assembly (100) is moved within the borehole (10).

13. A method as claimed in claim 11 or 12, said method including a step of operating said monitoring system (300) in at least one of first and second modes, wherein:

- 10 (a) said first mode results in said system (300) passively sensing noise sources present in the borehole (30) generating radiation (350) for sensing at the one or more sensors (320); and
- (b) said second mode results in said system (300) actively emitting radiation into the borehole (10) and receiving at said one or more sensors (320) corresponding
- 15 reflected radiation from a region in and/or around the borehole (10) for generating said sensor signals (360).

14. A method as claimed in claim 13, wherein said method includes a further step of dynamically reconfiguring said system (300) between said first and second modes when said

20 probe assembly (100) is being moved in operation within said borehole (10).

15. A method as claimed in any one of claims 11 to 14, wherein said method includes a step of:

- 25 (f) communicating data bi-directionally between said data processing arrangement (110) and said probe assembly (100), wherein said digital signal processor (310) of said probe assembly (100) is operable to being reconfigured between a first function of generally sensing around in a region of the borehole (10) in a vicinity of the probe assembly (100), and a second function of specific sensing in a sub-region of said region of the borehole (10) in a vicinity of the probe assembly (100).

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16. A method as claimed in any one of claims 11 to 15, wherein said one or more sensors (320) are implemented as one or more ultrasonic transducer arrays disposed at one or more positions on the probe assembly (100) including:

- (a) as an array at a bottom surface of the probe assembly (100) facing down the
- 35 borehole (10) when the probe assembly (100) is inserted into the borehole (10) in operation;

- (b) one or more ring formations (810) at one or more ends of the probe assembly (100), or radially around an radial side wall of the probe assembly (100);
- (c) in one or more rows (830) or one or more spiral formations (840) around a peripheral surface of the probe assembly (100) in a substantially longitudinal direction along the probe assembly (100).

17. A method as claimed in any one of claims 11 to 16, wherein said method includes a further step of:

- (g) processing the sensor signals (360) to generate corresponding processed signals; and then
- (h) comparing the processed signals with one or more signal templates for automatically detecting features present in the borehole (10) which are encountered in operation by the probe assembly (100).

18. A method as claimed in any one of claims 11 to 17, wherein said data communication link (120) is implemented using one or more twisted-wire pairs including plastics material insulation and copper electric conductors embedded within said plastics material, the data communication link (120) being clad by cladding (200) susceptible to bearing a weight of the probe assembly (100) when said assembly (100) moved in operation within the borehole (10).

19. A method as claimed in any one of claims 11 to 18, wherein said method includes a step of:

- (i) locating said data processing arrangement (110) in operation remotely from the probe assembly (100), said data processing arrangement (110) providing an interface for one or more users (450) to control in real-time operation of the probe assembly, and for generating graphical images for presentation on one or more displays (130) to the one or more users (450), said graphical images being representative of spatial features present within and/or around said borehole (10) in a vicinity of said probe assembly (100).

20. A computer software product recorded on a data carrier, said computer software product being executable on computing hardware for implementing a method as claimed in any one of claims 11 to 19.

21. A probe assembly (100) for use in monitoring within a borehole (10), said probe assembly (100) being adapted for use in a monitoring system (300) as claimed in any one of claims 1 to 10.

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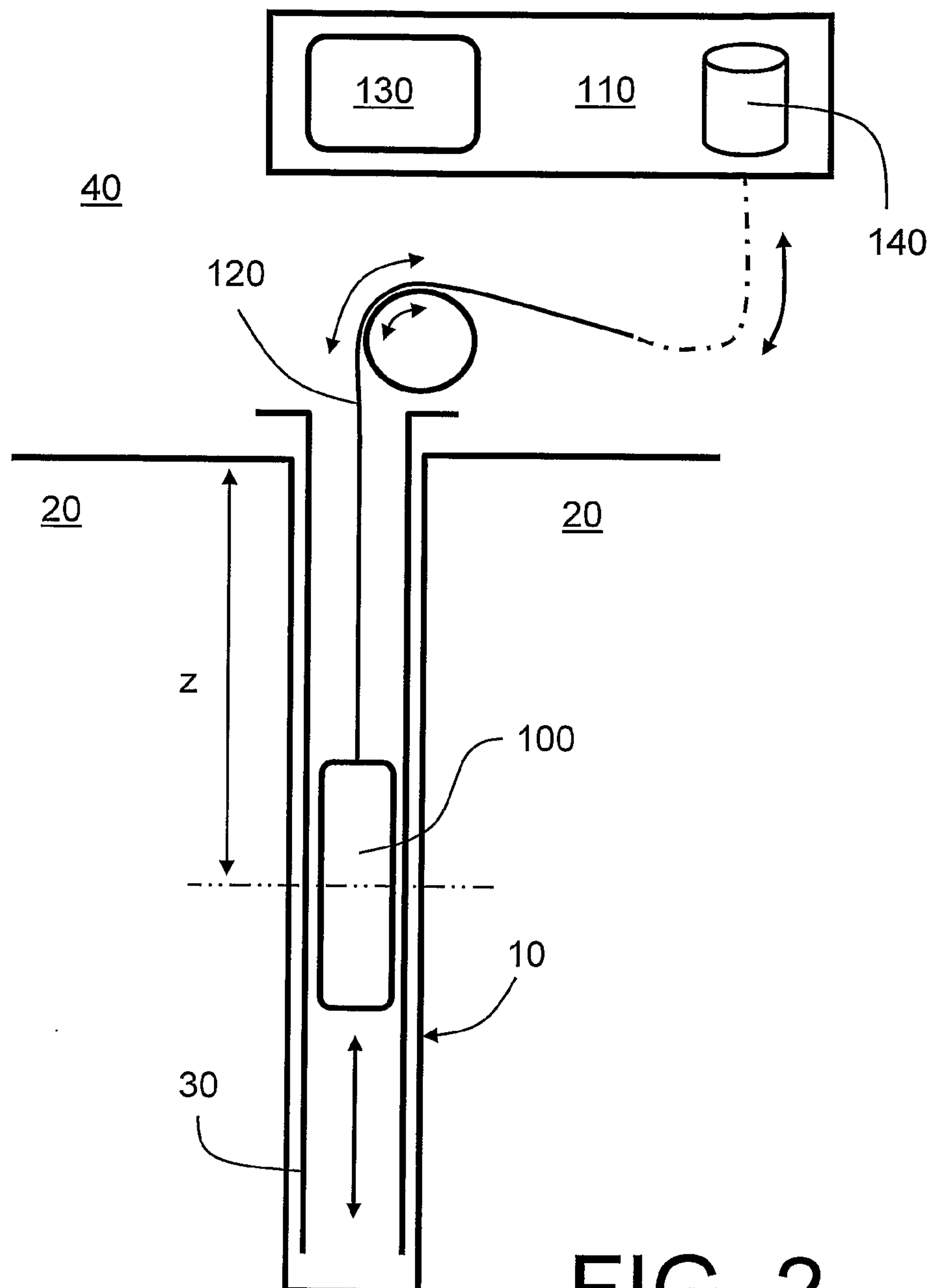
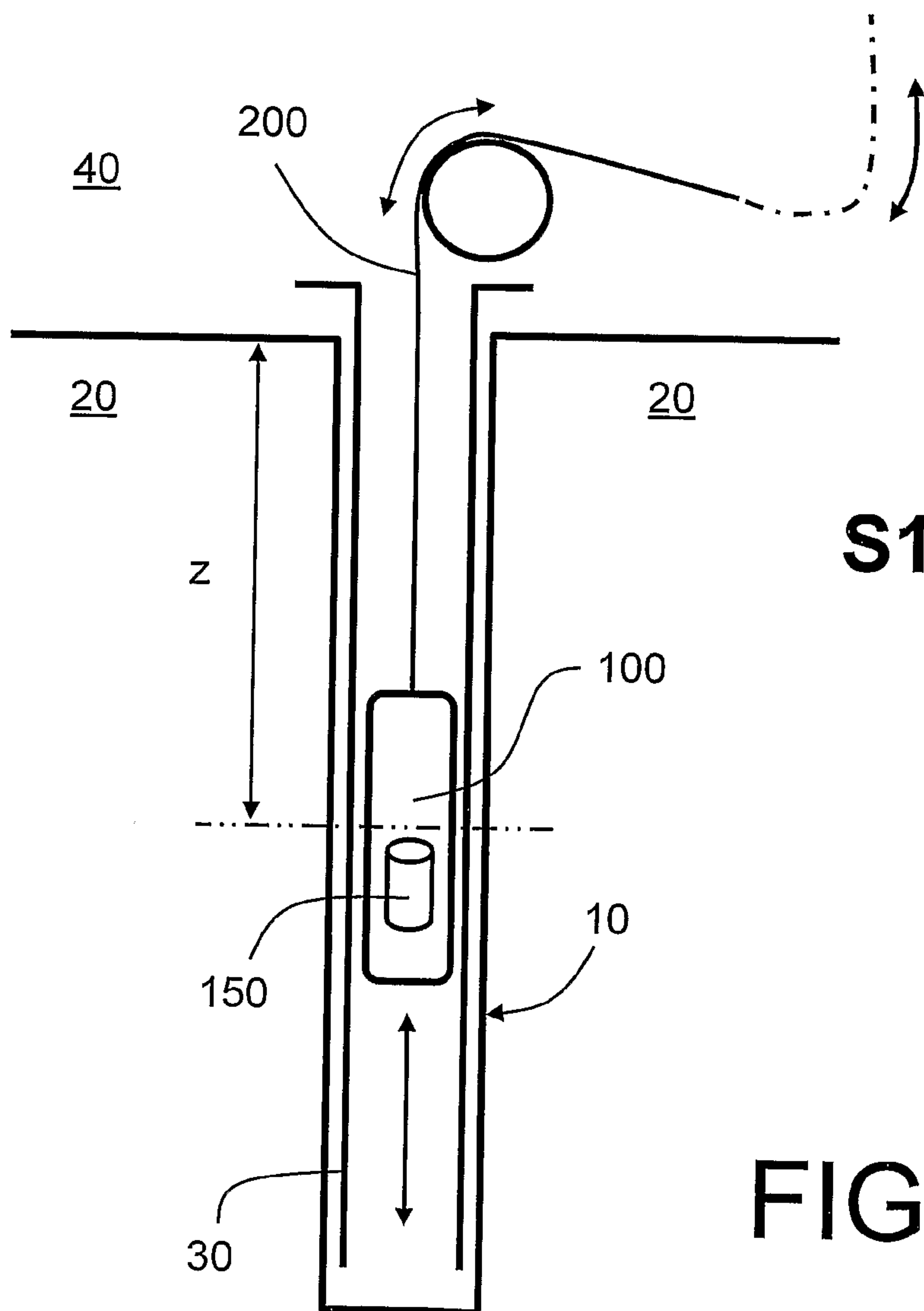
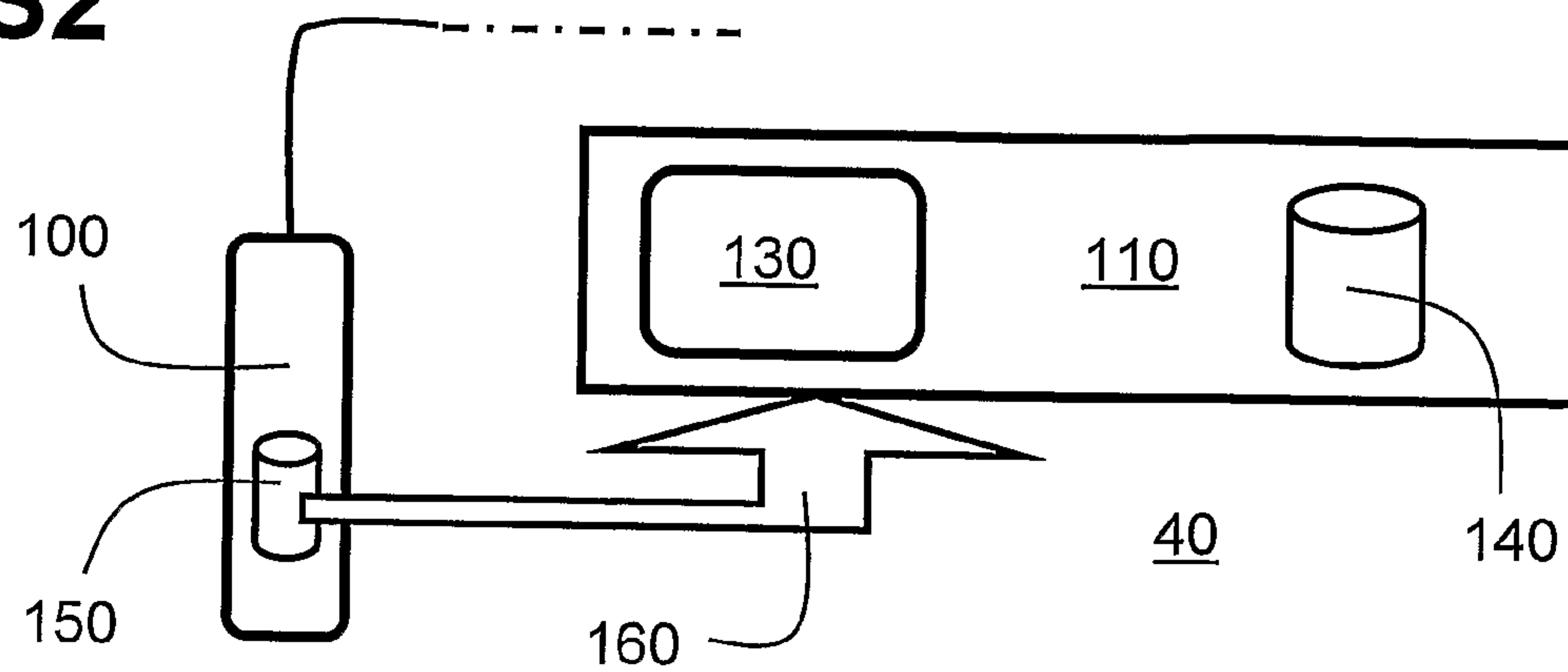


FIG. 2

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**S2****FIG. 3**

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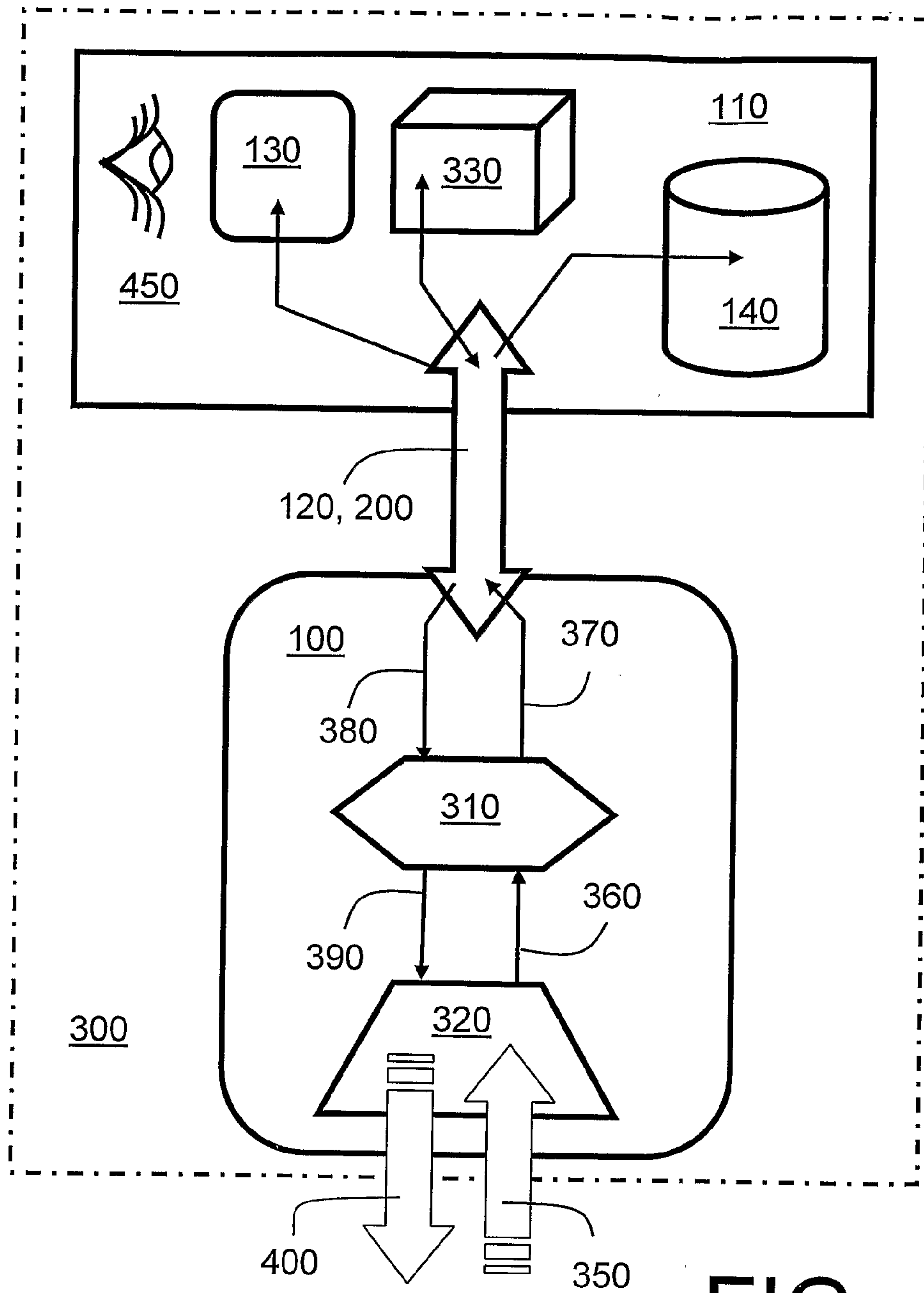


FIG. 4

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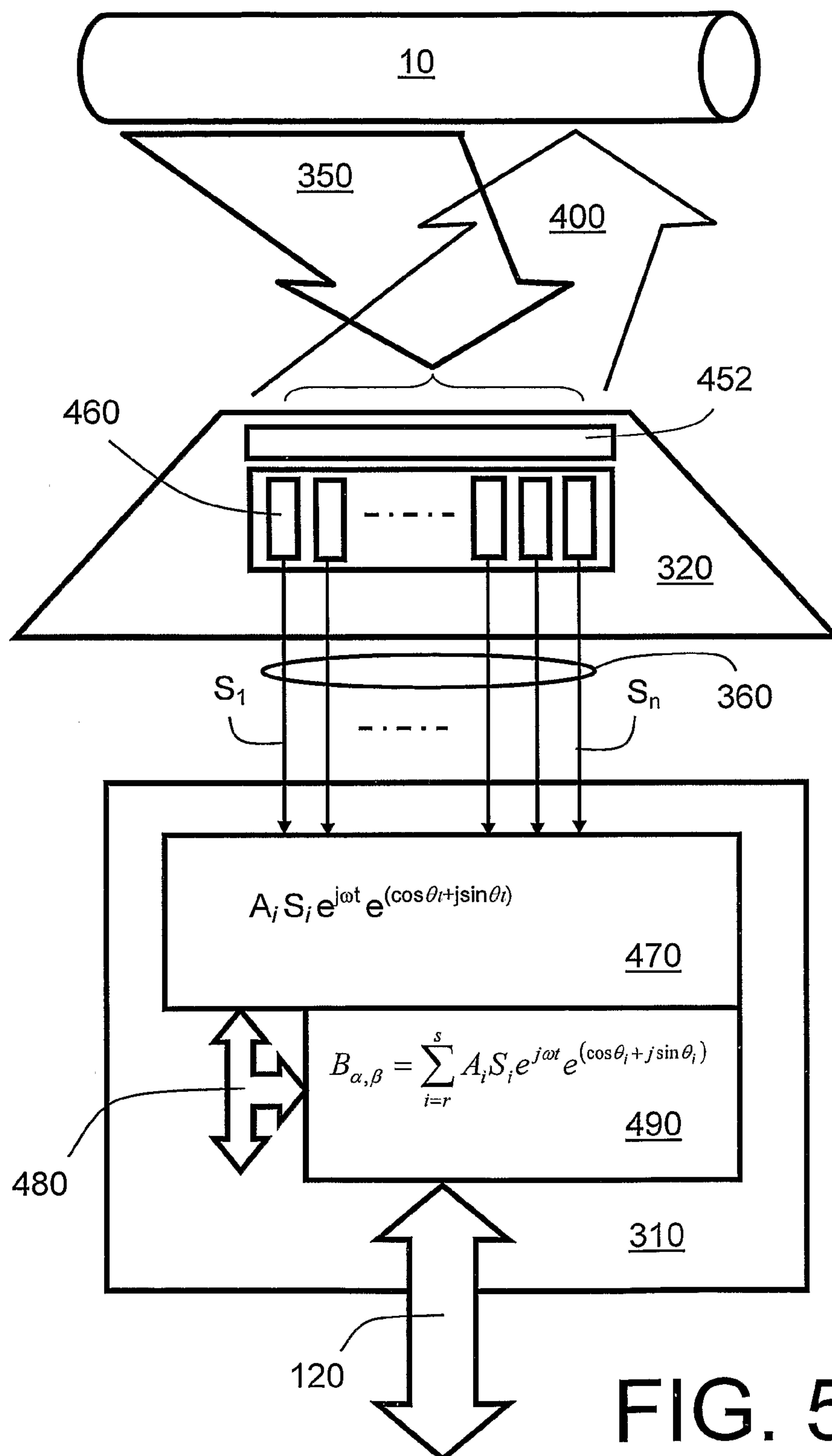


FIG. 5

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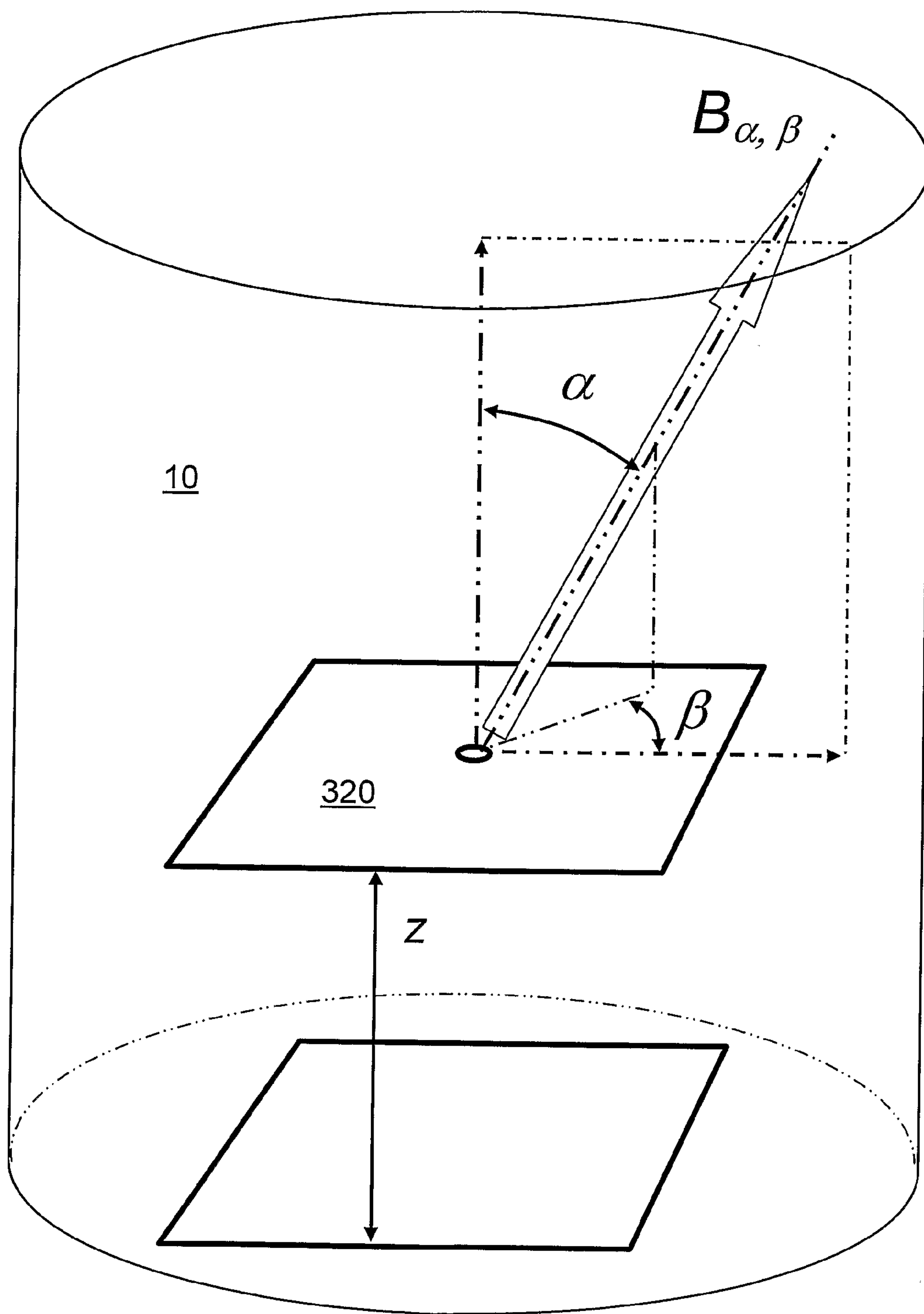


FIG. 6

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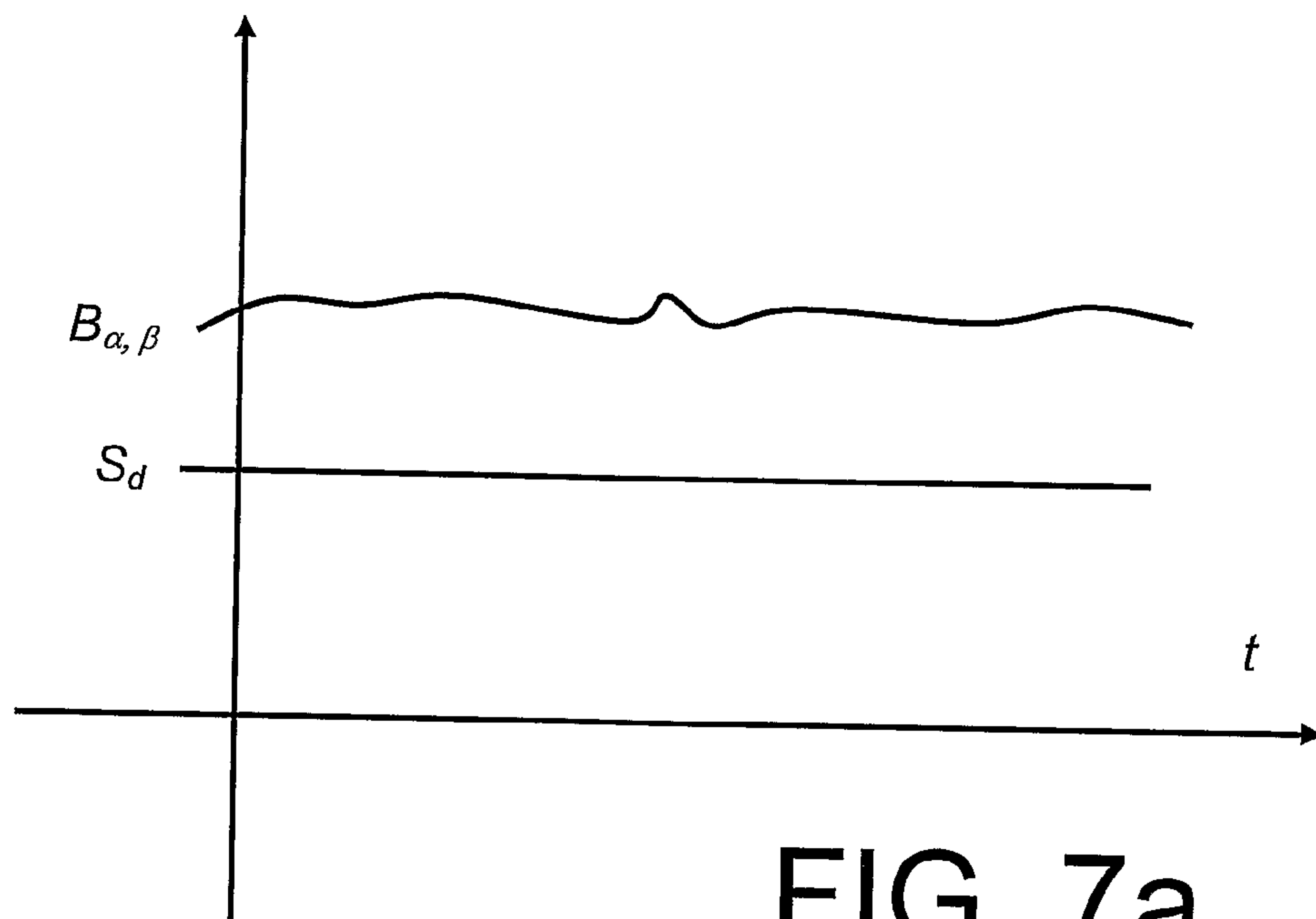


FIG. 7a

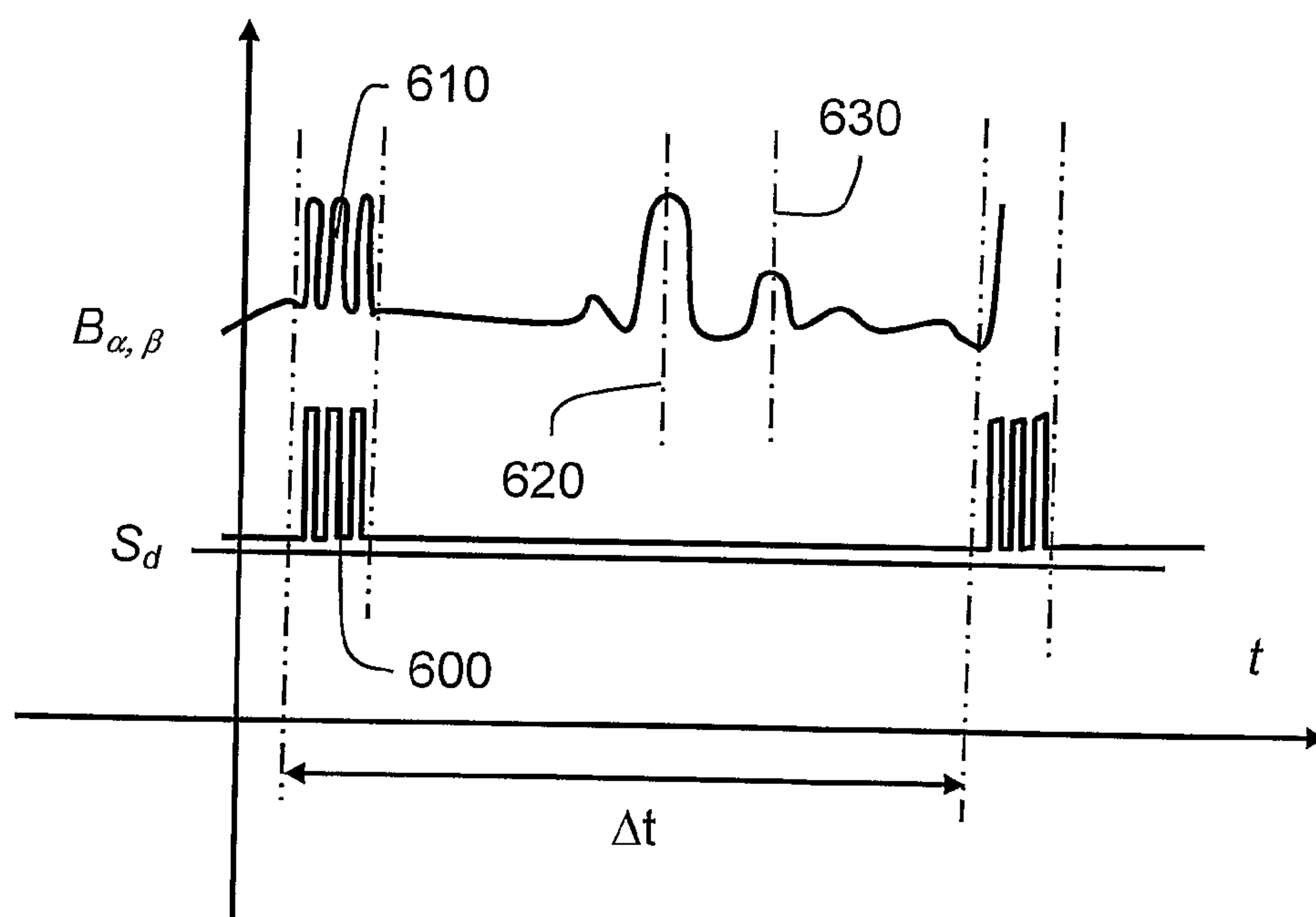


FIG. 7b

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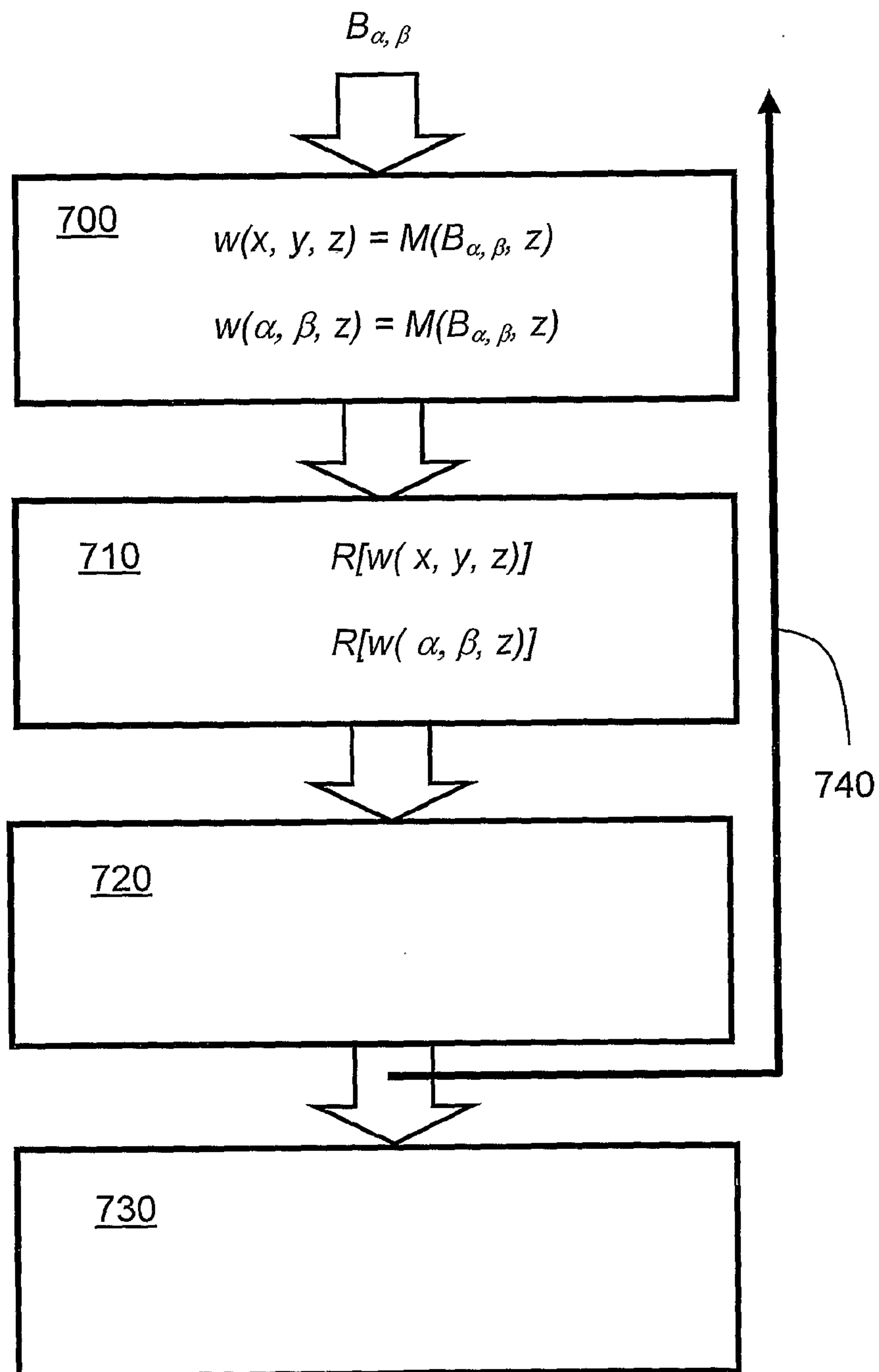


FIG. 8

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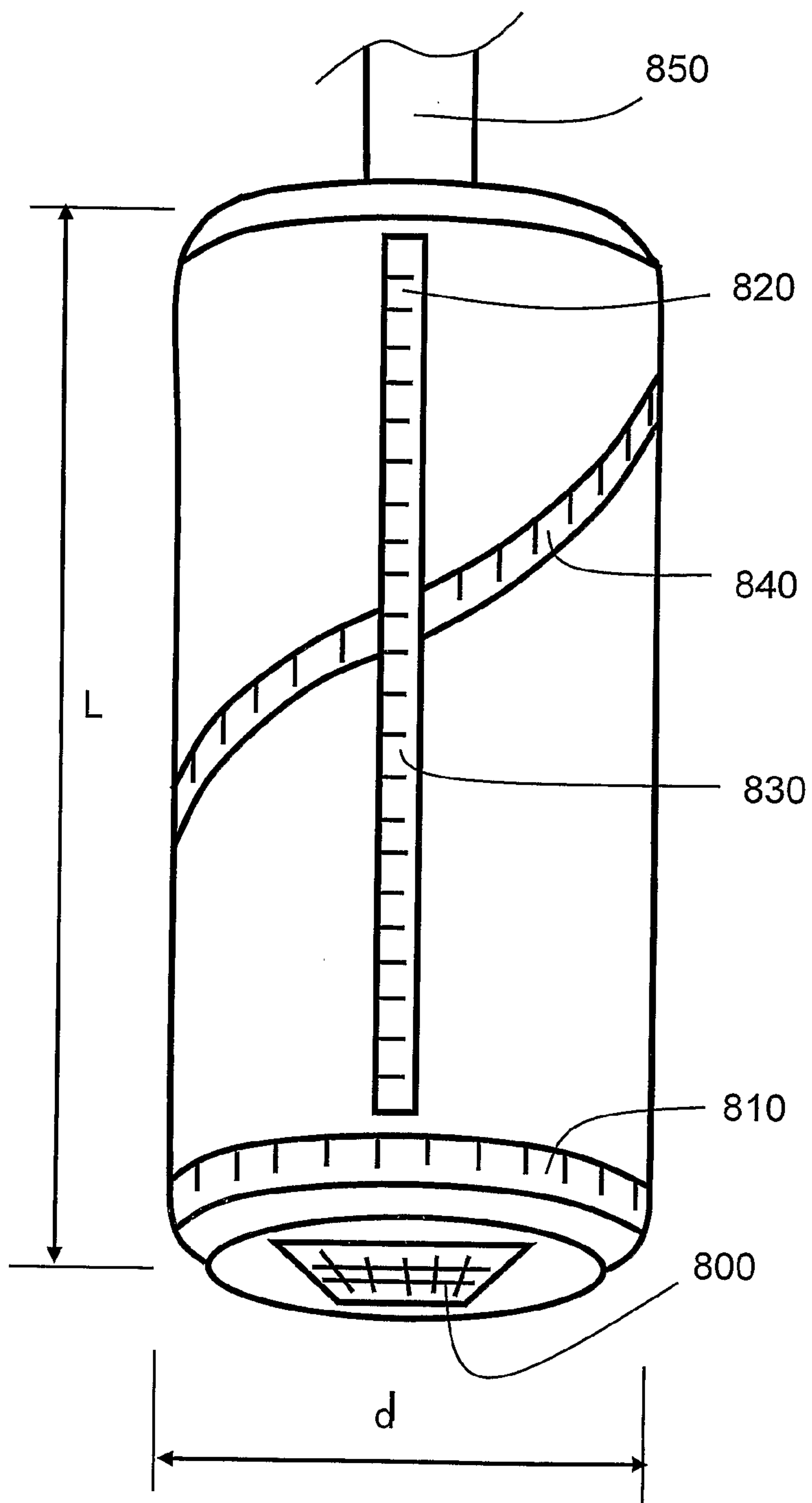


FIG. 9

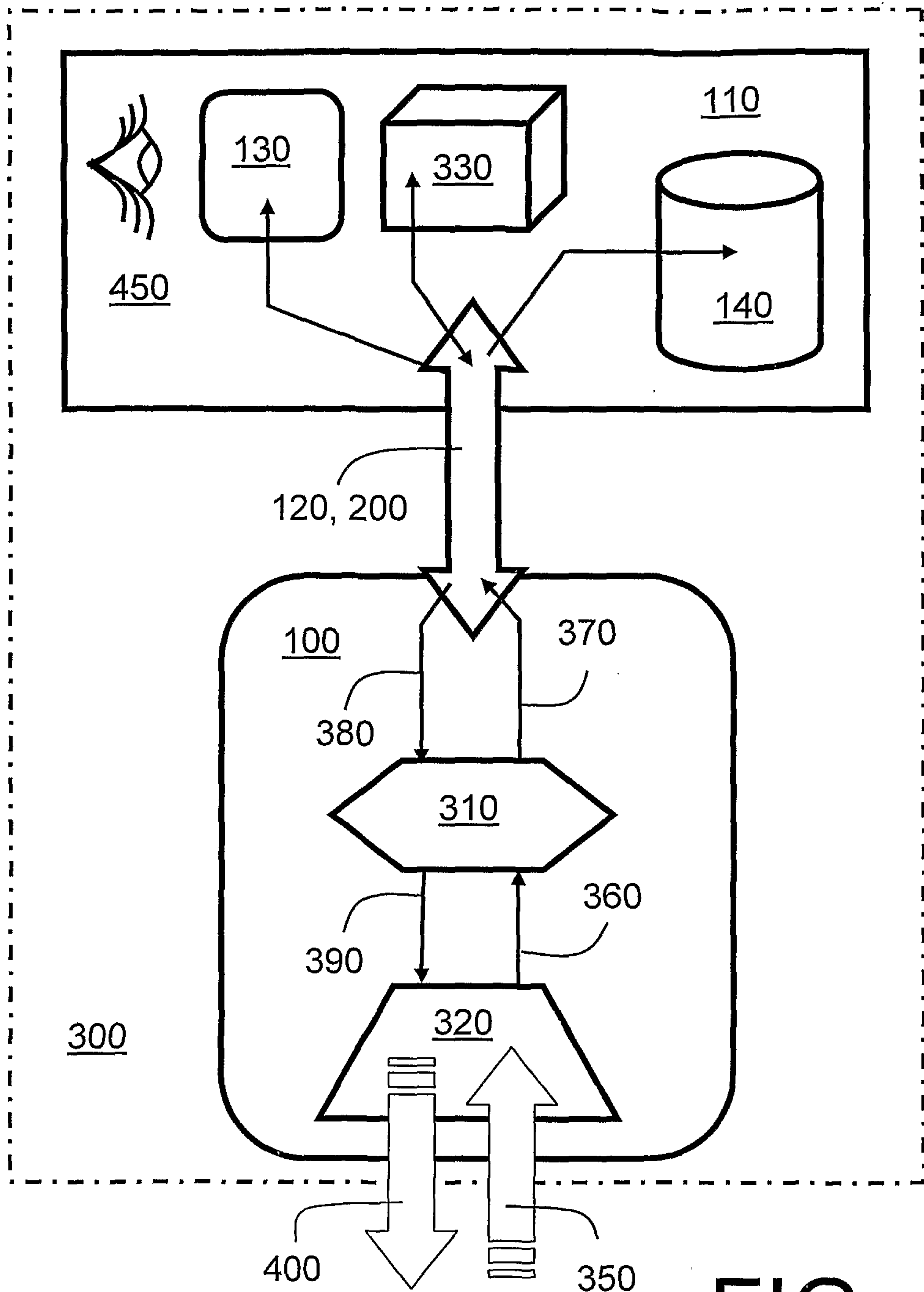


FIG. 4