(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
20 August 2020 (20.08.2020)

WIPO | PCT

(10) **International Publication Number**
WO 2020/165098 A1

(51) **International Patent Classification:**
E21B 41/00 (2006.01) ***E21B 49/00*** (2006.01)
E21B 47/00 (2012.01)

(21) **International Application Number:**
PCT/EP2020/053341

(22) **International Filing Date:**
10 February 2020 (10.02.2020)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
19156494.7 11 February 2019 (11.02.2019) EP

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(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:
— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:
— *with international search report (Art. 21(3))*

(54) **Title:** METHOD FOR DETERMINING DOWNHOLE CHARACTERISTICS IN A PRODUCTION WELL

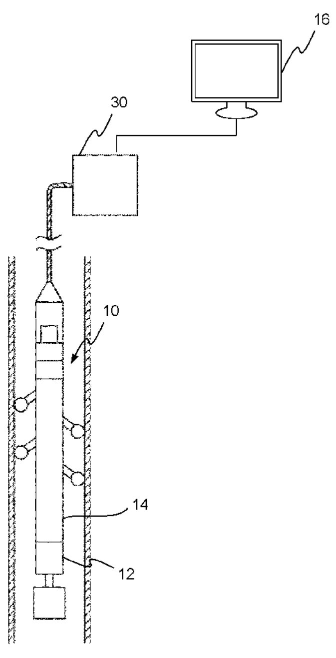

Fig. 1

(57) **Abstract:** A method for determining one or more downhole characteristic(s) in a production well (10), comprising the steps of: measuring (110) a physical property of the production well (10) using at least one sensor (12); pre-processing (130) the measured values of the physical property using feature scaling or automatic gain control techniques; and determining (150) one or more downhole characteristic(s) using a supervised machine learning method (200). The supervised machine learning method (200) comprises the steps of: cross- validating (210) a predictive analytics algorithm with training data that are previously measured physical properties and applying (220) one or more algorithms to the measured values of the physical property to converge on an estimate for the determined downhole characteristic(s).

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METHOD FOR DETERMINING DOWNHOLE CHARACTERISTICS IN A PRODUCTION WELL

Field of the invention

The present invention relates to a method for determining downhole characteristics in a production well.

Background art

Production wells are an important part of certain industries, especially for mining and oil drilling. When performing various types of operations downhole, such as drilling, cutting, etc., it is desirable to monitor the downhole characteristics during the operation. However, in practice, it is often difficult to achieve accurate measurements of downhole characteristics. For example, downhole measurements usually require interruption of production, which costs precious operational time. Yet further, while certain measurements may be made, not all downhole characteristics are easily measured.

Traditional approaches that determine downhole characteristics in a production well require certain physical models or assumptions. In practice, it is very challenging to get accurate and reliable models. In most cases, the designed models are simplifying the downhole environment too much. Hence, it is normal to obtain large errors from the simple physical model-based approaches. There is therefore a need to provide an improved method for determining downhole characteristics in a production well.

Summary of the invention

In order to find a way to determine downhole characteristics that are not easily measured, an object of the present invention is to provide a method for determining these downhole characteristics using estimations from more easily measured data.

According to a first aspect of the invention, the above and other objects of the invention are achieved, in full or in part, by a method for determining one or more downhole characteristic(s) in a production well. The method comprises measuring a physical property of the production well using at least one sensor; pre-processing the measured values of the physical property using feature scaling and/or an automatic gain control technique; and determining one or more downhole characteristic(s) using a supervised machine learning method. The supervised machine learning method comprises cross-validating a predictive analytics algorithm with training data that are previously measured physical properties, and applying one or more algorithms to the measured values of the physical property to converge on an estimate for the determined downhole characteristic(s).

In addition, said physical property may be the permittivity of a fluid in the well and/or the current provided to a downhole tool of the well.

The present solution is purely data-driven, and no physical model is required. In particular, the present invention provides a regression model to predict a quantity of the downhole characteristic(s) from measured data in the production well.

By physical model is meant a mathematical model which describes how the earth formation responds to the transmitting signal from the downhole tool.

Using feature scaling and/or an automatic gain control technique changes how the data is distributed across the possible data values. Such pre-processing will improve any machine learning classifier to more accurately perform classification.

In an embodiment, the training data, which are previously measured physical properties, are measured using the at least one sensor.

The method may further comprise transmitting a control signal based on the determined downhole characteristic(s). This is advantageous in that improved control of equipment can be accomplished.

The control signal may be transmitted to a data-processing unit at the surface or to an operator.

The control signal may be transmitted to a downhole tool. Hence, real-time control of downhole equipment is possible.

The method may further comprise displaying the measured physical property and/or the determined downhole characteristic(s) on a display, which allows for immediate feedback of the downhole characteristic to an operator.

The method may further comprise a pre-determining step comprising using a non-linear or a linear system identification. Improved pre-determining of the downhole characteristic is thereby provided for.

The pre-determining step may be performed after the step of measuring a physical property of the production well using at least one sensor and before the step of pre-processing the measured values of the physical property using feature scaling and/or automatic gain control techniques.

The physical property may be measured using multiple sensors in at least two different configurations, and pre-determining the downhole characteristic(s) comprises using the non-linear or linear system identification. The method will thereby have access to an increased amount of data, thus improving the accuracy of the method.

The physical property may comprise the permittivity of a fluid in the well. The method can thereby be performed in order to determine the water flow regime downhole, i.e. a representation of the different fluids in the well, preferably at a common cross-section of the well.

The physical property may comprise the current provided to a downhole tool of the well. The downhole tool may be a suction tool comprising a bailer, and in an embodiment, the downhole characteristics may comprise the fullness of the bailer. The method will thereby provide accurate and reliable information of the downhole tool operation, which will allow for improved monitoring of downhole operation as well as predictive operation and maintenance.

In an embodiment, the downhole tool is a milling tool having miller teeth, and the downhole characteristics may comprise the miller teeth health.

As for the embodiment including the suction tool, the method will provide accurate and reliable information of the downhole tool operation, which will allow for improved monitoring of downhole operation as well as predictive operation and maintenance.

In another embodiment, the downhole tool may be a sleeve manipulation tool, and the downhole characteristics may comprise the sleeve position. In this way, the sleeve manipulation tool can predict when the sleeve is half open or fully open/closed, e.g. from current in the wireline.

In yet another embodiment, the downhole tool may be a tubing cutting tool cutting the tubing with one or more cutting bit(s), and the downhole characteristics may comprise the cutting bit health.

Furthermore, the downhole tool may be an opening drilling tool drilling one or more openings in the wall of the production casing/well tubular metal structure with at least one drilling bit, and the downhole characteristics may comprise the drilling bit health.

Thus, the method for determining one or more downhole characteristic(s) in a production well, may comprise:

- measuring a physical property of the production well using at least one sensor, said physical property being the permittivity of a fluid in the well and/or the current provided to a downhole tool of the well,
- pre-processing the measured values of the physical property using feature scaling and/or an automatic gain control technique, and
- determining one or more downhole characteristic(s) using a supervised machine learning method comprising the steps of:
- cross-validating a predictive analytics algorithm with training data that are previously measured physical properties, and
- applying one or more algorithms to the measured values of the physical property to converge on an estimate for the determined downhole characteristic(s), wherein the downhole characteristic(s) is the fullness of a bailer of a downhole suction tool comprising a bailer, miller teeth health of a downhole milling tool comprising milling teeth, drilling bit health of a downhole drilling tool comprising at least one drilling bit, cutting bit health of a tubing cutting tool, and/or a representation of the different fluids in the well.

At least one sensor may be an electrode and/or an ampere metre. The method can thereby be performed using standard equipment.

The method may further comprise registering the angle of the at least one sensor with respect to gravity, preferably using an accelerometer. Improved determining of the downhole characteristic is thereby possible.

The supervised machine learning method may be configured to operate a random forest algorithm.

In an embodiment, the method comprises pre-processing the measured values of the physical property by applying feature scaling or an automatic gain control technique to overcome data imbalance, e.g. by changing how the data are distributed across the possible data values. Such pre-processing will improve any machine learning classifier to more accurately perform classification.

According to a second aspect, a computer programme product comprising a computer-readable medium having thereon a computer programme comprising programme instructions is provided. The computer programme is loadable into a data-processing unit and adapted to cause execution of the method according to the first aspect when the computer programme is run by the data-processing unit.

Other objectives, features and advantages of the present invention will appear from the following detailed disclosure and from the attached claims as well as from the drawings. It is noted that the invention relates to all possible combinations of features.

It should be emphasised that the term “comprises/comprising” when used in this specification is taken to specify the presence of stated features, integers, steps, or components, but does not preclude the presence or addition of one or more other features, integers, steps, components, or groups thereof. All terms used in the claims are to be interpreted according to their ordinary meaning in the technical field, unless explicitly defined otherwise herein. All references to "a/an/the [element, device, component, means, step, etc.]" are to be interpreted openly as referring to at least one instance of the element, device, component, means, step, etc., unless explicitly stated otherwise.

Brief description of the drawings

By way of example, embodiments of the present invention will now be described with reference to the accompanying drawings, in which

Fig. 1 shows a schematic view of a system for determining downhole characteristics in a production well according to an embodiment,

Fig. 2a shows a schematic view of four different arrangements of electrodes for measuring fluid permittivity according to an embodiment,

Fig. 2b shows an isometric view of a downhole tool for measuring fluid permittivity according to an embodiment,

Fig. 3 shows a flowchart of a method for measuring downhole characteristics in a production well according to an embodiment, and

Fig. 4 shows a flowchart of a machine learning method for determining a downhole characteristic according to an embodiment.

Detailed description of the invention

Embodiments of the invention will now be described with reference to the accompanying drawings. The invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. The terminology used in the detailed description of the particular embodiments illustrated in the accompanying drawings is not intended to be limiting of the invention. In the drawings, like numbers refer to like elements.

Fig. 1 shows a system for determining one or more downhole characteristic(s) in a production well 10. The system comprises a data-processing unit 30 configured to execute a method 100 for measuring one or more physical properties and to determine the one or more downhole characteristic(s) in the production well 10.

The data-processing unit 30 is operatively connected to a sensor 12, which in turn is operatively connected to a downhole tool 14 of the well 10. As will be further explained in the following description, the downhole tool 14 may be a milling tool, a tubing cutting tool, an opening drilling tool, a suction tool, such as a cleaning tool with a bailer, or any other tool suitable to be lowered downhole. The downhole tool 14 may be provided with one or more sensor(s) 12. In the case of a milling tool, a tubing cutting tool, an opening drilling tool and/or a suction tool, the one or more sensor(s) 12 can be implemented as an ampere metre configured to measure 110 the current provided to the downhole tool 14.

In another embodiment, the downhole tool may be a sleeve manipulation tool, and the downhole characteristics may comprise the sleeve position. In this way, the sleeve manipulation tool can predict when the sleeve is half open or fully open/closed, e.g. from measuring the current in the wireline/cable. In yet another embodiment, the downhole tool may be a tubing cutting tool cutting the tubing with one or more cutting bit(s), and the downhole characteristics may comprise the cutting bit health which can be predicted e.g. from measuring the current in the wireline/cable. Furthermore, the downhole tool may be an opening drilling tool drilling one or more openings in the wall of the production casing/well tubular metal structure with a drilling bit, and the downhole characteristics may comprise the drilling bit health which can be predicted e.g. from measuring the current in the wireline/cable.

The current provided to the downhole tool 14 will normally vary over time; in the case of a milling tool, less current will be needed as the miller teeth become worn out and damaged. The same reasoning also applies for suction tools, as the drive current will vary depending on the fullness of the bailer of the suction tool. When cutting a tubing by means of a cutting tool, e.g. for retraction of an upper part of the tubing, and the bits of the cutting tool become worn out or damaged, then the power consumption will also change.

Again referring to the downhole tool 14 being a milling tool, by measuring 110 the current provided to the milling tool 14, a machine learning method 200 is used to determine the miller teeth health based on the measured current values. The machine learning method 200 will be further detailed with reference to Fig. 4. The method is preferably used to classify the working status of the milling tool and to predict its remaining teeth life. The working status of the milling tool could be clogged, break through, or that the miller teeth are reaching the end of their lifetime. Machine learning classifiers can therefore be used to classify the working status of the milling tool, and machine learning regressors can be used to predict the residue of the teeth life.

The downhole tool 14 may in an alternative embodiment be a suction tool comprising a bailer. The current provided to the suction tool 14 also varies over time as the bailer fills up. The machine learning method 200 may consequently be used in a similar manner to determine the fullness of the bailer from initial measurements of the current supplied to the suction tool. When using a suction tool 14, the method can be used to predict how full the associated bailors are. The bailors store the debris and/or sand, and the ability to predict its fullness during an operation helps the field personnel plan for operation. In particular, machine learning is used to help predict the fullness of the bailor based on the electrical current as the input.

The downhole tool 14 may also in an alternative embodiment be a downhole fluid property detection tool comprising multiple electrodes arranged in a circle or along a cylinder periphery as in Fig. 2b. Moreover, the side view of the sensors 12 for measuring the fluid physical property downhole is shown in Fig. 2a. Four different arrangements of the sensors 12 are implemented by the tool. These arrangements are particularly suited for measuring fluid permittivity using electrodes 12, which may be used to determine a water flow regime of the production well 10. The term “water flow regime” should in this context be interpreted as a representation of the different fluids in the well, in particular at a common cross-section of the well.

As is shown in Fig. 2a, eight electrodes are distributed along the circumference of the tool. In a first measurement, two adjacent electrodes 12 are used. In a second measurement, two electrodes are used being spaced apart by one intermediate electrode. In a third measurement, two electrodes are used being spaced apart by two intermediate electrodes. In a fourth measurement, two electrodes are used being spaced apart by three intermediate electrodes. During the measurements, the intermediate electrodes are not used. When measuring the potential difference between two different electrodes 12, four different types of measurements are thereby possible depending on which arrangement of electrodes is used. The measured values will be lower in the arrangements labelled with higher numbers in Fig. 2a, which means that these measurements are more susceptible to noise. The machine learning method 200 may be used to determine how these different types of measurements are to be processed, e.g. to outbalance the influences of noise. Furthermore, the downhole fluid property detection tool 14 comprises an accelerometer 18 in order to measure the gravitational force acting on the downhole fluid property detection tool 14. The measured gravitational force is used to register 120 the angle of the electrodes 12. The angle of the electrodes 12 may be input to the machine learning method 200 to further improve the results.

It would also be possible to provide a temperature sensor for measuring the temperature downhole and to use the measured temperature as an additional downhole property. In the case of permittivity, as this property is dependent on the temperature, it will be possible for the machine learning model to more accurately determine the downhole characteristic, such as the water flow regime, i.e. a representation of the different fluids in the well, in particular at a common cross-section of the well. The data processing unit 30 of Fig. 1 is further operatively connected to a display 16. The data processing unit 30 may be configured to display 160 measured values of physical properties, determined downhole characteristics, or a combination of both on the display 16.

Fig. 3 schematically shows a method 100 for measuring downhole characteristics in a production well 10. The method 100 comprises several steps 110-170. These steps 110-170 may be performed in any order, some may be skipped, and others repeated, and different steps may be performed by different units of the data processing unit 30 and/or the downhole tool 14.

A measuring step 110 comprises measuring a physical property of the production well 10 using at least one sensor 12. The sensor 12 may be any sensor suitable for measuring physical properties, such as an electrode, an ampere metre, a thermometer, or an optical sensor to mention a few. More than one sensor 12 may further be used, and more than one type of sensor 12 may be combined.

A registering step 120 comprises registering the angle of the at least one sensor 12 with respect to gravity, e.g. by using an accelerometer 18. The accelerometer 18 may also be configured to register 120 the movement of the at least one sensor 12.

A pre-processing step 130 comprises pre-processing the measured values of the physical property using feature scaling and/or an automatic gain control technique to overcome data imbalance. This may also comprise using min-max normalisation, mean normalisation, Gaussian standardisation, amplifying and/or averaging measurements. The purpose of performing feature scaling and/or automatic gain control may be to balance highly varying magnitudes from the at least one sensor.

The method 100 may comprise an optional pre-determining step 125 before the processing step 140 and even before the optional pre-processing step 130. The pre-determining step 125 comprises using linear or non-linear system identification. Thus, before performing feature scaling and/or automatic gain control, the method may also comprise linear regression and/or fitting to known models. By having a pre-determining step 125, the measured values of the physical property are determined to be linear or stepwise-linear (non-linear), and from such pre-determining step, the most suited feature scaling or automatic gain control can be chosen. From the test data, such linear or non-linear system identification may be unnecessary as such information may be known.

A determining step 150 comprises determining a downhole characteristic using a supervised machine learning method 200. This step is discussed further with reference to Fig. 4.

An optional displaying step 160 comprises displaying the measured physical property and/or the determined downhole characteristic on a display 16. The displaying step 160 may further comprise displaying the registered 120 angle or movement of the at least one sensor 12 on a display 16. The displayed content may be useful for an operator to improve the operation of the production well 10.

The displaying step 160 may further comprise alerting an operator to a problem with the production well 10 based on the measurements made. The alert may be visual or audial according to methods known by the skilled person.

An optional sending/transmitting step 170 comprises sending a control signal based on the determined downhole characteristic. The signal may be sent to a downhole tool 14 in the well 10. The control signal can e.g. stop a milling tool 14 because its teeth are too worn out or stop a suction tool 14 because its bailer is full. Alternatively or additionally, the control signal can be used to control various operations downhole in order to improve the productivity of the well.

Fig. 4 shows a machine learning method 200 for determining a downhole characteristic. The machine learning method 200 shown is a supervised machine learning method using a random forest algorithm. Alternatively, a neural network, a Bayesian regression algorithm, or any supervised machine learning method may be used.

The machine learning method 200 starts by cross-validating 210 a predictive analytics algorithm with training data that are previously measured physical properties measured by the sensor of the downhole tool, e.g. in another well or a testing facility. This comprises inputting a subset of previously measured physical properties with known corresponding downhole characteristics into the machine learning method 200 as training data, and the remaining subset of previously measured physical properties acts as test data to verify the estimation. The set may have any number and range of data points sufficient to provide a reliable estimation.

The machine learning method 200 may use the training data to find a relationship between the measured physical property of the production well 10 and the corresponding downhole characteristics. Based on this, any new measurement 110 may apply 220 the found relationship to estimate downhole characteristics.

The machine learning method 200 further comprises applying 220 one or more algorithms, such as data mining algorithms, to the measured 110 values of the physical property to converge on an estimate for the determined downhole characteristic. This comprises using algorithms such as random forest to find a correlation between the measured 110 values of the physical property and the downhole characteristic using the training data. Once found, the relationship is applied to all new measured 110 values. Newly measured 110 values may also be fed back into the machine learning method 200 to further improve the algorithm used.

As mentioned previously, the registered 120 acceleration data may be used instead of or in addition to the measured physical property, and a number of different physical properties may be used related to different downhole characteristics. In the case of several different measurement data being used in the same machine learning method 200, the method 200 may find them to be correlated or not, which may or may not improve the estimation of the downhole characteristics.

Many modifications and other embodiments of the inventions set forth herein will come to mind to one skilled in the art to which these inventions pertain having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the inventions are not to be limited to the specific embodiments disclosed, and that modifications and other embodiments are intended to be included within the scope of the appended claims. Moreover, although the foregoing descriptions and the associated drawings describe exemplary embodiments in the context of certain exemplary combinations of elements and/or functions, it should be appreciated that different combinations of elements and/or functions may be provided by alternative embodiments without departing from the scope of the appended claims. In this regard, for example, different combinations of elements and/or functions than those explicitly described above are also contemplated as may be set forth in some of the appended claims. In cases where advantages, benefits, or solutions to problems are described herein, it should be appreciated that such advantages, benefits and/or solutions may be applicable to some example embodiments, but not necessarily all example embodiments. Thus, any advantages, benefits, or solutions described herein should not be thought of as being critical, required, or essential to all embodiments or to that which is claimed herein. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

Claims

1. A method for determining one or more downhole characteristic(s) in a production well (10), comprising the steps of:
- measuring (110) a physical property of the production well (10) using at least one sensor (12),
- pre-processing (130) the measured values of the physical property using feature scaling and/or automatic gain control techniques, and
- determining (150) one or more downhole characteristic(s) using a supervised machine learning method (200) comprising the steps of:
- cross-validating (210) a predictive analytics algorithm with training data that are previously measured physical properties, and
- applying (220) one or more algorithms to the measured values of the physical property to converge on an estimate for the determined downhole characteristic(s).

2. The method according to claim 1, further comprising a step of transmitting (170) a control signal based on the determined downhole characteristic(s).

3. The method according to claim 2, wherein the control signal is transmitted to a downhole tool (14).

4. The method according to any one of the preceding claims, wherein said physical property is the permittivity of a fluid in the well and/or the current provided to a downhole tool of the well.

5. The method according to any one of the preceding claims, further comprising pre-determining (125) said one or more downhole characteristic(s) using a linear or non-linear system identification.

6. The method according to claim 4, wherein the physical property is measured (110) using multiple sensors (12) in at least two different configurations, and wherein pre-determining (125) the downhole characteristic(s) comprises using the non-linear or linear system identification.

7. The method according to any one of claims 1-5 or 7, wherein the downhole tool (14) is a suction tool comprising a bailer, and the downhole characteristic(s) comprises the fullness of the bailer.

8. The method according to any one of claims 1-5 or 7, wherein the downhole tool (14) is a milling tool having miller teeth, and the downhole characteristic(s) comprises the miller teeth health.

9. The method according to any one of claims 1-5 or 7, wherein the downhole tool is an opening drilling tool having at least one drilling bit, the downhole characteristic(s) comprising the drilling bit health.

10. The method according to any one of claims 1-5 or 7, wherein the downhole tool is a tubing cutting tool having one or more cutting bit(s), the downhole characteristic(s) comprising the cutting bit health.

11. The method according to any one of the preceding claims, wherein at least one sensor (12) comprises an electrode and/or an ampere metre.

12. The method according to any one of the preceding claims, further comprising the step of registering an angle of the at least one sensor (12) with respect to gravity using an accelerometer (18).

13. The method according to any one of the preceding claims, wherein the supervised machine learning method (200) is configured to operate a random forest algorithm.

14. The method according to any one of the preceding claims, further comprising the step of pre-processing (130) the measured values of the physical property by applying feature scaling and/or an automatic gain control technique to overcome data imbalance.

15. A computer programme product comprising a computer readable medium, having thereon a computer programme comprising programme instructions, the computer programme being loadable into a data-processing unit (30) and adapted to cause execution of a method (100) according to any one of the preceding claims when the computer programme is run by the data-processing unit (30).

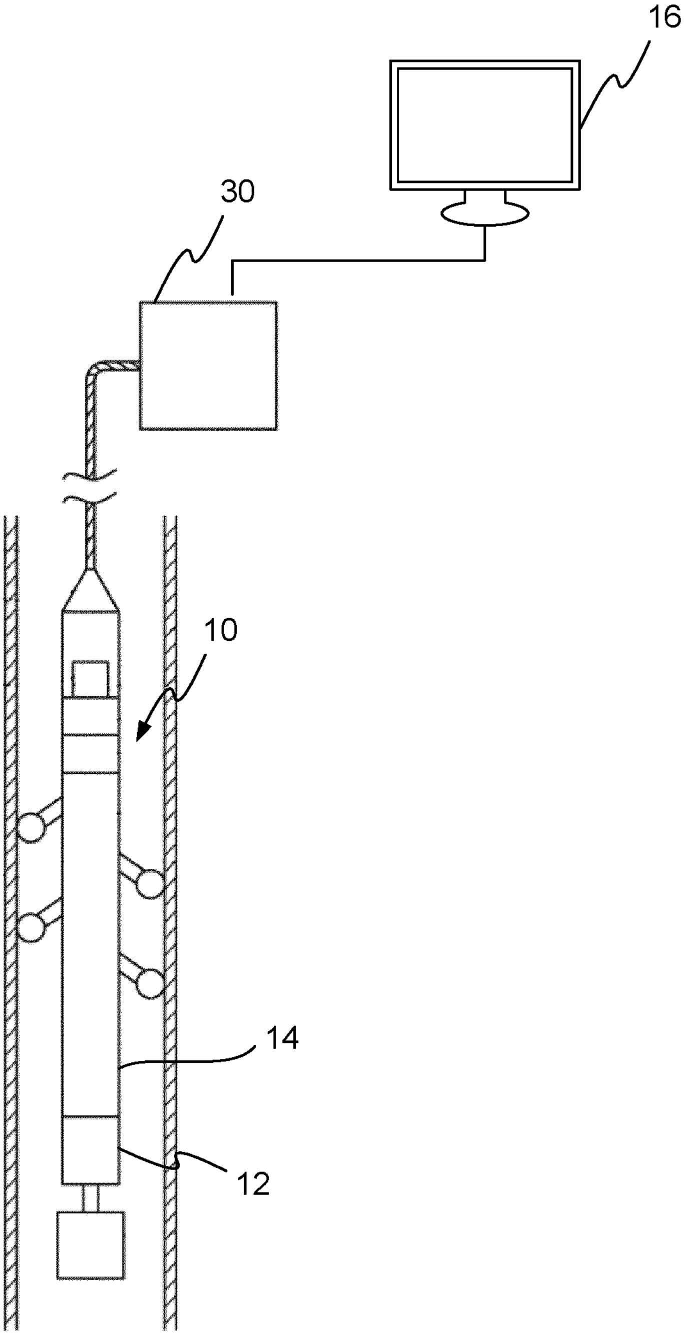


Fig. 1

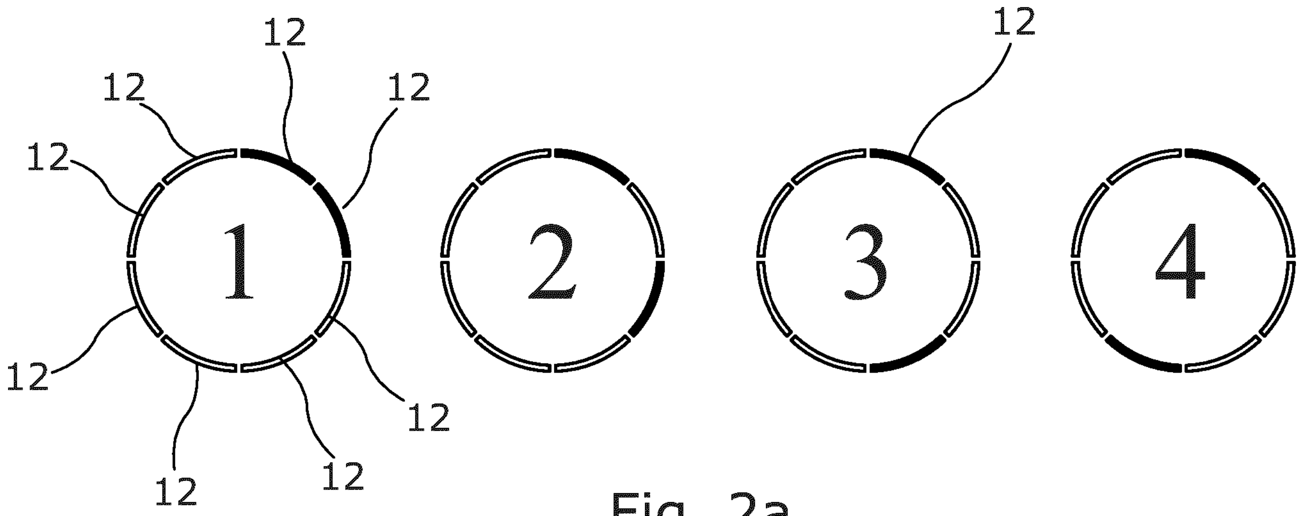


Fig. 2a

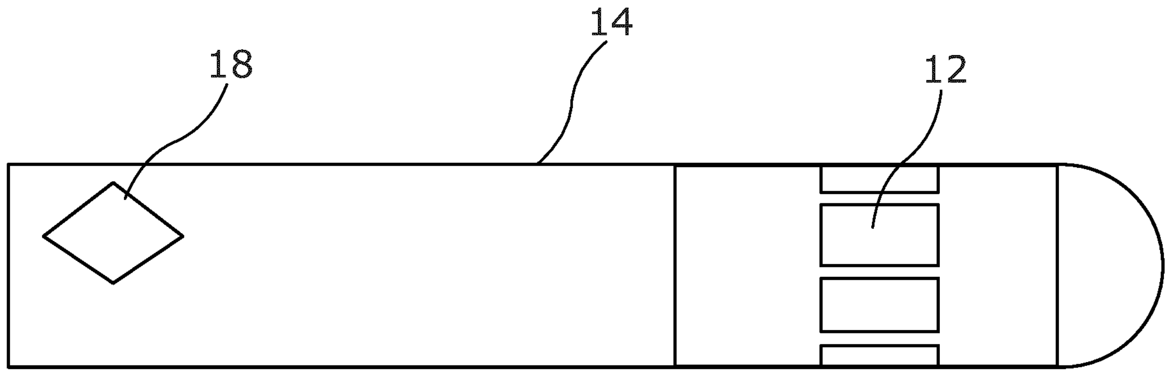


Fig. 2b

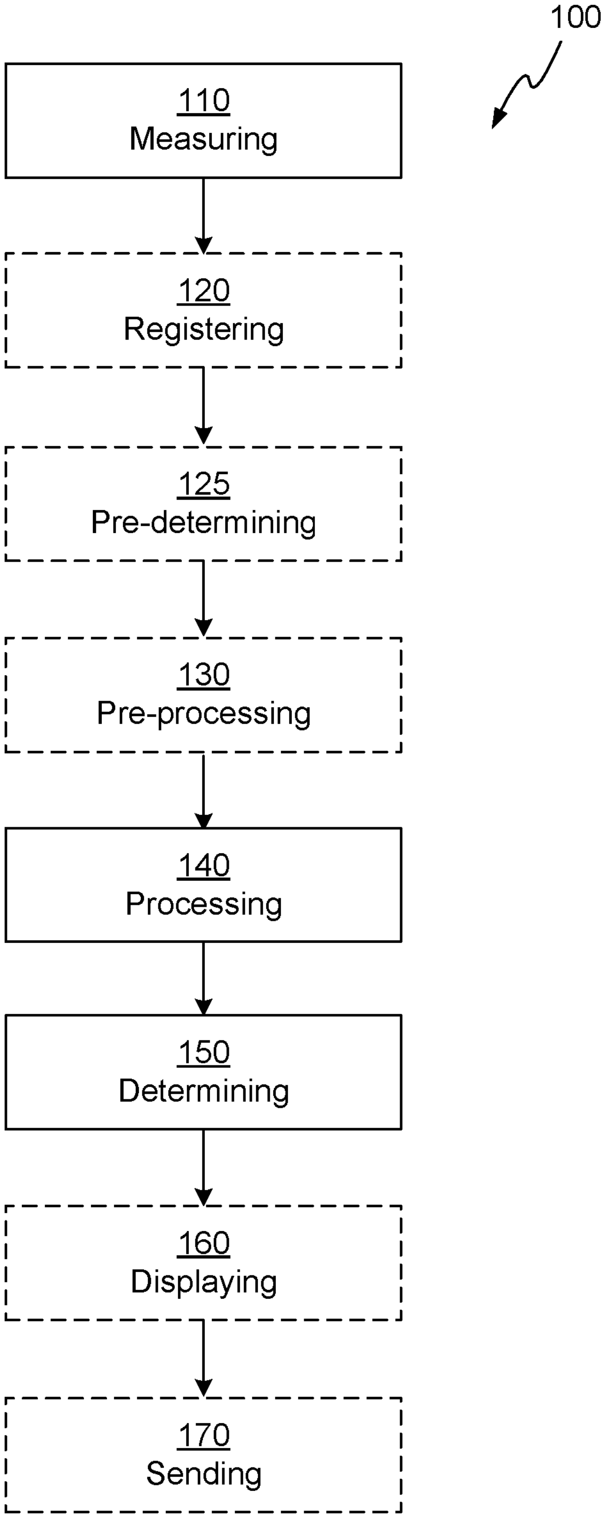
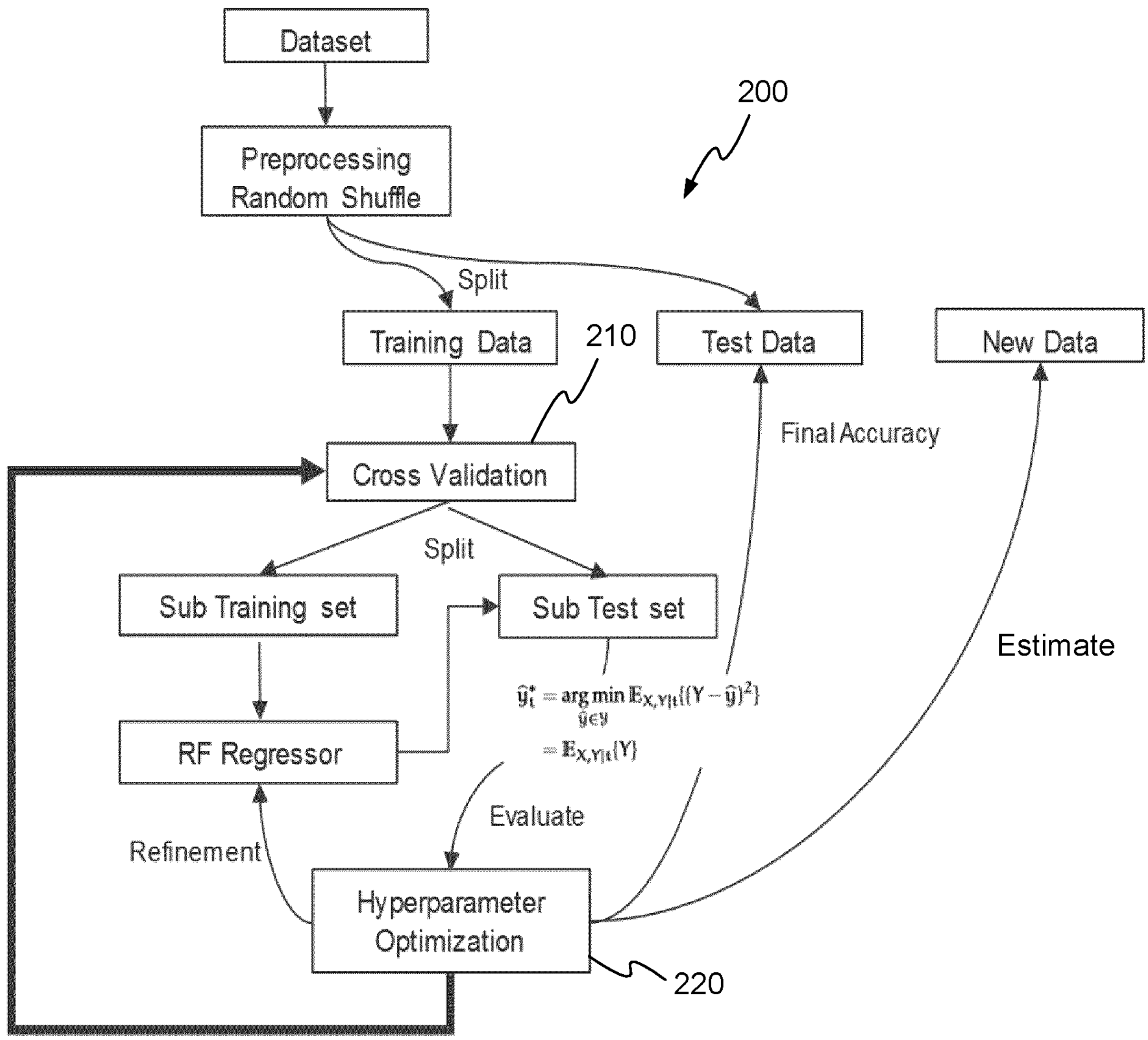

100
110
Measuring
120
Registering
125
Pre-determining
130
Pre-processing
140
Processing
150
Determining
160
Displaying
170
Sending

Fig. 3



Dataset
Preprocessing Random Shuffle
200
Split
Training Data
210
Test Data
New Data
Final Accuracy
Cross Validation
Split
Sub Training set
Sub Test set
Estimate
$\hat{y}_t^* = \arg\min_{\hat{y} \in y} \mathbb{E}_{X,Y|t}\{(Y-\hat{y})^2\} = \mathbb{E}_{X,Y|t}\{Y\}$
RF Regressor
Evaluate
Refinement
Hyperparameter Optimization
220

Fig. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2020/053341

A. CLASSIFICATION OF SUBJECT MATTER
INV. E21B41/00 E21B47/00 E21B49/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
E21B

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 9 022 140 B2 (RESOURCE ENERGY SOLUTIONS INC [CA]) 5 May 2015 (2015-05-05) column 6, line 4 - column 10, line 41 column 15, line 12 - column 23, line 14	1-3,5,6, 8-10, 13-15
X	US 2014/121973 A1 (BUCHANAN STEVEN EUGENE [US] ET AL) 1 May 2014 (2014-05-01) paragraphs [0002], [0003], [0019], [0020], [0022], [0028], [0032], [0035], [0036], [0042], [0048]; figures 1-3,9-10	1-4, 11-15
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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
16 April 2020	24/04/2020

Name and mailing address of the ISA/	Authorized officer
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