

(21) Application No: 1618623.1
 (22) Date of Filing: 04.11.2016

(51) INT CL:
 B60W 50/00 (2006.01)

(56) Documents Cited:
 EP 1936465 A2 CN 203385554 U
 CN 103162964 A US 20150039206 A1

(71) Applicant(s):
Jaguar Land Rover Limited
 (Incorporated in the United Kingdom)
 Abbey Road, Whitley, Coventry, Warwickshire,
 CV3 4LF, United Kingdom

(58) Field of Search:
 INT CL B60W
 Other: WPI; EPODOC

(72) Inventor(s):
David James Battersby
Charles Dickerson
Siyuan Ji

(74) Agent and/or Address for Service:
Jaguar Land Rover
 Patents Department W/1/073, Abbey Road, Whitley,
 COVENTRY, CV3 4LF, United Kingdom

(54) Title of the Invention: **Calibration system and method**
 Abstract Title: **A calibration system for a motor vehicle and a method**

(57) A calibration system 20a, 20b, 20c for determining calibration parameter values for a vehicle 10 and a method are provided. The calibration system (20a, 20b, 20c) comprises an input 22a, 22b arranged to receive sensor output data from a plurality of vehicle sensors 16, 116, the sensor output data of each vehicle sensor 16, 116 relates to a measured value of an objective variable of a vehicle subsystem or component 12, 112 at a current value of a calibration parameter of the vehicle 10. A processor 20b is arranged to determine a permissible range of values for the calibration parameter, the processor being further arranged, for each objective variable, to adjust the current value of the calibration parameter until a calculated object variable value reaches an objective variable constraint value, each calculated object variable value being calculated in dependence on the received sensor output data. An output 24, 124 is arranged to output the permissible range of values to a control unit 14, 114 in order to control the vehicle subsystem or component 12, 112.

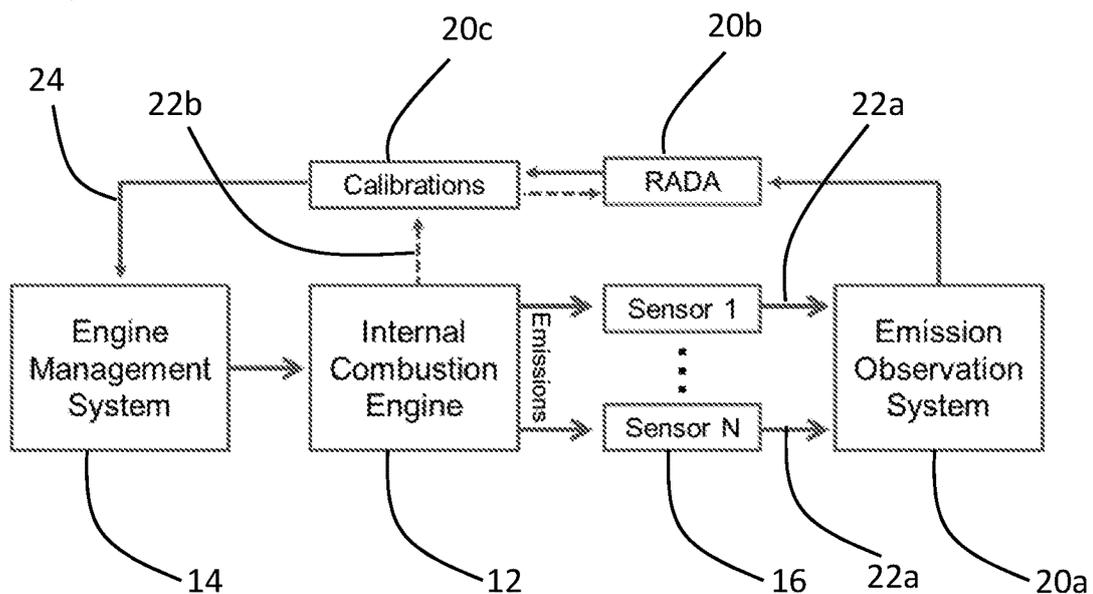
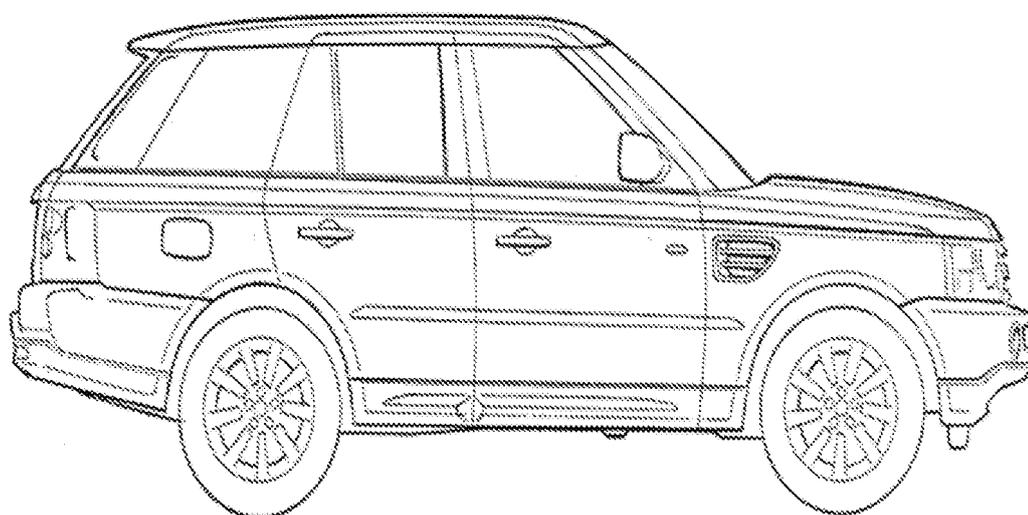


Figure 2



10

09 02 18

Figure 1

09 02 18

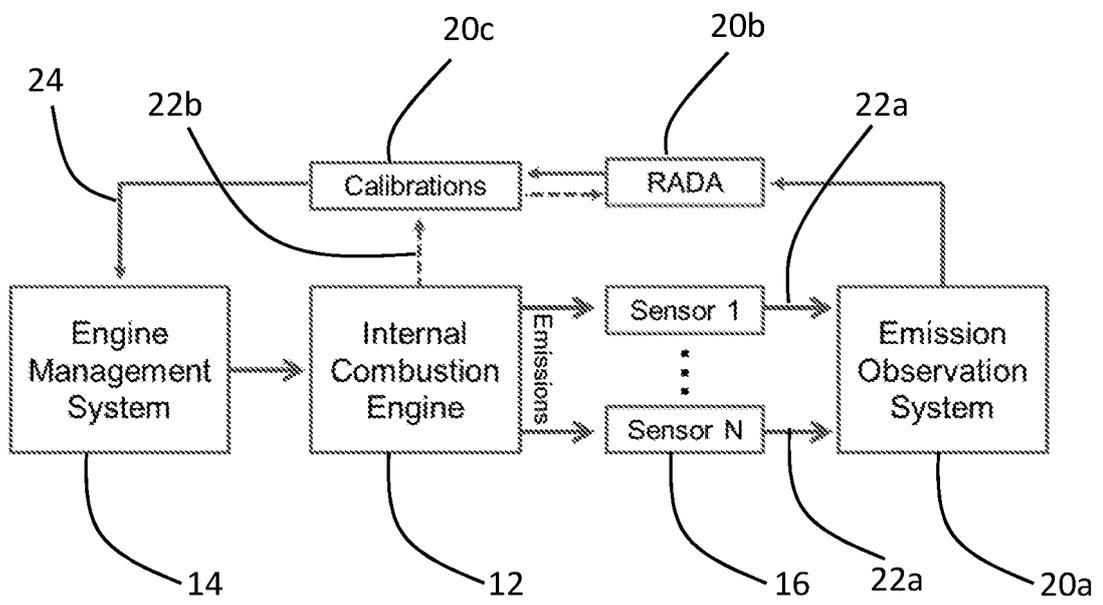


Figure 2

09 02 18

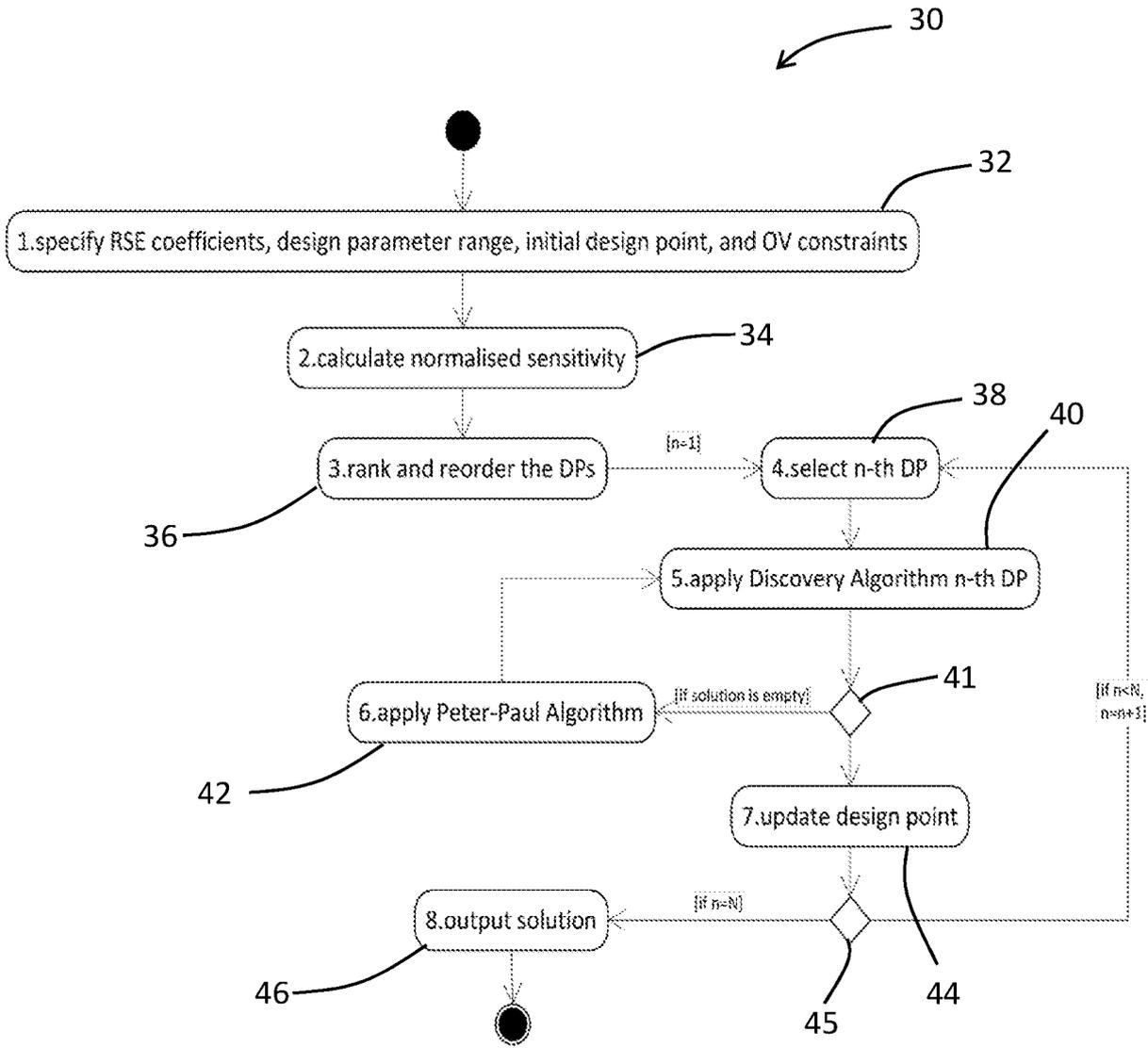


Figure 3

09 02 18

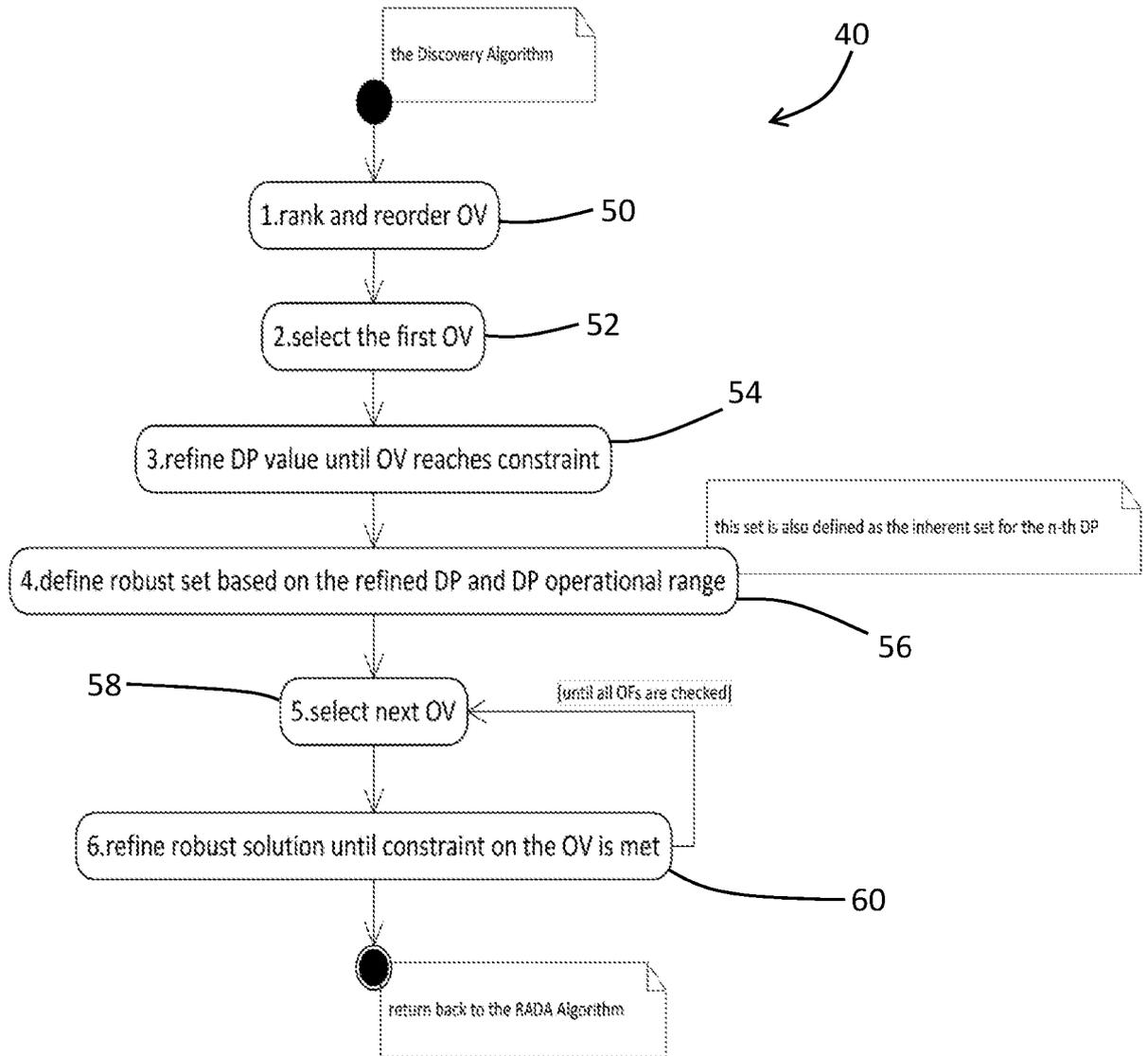


Figure 4

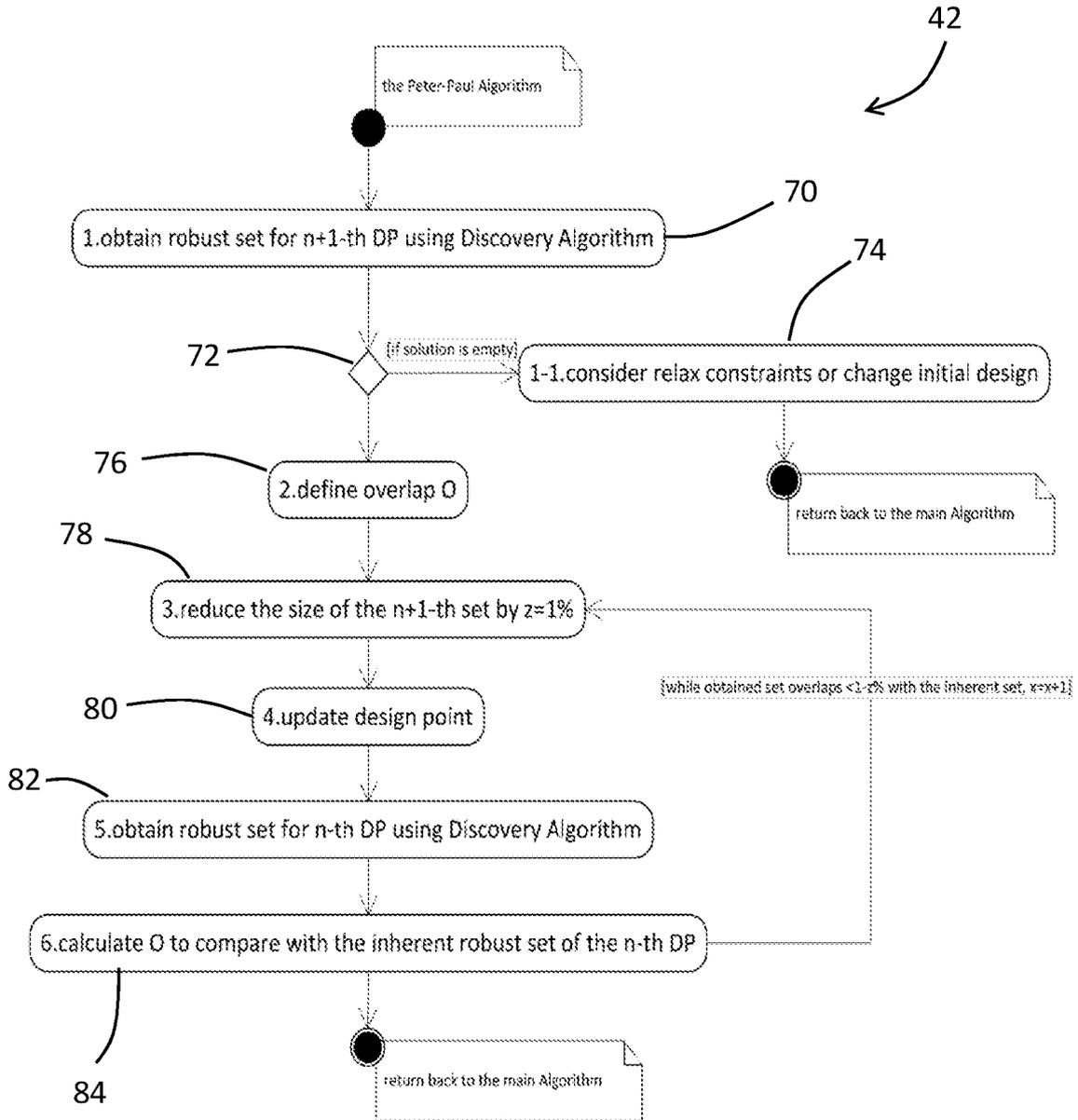


Figure 5

09 02 18

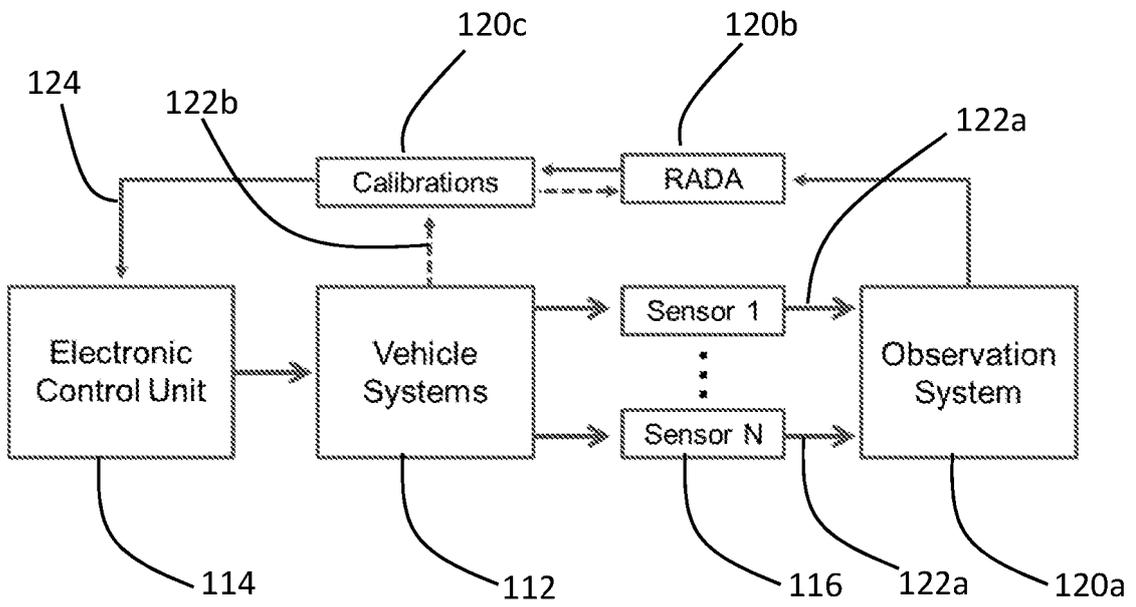


Figure 6



The following terms are registered trade marks and should be read as such wherever they occur in this document:

RADA (page 8,9,10,11,12,14,15,16,17,18,21,22)

ROSETTA (page 9,17,18,19)

RSE (10,18)

CALIBRATION SYSTEM AND METHOD

TECHNICAL FIELD

- 5 The present disclosure relates to calibration system and method and particularly, but not exclusively, to a calibration system and method for use in a vehicle. Aspects of the invention relate to a calibration system, to a method, and to a vehicle.

BACKGROUND

10

The calibration of systems and subsystems in high interaction complex vehicles is becoming a Big Data problem. This is placing greater demands on vehicle management and control systems and, in particular, the associated calibrations of such control systems. These types of problems occur in, for example, systems for
15 vehicle emissions control, electric vehicle energy and battery management, advanced driver assistance systems, and chassis control.

In the case of vehicle emissions control, expensive physical tests and design of experiments are typically used to collect large sets of observations of emissions from
20 an internal combustion engine measured under known conditions and values of calibration parameters. Final calibrations are made using expert opinion.

Measurements and calibrations are currently made prior to production of the vehicle then applied across the associated product line. The suitability of these calibrations
25 can degrade after vehicle deployment and use by a vehicle user. Furthermore, actual driver behaviour may not be ideally matched to the expected use of the vehicle by regulators and manufacturers.

Also, regulations on automotive vehicle emissions are becoming significantly stricter.
30 The challenges to automotive manufacturers may increase as future regulations seek to observe and measure emissions during vehicle operation.

For the case of electric or hybrid vehicles, battery systems need to be monitored and adjusted to better manage energy and extend vehicle operating range.

It is an aim of certain embodiments of the present invention to address at least some disadvantages associated with the prior art.

5 SUMMARY OF THE INVENTION

Aspects and embodiments of the invention provide a calibration system, a method, and a vehicle as claimed in the appended claims.

10 According to an aspect of the present invention there is provided a calibration system for determining calibration parameter values for a vehicle. The calibration system comprises an input arranged to receive sensor output data from a plurality of vehicle sensors, the sensor output data of each vehicle sensor relating to a measured value of an objective variable of a vehicle subsystem or component at a current value of a
15 calibration parameter of the vehicle. The calibration system also comprises a processor arranged to determine a permissible range of values for the calibration parameter, the processor being arranged, for each objective variable, to adjust the current value of the calibration parameter until a calculated object variable value reaches an objective variable constraint value, each calculated object variable value
20 being calculated in dependence on the received sensor output data. The calibration system also comprises an output arranged to output the permissible range of values to a control unit in order to control the vehicle subsystem or component.

The calibration system may comprise a vehicle calibration system for determining
25 calibration parameter values for the vehicle.

The present invention is advantageous in that the permissible range of values that a calibration parameter may be set at is updated during use of the vehicle to account for changes in measured sensor values over time caused by, for example, different
30 conditions external to the vehicle or degradation of vehicle systems. Such updates to the permissible range of values ensure that the measured sensor values continue to satisfy one or more constraints, for example in respect of vehicle emissions levels. The permissible range of values may be updated in real time, after the vehicle has travelled a prescribed distance, or after a prescribed amount of time, for example.

Also, the present invention ensures that the updated permissible range of values is maximised so that there is a maximal amount of freedom in controlling the value of the calibration parameter with which to operate the vehicle subsystem or component: this
5 may be beneficial from a performance or cost perspective, for example. That is, the calibration system determines a range or set of values that are maximal, not just individual values of the calibration parameter.

The present invention is deterministic, repeatable, and scales linearly, and so also
10 benefits from being significantly less computationally expensive compared with prior art constrained objective optimisation systems.

The processor may comprise an electronic processor and the input may be an electrical input. The calibration system may have an electronic memory device
15 electrically coupled to the electronic processor and having instructions stored therein. The processor may be configured to access the memory device and execute the instructions stored therein such that it is operable to determine the permissible range of values for the calibration parameter.

20 The processor may be arranged to set a boundary calibration parameter value in dependence on the adjusted value of the calibration parameter, the permissible range of values being based on the boundary calibration parameter value.

The boundary calibration parameter value may be set to be equal to the adjusted value
25 of the calibration parameter.

The processor may be arranged to calculate a level of sensitivity between each of the measured objective variable values and the current value of the calibration parameter.

30 The processor may be arranged to form a ranked set of each of the objective variables in dependence on the calculated levels of sensitivity.

The processor may be arranged to cycle through each objective variable in the order in which they appear in the ranked set in order to adjust the current value of the
35 calibration parameter.

The objective variables may be ranked in order of decreasing level of sensitivity.

5 Calculating the level of sensitivity may include calculating a normalised sensitivity value for each of the objective variables.

The normalised sensitivity value S_j^i may be defined by

$$S_j^i = \left| \frac{\partial y_j}{\partial x_i} \frac{x_i}{y_j} \right|_{x_i=x_i^d, y_j=y_j^d} = \left| (\beta_{ij} + 2\beta_{iij}x_i^d) \frac{x_i^d}{y_j^d} \right|$$

10 where S_j^i is the normalised sensitivity value, x_i is the calibration parameter, y_i is the objective variable, x_i^d is the current value of the calibration parameter, y_i^d is the measured objective variable value, and β_{ij} and β_{iij} are fitting coefficients.

15 The determination of the permissible range of values may be performed cumulatively such that the permissible range of values for the calibration parameter satisfies each of the object variable constraint values.

The sensor output data may relate to measured objective variable values at current values of a plurality of calibration parameters.

20 The processor may be arranged to calculate an overall level of sensitivity for each of the plurality of calibration parameters.

25 The processor may be arranged to form a ranked set of the plurality of calibration parameters, in which the calibration parameters are ranked in order of decreasing value of the calculated overall level of sensitivity of the calibration parameters.

30 The processor may be arranged to determine the permissible range of values for each of the plurality of calibration parameters in order of decreasing value of the calculated overall level of sensitivity of the calibration parameters.

The overall level of sensitivity S^i may be defined by

$$S^i = S_1^i + S_2^i + \dots + S_M^i$$

where M is the number of object variables.

If the determined permissible range of values for a first one of the calibration
 5 parameters in the ranked set is empty, then the permissible range of values for a
 second calibration parameter next in the ranked set may be used to determine the
 permissible range of values for the first calibration parameter.

If the permissible range of values for a second calibration parameter is also empty,
 10 then the processor may be arranged to prompt a user to adjust one or more of the
 objective variable constraint values or the current value of the first calibration
 parameter, or the processor is arranged to automatically adjust one or more of the
 objective variable constraint values or the current value of the first calibration
 parameter.

15 The processor may be arranged to ensure that an overlap value between the
 permissible range of values for the first calibration parameter that is empty and the
 permissible range of values for the first calibration parameter is above a predetermined
 threshold percentage value.

20 The calculated object variable value may be calculated using a relational function
 dependent on the current value or values of the calibration parameter or parameters
 and one or more fitting coefficients.

25 The relational function may comprise response surface equations.

The response surface equations may be pure quadratic response surface equations.

The relational function may be defined by

30

$$y_j^t = \beta_{0j} + \sum_{i=1}^N \beta_{ij} x_i^d + \sum_{i=1}^N \beta_{ii} (x_i^d)^2$$

where y_j^t is the theoretical objective variable values, β_{0j} is one of the fitting coefficients, and N is the number of calibration parameters.

5 The calibration system may include the control unit for controlling the vehicle subsystem or component, and the control unit may be arranged to control the current value or values of the calibration parameter or parameters to be within the respective permissible range of values.

10 The control unit may be arranged to control the current value of at least one of the calibration parameters to be a centre point of the respective permissible range of values.

The vehicle subsystem or component may be an internal combustion engine of the vehicle and the control unit may be an engine management system.

15 The sensor output data may be indicative of a level of emissions from the internal combustion engine.

20 The vehicle subsystem or component may be a vehicle battery and the control unit may be an electric vehicle energy and battery management system.

The sensor output data may be indicative of at least one of: a battery state-of-charge value, a battery temperature and/or a vehicle range value.

25 The vehicle subsystem or component may be one of an advanced driver assistance system and a chassis control system.

The calibration system may be operable to determine the permissible range of values for the calibration parameter in dependence on one or more trigger conditions.

30 The trigger condition may be that a predetermined amount of time has elapsed since a previous determination of the permissible range of values.

35 The trigger condition may be that an external temperature changes by a predetermined amount.

According to another aspect of the present invention there is provided a calibration method for determining calibration parameter values for a vehicle. The calibration method comprises receiving sensor output data from a plurality of vehicle sensors, the sensor output data of each vehicle sensor relating to a measured value of an objective variable of a vehicle subsystem or component at a current value of a calibration parameter. The calibration method also comprises determining a permissible range of values for the calibration parameter that includes, for each objective variable, adjusting the current value of the calibration parameter until a calculated object variable value reaches an objective variable constraint value, each calculated object variable value being calculated in dependence on the received sensor output data. The calibration method also comprises outputting the permissible range of values to a control unit in order to control the vehicle subsystem or component.

The method may comprise a vehicle calibration method for determining calibration parameter values for the vehicle.

According to another aspect of the present invention there is provided a vehicle comprising a vehicle calibration system as described above.

According to yet another aspect of the present invention there is provided a non-transitory, computer-readable storage medium storing instructions thereon that when executed by one or more processors causes the one or more processors to carry out the method described above.

Within the scope of this application it is expressly intended that the various aspects, embodiments, examples and alternatives set out in the preceding paragraphs, in the claims and/or in the following description and drawings, and in particular the individual features thereof, may be taken independently or in any combination. That is, all embodiments and/or features of any embodiment can be combined in any way and/or combination, unless such features are incompatible. The applicant reserves the right to change any originally filed claim or file any new claim accordingly, including the right to amend any originally filed claim to depend from and/or incorporate any feature of any other claim although not originally claimed in that manner.

BRIEF DESCRIPTION OF THE DRAWINGS

One or more embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

5

Figure 1 is a side view of a vehicle having a calibration system (not shown) according to an embodiment of the invention;

10 Figure 2 is a diagram showing the component parts of the calibration system of Figure 1, together with the inputs to, and outputs from, the calibration system;

Figure 3 is a flow diagram which illustrates a RADA algorithm (defined below) process carried out by the calibration system of Figure 1 for determining a permissible range of values for each of a plurality of calibration parameters;

15

Figure 4 is a flow diagram which illustrates a Discovery algorithm process for carrying out the Discovery algorithm step in the RADA algorithm process of Figure 3;

20 Figure 5 is a flow diagram which illustrates a Peter-Paul algorithm process for carrying out the Peter-Paul algorithm step in the RADA algorithm process of Figure 3; and

Figure 6 is a diagram showing the component parts of a calibration system according to another embodiment of the invention, together with the inputs to, and outputs from, the calibration system.

25

DETAILED DESCRIPTION

30 According to an embodiment of the invention, calibration parameters (CPs) or design parameters (DPs) associated with an internal combustion engine (ICE) of a vehicle are controlled such that emissions levels from the ICE as measured by one or more on-board vehicle sensors fall within levels allowed by regulations. In particular, the sensor measurements indicative of emissions levels are observed and used to define and update in real time a permissible range of values for each CP so as to ensure that allowed emissions level thresholds are not exceeded. An engine management system

(EMS) of the vehicle controls the one or more CPs to take a value within the appropriate permissible range of values.

5 Figure 1 shows a side view of a vehicle 10. With additional reference to Figure 2, the vehicle 10 includes an ICE 12 for providing mechanical power to drive the vehicle 10, an EMS 14 for controlling one or more calibration parameters associated with the ICE 12, and one or more on-board vehicle sensors 16 for measuring values of objective variables (OVs) indicative of the level of emissions from the ICE 12.

10 For example, the calibration parameters can include a manifold air flow rate, main fuel injection timing, intake manifold pressure, fuel rail pressure, and low pressure exhaust gas recirculation (EGR) fraction.

Also, the objective variables indicative of emissions levels can include measurements
15 of soot, NO_x gases, engine noise, exhaust temperature, mean effective pressure and combustion temperature.

The vehicle additionally includes a calibration system 20a, 20b, 20c. In particular, the calibration system 20a, 20b, 20c has: inputs 22a, 22b arranged to receive sensor
20 output data from the one or more sensors 16 and to receive a current value of each calibration parameter from the ICE 12; a so-called 'RADA' algorithm module 20b including a processor; and, an output 24 arranged to send to the EMS 14 a calculated permissible range of values for each of the calibration parameters. The acronym RADA means ROSETTA Axiomatic Design Algorithms, and this algorithm is based on
25 the principles of the Relational Oriented System Engineering Technology Trade-off Analysis (ROSETTA) framework and Axiomatic Design. The steps carried out by the processor in the RADA algorithm module 20b to calculate permissible ranges of values for each calibration parameter are discussed in detail below.

30 Controlling the EMS 14 to vary the value of one or more of the calibration parameters results in variation of the emission levels from the ICE 12 as measured by the sensors 16, i.e. variations in the measured OV values. Each OV has a respective OV constraint value, for example a regulation requirement, and the calibration parameter values need to be controlled such that each of the OV constraints are satisfied. The OV

constraints can include ensuring that NO_x emissions are below a threshold value (e.g. below 4.8 g/h), soot emissions are below a threshold value (e.g. 1.7 g/h), engine noise is lower than a prescribed value (e.g. 77 dB), and fuel consumption is below a certain level (e.g. 5.5 kg/h).

5

The principle of the RADA algorithm 20b is to determine the largest range of values, also referred to as a maximal robustness set, that each calibration parameter may take such that each measurement indicative of emissions levels is at an allowable level, i.e. each objective variable constraint is satisfied.

10

Figure 3 shows a method 30 undertaken by the processor of the RADA module 20b for determining the largest permissible range of values that each calibration parameter may take with the objective variable constraints still being satisfied. When the RADA algorithm is run initially, there are several inputs received at step 32. In particular, a user provides an initial (current) value of each of the N calibration parameters x_i^d , $i = 1..N$, and an initial (current) design range of values $[x_i^{min}, x_i^{max}]$ for each calibration parameter, i.e. the range of values within which a given calibration parameter should be from a design point of view.

15

20

Also at step 32 the user inputs an objective variable constraint value $y_j^c, j = 1..M$ for each of the M objective variables, where y_j^c may be either an upper or lower threshold value above or below which a given objective variable value should not exceed, respectively. Note that it is possible that one or more of the objective variables could have both upper and lower constraint values; however, the present embodiment describes the case of a single constraint value associated with each of the OVs.

25

The RADA algorithm 20b uses pure quadratic response surface equations (RSEs) to describe the relationship between the calibration parameters and the objective variables. In particular, at step 32 the user inputs coefficients of the RSEs, that is, the user specifies the RSEs algebraically.

30

At step 34, the RADA algorithm 20b calculates a level of sensitivity between each of the OVs and each of the calibration parameters. In particular, the RADA algorithm 20b

calculates a normalised sensitivity S_j^i for each CP-OV pair, in particular the S_j^i are calculated using

$$S_j^i = \left| \frac{\partial y_j}{\partial x_i} \frac{x_i}{y_j} \right|_{x_i=x_i^d, y_j=y_j^d} = \left| (\beta_{ij} + 2\beta_{iij}x_i^d) \frac{x_i^d}{y_j^d} \right|,$$

5 where $x_i, i = 1..N$ are the calibration parameters, y_i are the objective variables, x_i^d is the initial or current value of the i^{th} calibration parameter and y_j^d is the measured value of the j^{th} objective variable provided as input for the RADA algorithm 20b, and β_{ij} and β_{iij} are fitting coefficients.

10 The normalised sensitivity is a metric for describing how sensitive a particular objective variable is to variation in a given calibration parameter, i.e. a relatively small variation in a given calibration parameter leading to a relatively large variation in a given objective variable would give a relatively high normalised sensitivity, whereas a relatively small variation in a given calibration parameter leading to a relatively small
 15 variation in a given objective variable would give a relatively low normalised sensitivity.

An overall normalised sensitivity value for the i th CP, $i = 1,2,..,N$ may then be calculated as follows:

$$S^i = S_1^i + S_2^i + .. + S_M^i$$

20 At step 36, the overall normalised sensitivity values for the CPs are ranked in order of sensitivity from highest to lowest, i.e. the S^i values are ranked in descending order of value. The S^i 's are then renumbered so that S^1 has the largest overall normalised sensitivity value and S^N has the smallest overall normalised sensitivity value. Such ranking not only allows linearisation of the problem, but means that the maximal
 25 possible range of robust values may be found, as described below.

Starting with the calibration parameter corresponding to S^1 , i.e. the most sensitive calibration parameter, a so-called Discovery algorithm is applied to each calibration parameter in turn from the highest to the lowest overall normalised sensitivity value,
 30 i.e. to each S^i from $i = 1$ to $i = N$. Specifically, at step 38 the first, i.e. most sensitive,

calibration parameter (corresponding to S^1) is selected and the Discovery algorithm is applied to this calibration parameter at step 40.

Figure 4 shows the steps undertaken by the processor of the RADA module 20b in order to apply the Discovery algorithm 40 to the first calibration parameter. Specifically, at step 52 the values $S_j^1, j = 1..M$ calculated at step 34 are ranked in descending order of value. That is, the S_j^1 , which are normalised sensitivity values for the first CP with each of the OVs, are ranked from the highest to the lowest value of S_j^1 . Similarly to above, the S_j^1 s are then renumbered so that S_1^1 has the largest overall normalised sensitivity value and S_M^1 has the smallest overall normalised sensitivity value.

In general, a theoretical objective variable value, y_j^t , is calculated using the following relational function:

$$y_j^t = \beta_{0j} + \sum_{i=1}^N \beta_{ij} x_i^d + \sum_{i=1}^N \beta_{ii} (x_i^d)^2,$$

where β_{0j} is a fitting coefficient. This equation is a pure-quadratic equation that is used as a response surface equation. The measured OV values from the sensors are discrete data points, whereas the theoretical objective variable values obtained from the above equation approximates the data into a continuous function.

At step 52 the most sensitive objective variable y_1 for the first parameter (corresponding to the normalised sensitivity S_1^1) is selected. At step 54, y_j^t is calculated using the above equation for the theoretical objective variable value.

The Discovery algorithm then adjusts x_1^d until the calculated theoretical OV value y_j^t equals the constraint value associated with the most sensitive OV, y_1^c , i.e. until $y_j^t = y_1^c$. Note that the direction of adjustment or refinement of x_1^d depends on whether y_1^c is a maximum or a minimum, and whether $y_j^t > y_1^c$ or $y_j^t < y_1^c$.

The robust set or permissible range of values for the calibration parameter is then updated at step 56 based on the adjusted x_1^d (also referred to as a boundary value)

and the design range $[x_1^{min}, x_1^{max}]$. In particular, the minimum and maximum values x_1^c and $x_1^{c'}$ are defined such that the value of the OV y_1 satisfies the OV constraint y_1^c for any y_1 calculated using a value in the range $[x_1^c, x_1^{c'}]$. Note that at this stage it may be that $x_1^c = x_1^{min}$ or $x_1^{c'} = x_1^{max}$.

5

At step 58, the next most sensitive objective variable for the first parameter (corresponding to the normalised sensitivity S_1^2) is selected, and y_2^t is calculated using the above equation for y_j^t . In a corresponding manner to step 56, at step 60 the first calibration parameter x_1^d is adjusted until the calculated y_2^t value equals the constraint value associated with the second most sensitive OV, i.e. until $y_2^t = y_2^c$. The robust set or permissible range of values for the calibration parameter is then updated based on the adjusted x_2^d and the previously calculated range $[x_1^c, x_1^{c'}]$. That is, the boundary values x_1^c and $x_1^{c'}$ are updated so that such that y_2 satisfies the objective variable constraint y_2^c for any y_2 calculated using a value in the range $[x_1^c, x_1^{c'}]$. Note that this is cumulative from the previous iteration for the most sensitive OV, i.e. it must still be the case that y_1 satisfies the objective variable constraint y_1^c for any y_1 calculated using a value in the range $[x_1^c, x_1^{c'}]$. This means that the range $[x_1^c, x_1^{c'}]$ can only be narrowed, not broadened.

10

15

20

The method 40 then loops back to step 58 to select the next most sensitive objective variable for the first parameter, that is, the objective variable corresponding to the normalised sensitivity S_1^3 , and the refinement of the permissible range of values $[x_1^c, x_1^{c'}]$ is repeated until y_j satisfies the objective variable constraint y_j^c for any y_j calculated using a value in the range $[x_1^c, x_1^{c'}]$ for all j . Note that the range $[x_1^c, x_1^{c'}]$ may also be referred to as the inherent set.

25

Referring back to Figure 3, the method 30 then checks the range $[x_1^c, x_1^{c'}]$ at step 41 to determine whether it is empty, i.e. to check whether the y_j obtained from values in the calculated range $[x_1^c, x_1^{c'}]$ do not satisfy all of the objective variable constraints y_j^c for all j .

30

If it is determined at step 41 that the range $[x_1^c, x_1^{c'}]$ is empty, then the algorithm proceeds to step 42 where a so-called Peter-Paul algorithm is applied to the range $[x_1^c, x_1^{c'}]$. The Peter-Paul algorithm is used to adjudicate contentions between parameters and may be thought of as a trade-off algorithm. In particular, the steps
5 involved in the Peter-Paul algorithm are shown in Figure 5 and described below.

The input to the Peter-Paul algorithm is the empty set of first calibration parameter values $[x_1^c, x_1^{c'}]$. At step 70, the Discovery algorithm 40 (see Figure 4) is applied to the next (in this case, second) most sensitive calibration parameter x_2 (in general x_{i+1}),
10 i.e. corresponding to S^2 to obtain the range $[x_2^c, x_2^{c'}]$ (in general, $[x_{i+1}^c, x_{i+1}^{c'}]$).

At step 72, the Peter-Paul algorithm 42 checks whether the range $[x_2^c, x_2^{c'}]$ is also empty, i.e. checks whether the y_j obtained from values in the calculated range $[x_2^c, x_2^{c'}]$ do not satisfy all of the objective variable constraints y_j^c for all j .
15

If it is determined at step 72 that the range $[x_2^c, x_2^{c'}]$ is also empty, then the algorithm proceeds to step 74. Reaching this step may indicate that the OV constraints are overly stringent to be achievable or that the initial calibration parameter values x_i^d do not allow the OV constraints to be met. Therefore, at step 74 either: the user is
20 prompted to change, i.e. relax, one or more of the OV constraint values and/or change one or more of the initial calibration parameter values x_i^d ; or, the algorithm automatically changes the OV constraint values and/or the initial calibration parameter values. The Peter-Paul algorithm 42 is terminated at this point and returns to step 40 of the RADA algorithm 30 (see Figure 3) to apply the Discovery algorithm 40 (see
25 Figure 4) again to the first or most sensitive calibration parameter using the changed OV constraint values and/or initial calibration parameter values to re-calculate the permissible range of values $[x_1^c, x_1^{c'}]$.

Returning to Figure 5, if it is determined at step 72 that the range $[x_2^c, x_2^{c'}]$ is not empty,
30 then the algorithm proceeds to step 76. In particular, the range $[x_2^c, x_2^{c'}]$ is then used to refine the range $[x_1^c, x_1^{c'}]$ so that $[x_1^c, x_1^{c'}]$ is not empty. Specifically, at step 76 an

overlap O between a final, refined $[x_1^c, x_1^{c'}]$ that will be output by the Peter-Paul algorithm and the current, empty $[x_1^c, x_1^{c'}]$ that is input to the Peter-Paul algorithm is defined. The overlap O is a percentage overlap between the input and output ranges, and is initially set to zero, i.e., $O = 0$.

5

At step 78, the size of the range $[x_2^c, x_2^{c'}]$ is reduced by a set percentage value z . For example, z may initially be set to 1%; however, any other suitable value may be used. At step 80, an updated current value of the second calibration parameter x_2^d is calculated based on the updated range $[x_2^c, x_2^{c'}]$. For example, the updated current value x_2^d may be the centre point of the updated range $[x_2^c, x_2^{c'}]$, or a separate function
10 may be provided to calculate this value.

The updated current value of the second calibration parameter x_2^d is then used at step 82 to refine the current range $[x_1^c, x_1^{c'}]$ through application of the Discovery algorithm
15 40 (see Figure 4). That is, the value x_2^d is adjusted until the constraint values associated with each of the OVs are satisfied, i.e. until $y_j^f = y_j^c$ for all j .

An updated value of the overlap O is then calculated based on the percentage overlap of the range $[x_1^c, x_1^{c'}]$ input to the Peter-Paul algorithm and the refined range $[x_1^c, x_1^{c'}]$
20 calculated at step 82. In particular, if $O < 100 - z$ (%) then the Peter-Paul algorithm 42 loops back to step 78, where the value of z is increased by an incremental percentage value. For example, z may be increased by 1%; however, any other suitable incremental value may be used. Steps 80 and 82 are then repeated to calculate an updated range $[x_1^c, x_1^{c'}]$.

25

This process is repeated until it is determined at step 84 that $O \geq 100 - z$ (%). The updated, refined and non-empty range $[x_1^c, x_1^{c'}]$ is then output by the Peter-Paul algorithm 42 and the process returns to step 40 of the RADA algorithm 30.

30 Referring back to Figure 3, if it is determined at step 41 that the range $[x_1^c, x_1^{c'}]$ is not empty, then the algorithm proceeds to step 44 where a suggested updated value of the first calibration parameter x_1 is calculated based on the updated permissible range of

values $[x_1^c, x_1^{c'}]$. For example, the suggested updated calibration parameter value x_1 may be the centre point of the range $[x_1^c, x_1^{c'}]$, or a separate function may be provided to calculate this value.

5 The method then loops back to step 38 and selects the second most sensitive calibration parameter (corresponding to S^2). The Discovery algorithm is applied to this calibration parameter at step 40 in exactly the same manner as described above (with reference to Figure 4) so as to calculate the updated permissible range of values $[x_2^c, x_2^{c'}]$.

10

This process is repeated until it is determined at step 45 that all of the calibration parameters $x_i, i = 1..N$ have been considered. The calculated set of suggested updated calibration parameter values $x_i^d, i = 1..N$ is then output at step 46 to the EMS 14.

15

Note that the step of determining suggested updated calibration parameter values may instead be carried out by the EMS 14, in which case the output to the method 30 may simply be the updated permissible ranges of calibration parameter values $[x_i^c, x_i^{c'}], i = 1..N$.

20

The RADA algorithm 30 can be implemented in real time during operation of the vehicle 10. The RADA algorithm 30 can be implemented continuously or at predetermined intervals (e.g. periods of time, distance travelled by the vehicle).

25 It may be that a particular set of calibration parameter values and permissible ranges determined by the calibration system 20a, 20b, 20c is optimal only in certain conditions, for example at a particular external temperature, or it may be that the optimal permissible CP ranges for the ICE 12 when it is new differs from the optimal permissible CP ranges for the ICE 12 after months or years of use, i.e. as the engine
30 performance degrades. Furthermore, actual driver behaviour may not be ideally matched to the expected use of the vehicle by regulators and manufacturers who define initial calibration parameter ranges. Therefore, the calibration system 20a, 20b, 20c can be used to update the permissible range of calibration parameter values so

that an optimal set of permissible ranges is maintained for a variety of conditions. The present calibration system is an effective tool for ensuring that vehicles operate within increasingly stricter emissions regulations.

5 As the vehicle condition changes over time, it is expected that the measured values from the sensors will vary for given values of the engine calibration parameters. Hence, the change in the data leads to a change in the fitting coefficients β_{ij} and β_{iij} in the response surface equation for y_j^t above, which will both impact the normalised sensitivity calculation for S_j^t and the objective variable calculation for y_j^t . As the solution
10 of the algorithm is based on these coefficients, it is likely that the robust sets will change. For example, the algorithm may be executed (and the robust sets updated) in real time or in response to one or more trigger conditions such as predetermined amount of time elapsing since the previous update.

15 The principal design optimisation methods and algorithms related to the problem of constrained objective system design for maximal robustness are legacy algorithms for single objective linear and non-linear optimisation, the traditional Pareto optimality methods, algorithms for multi-objective problems, and state of the art algorithms such as genetic algorithms. Each of these seeks to optimise one or more objective
20 variables; then seeks robustness sets. Whilst legacy linear and quadratic programming algorithms are deterministic, Pareto methods and genetic algorithms are not. Furthermore, all of the approaches are computationally intensive and therefore can be slow and costly when applied to problems associated with robust design of high interaction complex vehicles.

25 The RADA calibration system is distinctly different from all of these and has advantages over each. The RADA algorithm is deterministic, repeatable (given an initial solution), and scales linearly.

30 Furthermore, the ROSETTA aspects of the algorithm are different from Axiomatic Design in the way the relationships between design parameters are exploited. Whilst RADA adopts the philosophy of Axiomatic Design, it uses normalised sensitivities to rank the design parameters then uses these to discover a *collection* of robustness sets which are maximal (not just individual values of calibration parameters).

The traditional way of finding an optimal design solution in a multi-objective problem, particularly for conflicting objectives in which a number of solutions may exist, is to use methods and algorithms to search for the so-called Pareto optimal. Previous
5 algorithms are genetic algorithms which contain the following key elements: population of chromosomes, fitness based selection process, new offspring generation, and random mutation of new offspring. Hence, the algorithm, in a way, mimics the natural selection process. Currently, development of genetic-type algorithms to solve multi-objective problems focuses on the emphasis of robustness to the solution due to the
10 existence of uncertainties in real world problems. To better deal with complex problems that contain many objective functions to optimise at once, the idea of decomposition of multi objectives to a set of single objective has been proposed.

The RADA algorithm uses a very different approach. The algorithm aims at searching
15 a space of design parameters in constrained objective complex system design problems for the purpose of discovering maximal robustness in the parameters. Using RSE, implementation uses an algorithm that automatically ranks and searches design parameters for maximal robustness. With the specification of RSE coefficient and treating all OVs as constrained OVs, the algorithm proceeds through the linear order of
20 ranking one calibration parameter at a time, determining a maximal robust set for each parameter in which the OVs constraints are all fulfilled automatically. Contentions between parameters are adjudicated by a trade-off algorithm. The algorithm constrains the objectives to required values and seeks to maximise permissible variation of the calibration parameters. The result is a maximal collection of robust sets of the
25 calibration parameters.

The Relational-Oriented Systems Engineering and Technology Trade-off Analysis (ROSETTA) framework is a matrix based framework that captures the relational
30 structure of a system of systems. This permits translation between mathematical models, analysis of physical systems, and disparate computer simulations. The central concept is to use available models of the system or its components, e.g. mathematical, simulation or data models to create a static relational structure of design solution space in which the time dependency is not exposed. If a system level model is not available or achievable then lower level models can be used to create the pairwise

sensitivities between the attributes of the operating environment and those of the system.

5 After first identifying the input variables and objectives of the stated problem the static relational structure can be defined. First to be defined is a transformational matrix that captures the relationships between the input variables and the objectives. These could be sensitivities (partial derivatives) of transfer or response surface functions. If there is no coupling between input variables or objective variables, then the transformation matrix alone provides the static relational structure. These transformation relationships
10 are sufficient for design and dynamic simulation. Any coupling between the objective variables is stored in a second matrix, and coupling of the system variables are stored in a further matrix. These matrices together define the static framework.

15 In the general problem, the partial derivatives at a given point in the design solution space, or estimates of their values can be used to populate the Jacobian matrices of the transformational matrix and of the system matrices. When properly combined using the chain rule, the resulting total differentials give system level directions of improvement for the calibration parameters. These are used in ROSETTA in place of a system level model or analytic when none is available.

20 The design algorithm developed to tackle a design problem such as the engine calibration originated from the ROSETTA framework and axiomatic design. In particular, it focuses on the transformational matrix in the ROSETTA framework that reveals the sensitivities of objective variables to calibration parameters. And, further,
25 by adopting the Axiomatic Design philosophy, the algorithm aims to obtain design solutions that are optimal in robustness with a given initial design.

The axiomatic design is a matrix based system design methodology that focuses on the mapping among domains including: customer attributes, functional requirements,
30 calibration parameters, and process variables. In particular, the design method uses two design principles, also known as Axioms:

- **The Independence Axiom:** maintain the independence of the functional requirements;
- **The Information Axiom:** minimise the information content of the design.

The purpose of both of the axioms is to reduce the complexity of the system. For instance, the independence of the functional requirements will minimise the dependencies in the calibration parameter allowing calibration parameters to be determined individually without considering the impact it has on the other calibration parameters. By further minimising the information content, the complexity of the system is purposely reduced even further.

In the Axiomatic Design approach, the first step is to extract the customer requirements into a set of functional requirements. Then, the next step is to select calibration parameters that could achieve the functional requirements. Followed by the step of checking validity against the Independent Axioms and step of evaluating the information content, the final design solution is selected based on the least information.

The design algorithm only focuses on linear and pure quadratic response surfaces; however, any algebraic response surface may be used, as well as to be able to implement different design philosophies that are available to the algorithm users.

In the above-described embodiment, the calibration parameters are ranked in order of decreasing sensitivity relative to their effect on the objective variables, and by considering a cumulative largest allowable range of values for the calibration parameters allows in order of decreasing sensitivity the *maximal* robustness set to be found. Note, however, that consideration of the calibration parameters in a different order is possible to determine a robust set of calibration parameter values, albeit this may not be the maximum possible range.

The above-described embodiment relates to controlling calibration parameters associated with an ICE with a view to ensuring ICE emissions are kept within allowable levels set by regulations; however, the calibration system described herein is equally applicable in controlling different subsystems or components of a vehicle. For example, Figure 6 shows a calibration system 120a, 120b, 120c, which is a generalised version of the calibration system 20a, 20b, 20c of Figure 2. In particular, the calibration system 120a, 120b, 120c includes a generalised observation system 120a receiving sensor output data for sensors 116. The permissible range of

calibration parameters are sent via an output (124) to an electronic control unit (ECU) 114 that controls a vehicle subsystem or component 112 such as, for example, a vehicle battery system, chassis control system or advanced driver assistance system (ADAS).

5

Many modifications may be made to the above examples without departing from the scope of the present invention as defined in the accompanying claims.

APPENDIX

10

The following pseudo code outlines the steps described above for the RADA algorithm 30, together with the inputs and outputs to the algorithm (Figure 3):

Input:

15

Response surface equation coefficients for N calibration parameters (CP) and M objective variables (OV)

Design range for each design parameter x_i^{min} , and x_i^{max}

Initial design point for each design parameter x_i^d

Constraints on objective functions y_j^c

20

Output:

Design robustness set is in the form of suggested operating range for each CP, $[x_i^c, x_i^{c'}]$

25

for each OV-DP pair, **do**

calculate normalised sensitivity S_j^i

do

reorder DP from highest S_j^i to lowest

for each DP in the new order, **do**

30

Discovery Algorithm to discover $[x_i^c, x_i^{c'}]$

if $[x_i^c, x_i^{c'}]$ is empty, **do**

Peter-Paul Algorithm

update design point x_i^d

```

else do
    update design point  $x_i^d$ 
return  $[x_i^c, x_i^{c'}]$ 

```

5 The following pseudo code outlines the steps described above for the Discovery algorithm 40, together with the inputs and outputs to the algorithm (Figure 4):

```

Input:
    Inputs from Algorithm RADA
10
Output:
    Design robustness set is in the form of suggested operating range for each CP,
     $[x_i^c, x_i^{c'}]$ 
15
do
    reorder OV from highest  $S_j^i$  to lowest
    for the first OV in the new order, do
        calculate OV value,  $y_j^d$  based on current design point,  $x_i^d$ 
        while  $y_j^d \neq y_j^c$ , do
20
            refine  $x_i^d$  until  $y_j^d = y_j^c$ 
            do
                define  $x_i^c$  and  $x_i^{c'}$  based on adjusted  $x_i^d$  and  $[x_i^{\min}, x_i^{\max}]$  such that  $y_j$ 
                obtained from any value in  $[x_i^c, x_i^{c'}]$  satisfy constraint  $y_j^c$ 
            for each remaining OV, do
25
                refine  $[x_i^c, x_i^{c'}]$  such that  $y_j$  obtained from any value in  $[x_i^c, x_i^{c'}]$  satisfy
                constraint  $y_j^c$  for all  $j$ 

```

The following pseudo code outlines the steps described above for the Peter-Paul algorithm 42, together with the inputs and outputs to the algorithm (Figure 5):

```

30
Input:
    Inputs from Algorithm RADA
     $[x_i^c, x_i^{c'}]$  before any refinement has been applied

```

Output:

$[x_i^c, x_i^{c'}]$ and $[x_{i+1}^c, x_{i+1}^{c'}]$

```
5   for the next CP, i.e.  $x_{i+1}$ , do
      solve  $[x_{i+1}^c, x_{i+1}^{c'}]$  using Discovery Algorithm
      if  $[x_{i+1}^c, x_{i+1}^{c'}]$  is empty, do
          display "Recommend to relax constraints or define new initial calibration
10  points"
      terminate algorithm
      else
          define
              overlap  $O$  as the percentage that final  $[x_i^c, x_i^{c'}]$  overlaps with the input
               $[x_i^c, x_i^{c'}]$ ,  $O = 0$  initially.
               $z = 1\%$ 
15  while  $O < (100 - z)\%$ , do
          reduce the size of  $[x_{i+1}^c, x_{i+1}^{c'}]$  by  $x\%$ 
          update  $x_{i+1}^d$ 
          solve  $[x_i^c, x_i^{c'}]$  using Discovery Algorithm with updated  $x_{i+1}^d$ 
          calculate  $O$ 
20  refine  $z$  by  $z = z + 1$ 
```

CLAIMS

1. A calibration system for determining calibration parameter values for a vehicle, the calibration system comprising:

5

an input arranged to receive sensor output data from a plurality of vehicle sensors, the sensor output data of each vehicle sensor relating to a measured value of an objective variable of a vehicle subsystem or component at a current value of a calibration parameter of the vehicle;

10

a processor arranged to determine a permissible range of values for the calibration parameter, the processor being arranged, for each objective variable, to adjust the current value of the calibration parameter until a calculated object variable value reaches an objective variable constraint value, each calculated object variable value being calculated in dependence on the received sensor output data; and

15

an output arranged to output the permissible range of values to a control unit in order to control the vehicle subsystem or component.

20

2. A calibration system according to Claim 1, wherein:

the processor comprises an electronic processor and the input is an electrical input;

25

the calibration system includes an electronic memory device electrically coupled to the electronic processor and having instructions stored therein, and

30

the processor is configured to access the memory device and execute the instructions stored therein such that it is operable to determine the permissible range of values for the calibration parameter.

3. A calibration system according to Claim 1 or Claim 2, wherein the processor is arranged to set a boundary calibration parameter value in dependence on the adjusted value of the calibration parameter, the permissible range of values being based on the boundary calibration parameter value.
- 5
4. A calibration system according to Claim 3, wherein the boundary calibration parameter value is set to be equal to the adjusted value of the calibration parameter.
- 10
5. A calibration system according to any previous claim, wherein the processor is arranged to calculate a level of sensitivity between each of the measured objective variable values and the current value of the calibration parameter.
- 15
6. A calibration system according to Claim 5, wherein the processor is arranged to form a ranked set of each of the objective variables in dependence on the calculated levels of sensitivity.
- 20
7. A calibration system according to Claim 6, wherein the processor is arranged to cycle through each objective variable in the order in which they appear in the ranked set in order to adjust the current value of the calibration parameter.
- 25
8. A calibration system according to Claim 6 or Claim 7, wherein the objective variables are ranked in order of decreasing level of sensitivity.
9. A calibration system according to any of Claims 5 to 8, wherein calculating the level of sensitivity includes calculating a normalised sensitivity value for each of the objective variables.
- 30
10. A calibration system according to Claim 9, wherein the normalised sensitivity value S_j^i is defined by

$$S_j^i = \left| \frac{\partial y_j}{\partial x_i} \frac{x_i}{y_j} \right|_{x_i=x_i^d, y_j=y_j^d} = \left| (\beta_{ij} + 2\beta_{iij}x_i^d) \frac{x_i^d}{y_j^d} \right|$$

where S_j^i is the normalised sensitivity value, x_i is the calibration parameter, y_i is the objective variable, x_i^d is the current value of the calibration parameter, y_i^d is the measured objective variable value, and β_{ij} and β_{iij} are fitting coefficients.

5

11. A calibration system according to any previous claim, wherein the determination of the permissible range of values is performed cumulatively such that the permissible range of values for the calibration parameter satisfies each of the object variable constraint values.

10

12. A calibration system according to any previous claim, wherein the sensor output data relates to measured objective variable values at current values of a plurality of calibration parameters.

15

13. A calibration system according to Claim 12, the processor being arranged to calculate an overall level of sensitivity for each of the plurality of calibration parameters.

20

14. A calibration system according to Claim 13, the processor being arranged to form a ranked set of the plurality of calibration parameters, in which the calibration parameters are ranked in order of decreasing value of the calculated overall level of sensitivity of the calibration parameters.

25

15. A calibration system according to Claim 14, wherein the processor is arranged to determine the permissible range of values for each of the plurality of calibration parameters in order of decreasing value of the calculated overall level of sensitivity of the calibration parameters.

30

16. A calibration system according to any of Claims 13 to 15, wherein the overall level of sensitivity S^i is defined by

$$S^i = S_1^i + S_2^i + \dots + S_M^i$$

where M is the number of object variables.

17. A calibration system according to any of Claims 14 to 16, wherein if the determined permissible range of values for a first one of the calibration

parameters in the ranked set is empty, then the permissible range of values for a second calibration parameter next in the ranked set is used to determine the permissible range of values for the first calibration parameter.

5 18. A calibration system according to Claim 17, wherein if the permissible
range of values for a second calibration parameter is also empty, then the
processor is arranged to prompt a user to adjust one or more of the
objective variable constraint values or the current value of the first
10 calibration parameter, or the processor is arranged to automatically adjust
one or more of the objective variable constraint values or the current value
of the first calibration parameter.

15 19. A calibration system according to Claim 17, wherein the processor is
arranged to ensure that an overlap value between the permissible range of
values for the first calibration parameter that is empty and the permissible
range of values for the first calibration parameter is above a predetermined
threshold percentage value.

20 20. A calibration system according to any previous claim, wherein the
calculated object variable value is calculated using a relational function
dependent on the current value or values of the calibration parameter or
parameters and one or more fitting coefficients.

25 21. A calibration system according to Claim 20, wherein the relational function
comprises response surface equations.

22. A calibration system according to Claim 21, wherein the response surface
equations are pure quadratic response surface equations.

30 23. A calibration system according to any previous claim, wherein the relational
function is defined by

$$y_j^t = \beta_{0j} + \sum_{i=1}^N \beta_{ij}x_i^d + \sum_{i=1}^N \beta_{ii}j(x_i^d)^2$$

where y_j^t is the theoretical objective variable values, β_{0j} is one of the fitting
coefficients, and N is the number of calibration parameters.

24. A calibration system according to any previous claim, the calibration system including the control unit for controlling the vehicle subsystem or component, and the control unit being arranged to control the current value or values of the calibration parameter or parameters to be within the respective permissible range of values.
- 5
25. A calibration system according to Claim 24, the control unit being arranged to control the current value of at least one of the calibration parameters to be a centre point of the respective permissible range of values.
- 10
26. A calibration system according to any previous claim, wherein the vehicle subsystem or component is an internal combustion engine of the vehicle and the control unit is an engine management system.
- 15
27. A calibration system according to Claim 26, wherein the sensor output data is indicative of a level of emissions from the internal combustion engine.
- 20
28. A calibration system according to any of Claims 1 to 25, wherein the vehicle subsystem or component is a vehicle battery and the control unit is an electric vehicle energy and battery management system.
- 25
29. A calibration system according to Claim 28, wherein the sensor output data is indicative of at least one of: a battery state-of-charge value, a battery temperature and/or a vehicle range value.
- 30
30. A calibration system according to any of Claims 1 to 25, wherein the vehicle subsystem or component is one of an advanced driver assistance system and a chassis control system.
31. A calibration system according to any previous claim, the calibration system being operable to determine the permissible range of values for the calibration parameter in dependence on one or more trigger conditions.

32. A calibration system according to Claim 31, wherein the trigger condition is that a predetermined amount of time has elapsed since a previous determination of the permissible range of values.
- 5 33. A calibration system according to Claim 31, wherein the trigger condition is that an external temperature changes by a predetermined amount.
34. A calibration method for determining calibration parameter values for a vehicle, the calibration method comprising:
- 10 receiving sensor output data from a plurality of vehicle sensors, the sensor output data of each vehicle sensor relating to a measured value of an objective variable of a vehicle subsystem or component at a current value of a calibration parameter;
- 15 determining a permissible range of values for the calibration parameter that includes, for each objective variable, adjusting the current value of the calibration parameter until a calculated object variable value reaches an objective variable constraint value, each calculated object variable value
- 20 being calculated in dependence on the received sensor output data; and
- outputting the permissible range of values to a control unit in order to control the vehicle subsystem or component.
- 25 35. A vehicle comprising a vehicle calibration system according to any of Claims 1 to 33.
36. A non-transitory, computer-readable storage medium storing instructions thereon that when executed by one or more processors causes the one or
- 30 more processors to carry out the method of Claim 34.
37. A calibration system, method or vehicle substantially as hereinbefore described with reference to the accompanying figures.



Application No: GB1618623.1

Examiner: Mr Kevin Hewitt

Claims searched: 1 to 36

Date of search: 3 May 2017

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
A	-	EP 1936465 A2 (HONDA MOTOR) See especially the Abstract, and Figure 6.
A	-	US 2015/0039206 A1 (STORCH et al.) See especially the Abstract; and Figure 1.
A	-	CN 203385554 U (ANHUI JIANGHUAI AUTOMOBILE) See especially the EPODOC & WPI Abstracts, Accession Number 2014-E26767.
A	-	CN 103162964 A (BEIGI FOTON MOTOR) See especially the EPODOC and WPI Abstracts, Accession Number 2013-S21227.

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^X :

--

Worldwide search of patent documents classified in the following areas of the IPC

B60W

The following online and other databases have been used in the preparation of this search report

WPI; EPODOC

International Classification:

Subclass	Subgroup	Valid From
B60W	0050/00	01/01/2006