



(22) Date de dépôt/Filing Date: 2013/01/09
(41) Mise à la disp. pub./Open to Public Insp.: 2013/09/12
(45) Date de délivrance/Issue Date: 2019/10/01
(62) Demande originale/Original Application: 2 801 306
(30) Priorité/Priority: 2012/03/12 (US13/418,081)

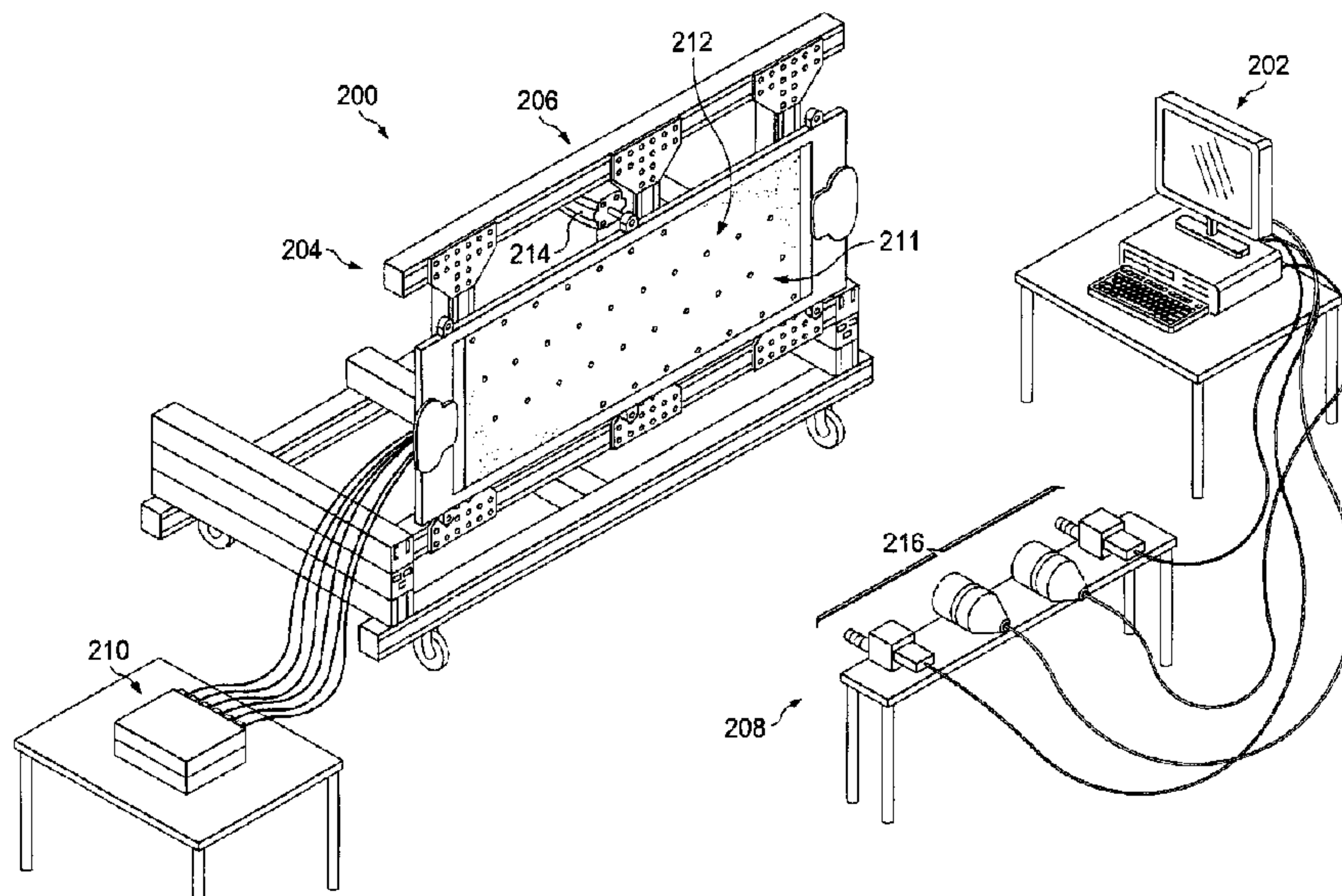
(51) Cl.Int./Int.Cl. *G01B 21/32* (2006.01),
H01Q 1/28 (2006.01), *H01Q 3/26* (2006.01),
G01R 29/10 (2006.01), *H01Q 21/00* (2006.01)

(72) Inventeurs/Inventors:
KEARNS, JUSTIN D., US;
URCIA, MANNY SALAZAR, JR., US;
DAVIS, CHRISTOPHER LEE, US;
GORDON, CLARENCE L., III, US

(73) Propriétaire/Owner:
THE BOEING COMPANY, US

(74) Agent: SMART & BIGGAR

(54) Titre : METHODE ET APPAREIL POUR L'IDENTIFICATION DES DEFORMATIONS STRUCTURALES
(54) Title: A METHOD AND APPARATUS FOR IDENTIFYING STRUCTURAL DEFORMATION



(57) Abrégé/Abstract:

A method and apparatus for identifying deformation of a structure (108). Training deformation data (142) is identified for each training case in a plurality of training cases (136). Training strain data (144) is identified for each training case in the plurality of training cases (136). The training deformation data (142) and the training strain data (144) are configured for use by a heuristic model (104) to increase an accuracy of output data generated by the heuristic model (104). A group of parameters (121) for the heuristic model (104) is adjusted using the training deformation data (142) and the training strain data (144) for the each training case in the plurality of training cases (136) such that the heuristic model (104) is trained to generate estimated deformation data (124) for the structure (108) based on input strain data (126). The estimated deformation data (124) has a desired level of accuracy.

ABSTRACT

A method and apparatus for identifying deformation of a structure (108).
5 Training deformation data (142) is identified for each training case in a plurality of training cases (136). Training strain data (144) is identified for each training case in the plurality of training cases (136). The training deformation data (142) and the training strain data (144) are configured for use by a heuristic model (104) to increase an accuracy of output data generated by the heuristic model (104). A
10 group of parameters (121) for the heuristic model (104) is adjusted using the training deformation data (142) and the training strain data (144) for the each training case in the plurality of training cases (136) such that the heuristic model (104) is trained to generate estimated deformation data (124) for the structure (108) based on input strain data (126). The estimated deformation data (124) has a desired level of
15 accuracy.

A METHOD AND APPARATUS FOR IDENTIFYING STRUCTURAL DEFORMATION

BACKGROUND

5

The present disclosure relates generally to structural deformation and, in particular, to identifying structural deformation. Still more particularly, the present disclosure relates to a method and apparatus for identifying the deformation of a structure using measured strain data and a heuristic model.

10

Some structures associated with a platform experience deformation during operation of the platform. As used herein, the “deformation” of a structure is any change in the shape of the structure from a reference shape for the structure. Typically, a structure associated with a platform deforms in response to one or more loads being applied to the structure during operation of the platform. Deformation of the structure during operation of the platform may reduce a performance of the structure from a desired level of performance.

15

As one illustrative example, an antenna system associated with an aircraft may deform in response to a number of loads and/or pressure applied to the antenna system during flight of the aircraft. Deformation of the antenna system reduces performance of the antenna system. In particular, deformation of the antenna system may cause the antenna system to operate outside of selected tolerances.

20

In one illustrative example, the antenna system may be a phased array antenna system. Deformation of this type of antenna system may affect the electronic beam steering capabilities of the antenna system more than desired. For example, the beam formed by the antenna system may be steered in a direction outside of selected tolerances with respect to a desired direction for the beam. This type of steering may occur when at least a portion of the antenna system deforms. Identifying the amount of deformation experienced by the antenna system can be used to electronically compensate for this deformation.

25

30

Some currently available systems for identifying the deformation of a structure associated with a platform include using optical systems, imaging systems, fiber optic systems, coordinate measuring machine (CMM) systems, cameras, and/or other types of devices. These different devices are used to identify the deformation of a structure associated with a platform during operation of the platform.

However, these currently available systems may be unable to identify the deformation of the structure with a desired level of accuracy. Further, these currently available systems for identifying the deformation of a structure may be more complex, time-consuming, and/or expensive than desired. Therefore, it would be desirable to have a method and apparatus that takes into account one or more of the issues discussed above as well as possibly other issues.

SUMMARY

The disclosure describes an apparatus for identifying deformation of a structure associated with a platform. The system includes at least one computer processor operably configured to execute a heuristic model configured to generate estimated deformation data in response to input strain data for the structure and a group of heuristic model control parameters. The accuracy of the estimated deformation data is controlled by the group of heuristic model control parameters. The at least one computer processor is configured to generate training strain data in response to measurements received from a sensor system associate with the structure. The heuristic model has been configured by the training strain data and corresponding training deformation data for the structure for each training case in a plurality of training cases. The group of heuristic model control parameters have

5 been adjusted based on the training strain data and training deformation data to
configure the heuristic model to generate the estimated deformation data with a
particular level of accuracy. The at least one computer processor is also operably
configured to receive actual strain data for the structure, from the sensor system,
during operation of the platform that causes deformation of the structure. The at
10 least one computer processor is also operably configured to apply the actual
strain data as input strain data to the heuristic model to produce estimated
deformation data signals, with the particular level of accuracy, for use in
controlling operational performance of the structure during the deformation of the
structure.

15 The system of may further include the sensor system, the sensor system
including a plurality of sensors positioned at a plurality of points on the structure.
The plurality of sensors may be configured to generate a plurality of strain
measurements for the plurality of points on the structure.

 The at least one computer processor may be configured to adjust a group
20 of structure control parameters for the structure in response to the estimated
deformation data signals generated by the heuristic model such that the structure
has a particular level of performance during the operation of the platform.

5

The at least one computer processor may be configured to adjust the group of structure control parameters to compensate for the deformation of the structure during the operation of the platform, based on the estimated deformation data signals generated by the heuristic model.

10

The structure may include a phased array antenna on an aircraft. The phased array antenna may deform from a reference shape to a deformed shape in flight.

The at least one computer processor may be configured to identify a deformation of the phased array antenna and beam steer the phased array
15 antenna to compensate for the deformation in substantially real-time, in response to the estimated deformation data signals.

The at least one computer processor may be configured to electronically adjust at least one of a phase and an amplitude of the phased array antenna in response to deformation of the phased array antenna.

20

The at least one computer processor may be configured to produce a group of performance parameters for the structure and to evaluate performance of the structure based on the group of performance parameters.

5

The structure may include a phased array antenna and the group of performance parameters may include at least one of peak sidelobe ratio (PSLR), gain loss, and beam steering angle deviation.

10 The at least one computer processor may be configured to adjust the group of structure control parameters in response to the group of performance parameters such that the phased array antenna has the particular level of performance during the operation of the platform.

15 The at least one computer processor may be configured to select a combination of sensors of the sensor system such that the selected combination of sensors has a minimum number of sensors needed for the heuristic model to generate the estimated deformation data with the particular level of accuracy.

The at least one computer processor may be configured to generate the training deformation data in response to imaging data from an imaging system.

20 The heuristic model may include at least one of a neural network, a learning-based algorithm, a regression model, a support vector machine, a data fitting model, a pattern recognition model, and an artificial intelligence system.

5

The at least one computer processor may be configured to identify training environmental data for the structure.

10 The at least one computer processor may be configured to adjust the group of heuristic model control parameters in response to the training deformation data, the training strain data, and the training environmental data.

The at least one computer processor may be configured to apply additional input data to the heuristic model for use in producing the estimated deformation data signals.

15 The at least one computer processor may generate the training strain data by generating strain data for the structure when the structure has a deformed shape.

A plurality of selected loads may be applied to a plurality of points on the structure such that the structure deforms into the deformed shape.

20 The at least one computer processor may include a trainer system processor for configuring the heuristic model based on the training strain data and corresponding training deformation data and a performance management processor associated with the platform for controlling operational performance of the structure during the deformation of the structure, in response to the heuristic
25 model configured by the trainer system processor.

In another embodiment there is provided a system for identifying deformation of a structure associated with a platform. The system includes a first computer operably configured to generate training strain data and training deformation data for the structure for each training case in a plurality of training cases and configure a heuristic model to generate estimated deformation data in response to input strain data for the structure, the accuracy of the estimated deformation data being controlled by a group of heuristic model control parameters. Configuring the heuristic model involves providing the training strain data and the training deformation data to the heuristic model and adjusting the group of heuristic model control parameters such that the heuristic model will, in response to the input strain data, produce the estimated deformation data with a particular level of accuracy. The heuristic model configured by the first computer is executed by the at least one processor.

The first computer may be part of a trainer system in a training environment, and the at least one processor is part of an aircraft, and the structure includes a phased array antenna of the aircraft.

5

These and other features and functions can be achieved independently in various embodiments of the present disclosure or may be combined in yet other
10 embodiments in which further details can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

15 The novel features believed characteristic of the illustrative embodiments are set forth in the appended claims. The illustrative embodiments, however, as well as a preferred mode of use, further objectives and features thereof, will best be understood by reference to the following detailed description of an illustrative embodiment of the present disclosure when read in conjunction with the
20 accompanying drawings, wherein:

Figure 1 is an illustration of a block diagram of a training environment in accordance with an illustrative embodiment;

Figure 2 is an illustration of a training environment in accordance with an illustrative embodiment;

25

5

Figure 3 is an illustration of a plurality of sensors associated with a phased array antenna in accordance with an illustrative embodiment;

Figure 4 is an illustration of a table of estimated deformation data in accordance with an illustrative embodiment;

10 **Figure 5** is an illustration of a table of actual deformation data in accordance with an illustrative embodiment;

Figure 6 is an illustration of a table of differences between estimated deformation measurements and actual deformation measurements in accordance with an illustrative embodiment;

Figure 7 is an illustration of a flowchart of a process for managing the
5 performance of a structure in the form of a flowchart in accordance with an illustrative embodiment;

Figure 8 is an illustration of a flowchart of a process for training a heuristic model in the form of a flowchart in accordance with an illustrative embodiment;

Figure 9 is an illustration of a flowchart of a process for training a heuristic
10 model in the form of a flowchart in accordance with an illustrative embodiment;

Figure 10 is an illustration of a flowchart of a process for identifying a configuration of sensors for use on a structure in the form of a flowchart in accordance with an illustrative embodiment;

Figure 11 is an illustration of a comparison of graphs for the peak sidelobe
15 ratio of a phased array antenna in accordance with an illustrative embodiment;

Figure 12 is an illustration of a comparison of graphs for a reduction in gain in accordance with an illustrative embodiment;

Figure 13 is an illustration of a comparison of graphs for phase in accordance with an illustrative embodiment;

Figure 14 is an illustration of a comparison of graphs for beam steering
20 angle deviation in accordance with an illustrative embodiment; and

Figure 15 is an illustration of a data processing system in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

The different illustrative embodiments recognize and take into account one or more different considerations. For example, the different illustrative embodiments
5 recognize and take into account that some currently available systems for measuring the deformation of a structure may not provide a desired level of accuracy. For example, these currently available systems may be unable to provide the level of accuracy needed to compensate for the deformation of the structure.

10 Optical systems comprising devices, such as, for example, three-dimensional coordinate measuring machine systems, fiber optic systems, cameras, and/or other suitable devices, may be unable to measure the three-dimensional deformation of a structure associated with an aircraft, while in flight, with a desired level of accuracy. The different illustrative embodiments recognize and take into account that these
15 devices may not provide the desired level of spatial resolution needed to measure the deformed shape of the structure with the desired level of accuracy.

The different illustrative embodiments also recognize that optical systems having cameras require that these cameras be pointed at the structure. Further, operating these optical systems in certain environmental conditions may be more
20 difficult than desired. For example, operating these optical systems in conditions such as, rain, extreme temperatures, wind, snow, nighttime, low light levels, fog, and/or other conditions may be more difficult than desired. Additionally, measuring a three-dimensional shape of a structure using an optical system having cameras may involve using multiple views. Using multiple views may increase the
25 processing resources, effort, and/or time needed to measure the three-dimensional shape of the structure.

The different illustrative embodiments recognize and take into account that a phased array antenna on an aircraft may be deformed during flight of the aircraft. The different illustrative embodiments also recognize and take into account that it
30 may be desirable to have a system configured to identify the deformation of the

phased array antenna with the level of accuracy needed to electronically beam steer a phased array antenna to compensate for the deformation of the phased array antenna during flight of the aircraft, within selected tolerances.

Further, the different illustrative embodiments recognize and take into account that it may be desirable to have a system capable of identifying the deformation of the phased array antenna and electronically beam steering the phased array antenna to compensate for this deformation in substantially real-time. In this manner, undesired changes or inconsistencies in the performance of the phased array antenna caused by deformation of the phased array antenna during flight of the aircraft may be reduced and, in some cases, prevented.

Thus, the different illustrative embodiments provide a method and apparatus for managing the performance of a structure. In one illustrative embodiment, a method for identifying deformation of a structure is provided. Training deformation data is identified for each training case in a plurality of training cases. Training strain data is identified for each training case in the plurality of training cases. The training deformation data and the training strain data are configured for use by a heuristic model to increase an accuracy of output data generated by the heuristic model. A group of parameters for the heuristic model is adjusted using the training deformation data and the training strain data for the each training case in the plurality of training cases such that the heuristic model is trained to generate estimated deformation data for the structure based on input strain data. The estimated deformation data has a desired level of accuracy.

The estimated deformation data may be used to adjust a group of control parameters for the structure such that the structure has a desired level of performance during the operation of the platform. In particular, the estimated deformation data may be used to control the structure in a manner that compensates for the deformation of the structure during the operation of the platform.

Referring now to the figures, and in particular, with reference to **Figure 1**, an illustration of a training environment is depicted in accordance with an illustrative

embodiment. In these illustrative examples, training environment **100** includes trainer **102**. Trainer **102** is configured to train heuristic model **104** to identify deformation **106** of structure **108** associated with platform **110**.

As used herein, when one component is “associated” with another
 5 component, this association is a physical association in these depicted examples.

For example, a first component, such as structure **108**, may be considered to be associated with a second component, such as platform **110**, by being secured to the second component, bonded to the second component, mounted to the second component, welded to the second component, fastened to the second component,
 10 and/or connected to the second component in some other suitable manner. The first component also may be connected to the second component using a third component. The first component may also be considered to be associated with the second component by being formed as part of and/or an extension of the second component.

15 In these illustrative examples, platform **110** may be, for example, without limitation, an aircraft, a helicopter, a jet, an unmanned aerial vehicle (UAV), a space shuttle, an automobile, a rocket, a missile, a watercraft, a propulsion system, a building, a manmade structure, a bridge, a satellite, or some other suitable type of platform. Structure **108** associated with platform **110** may be, for example, without
 20 limitation, an imaging system, a communications system, an antenna system, a phased array antenna system, a wing, a skin panel, a cable, a rod, a beam, or some other suitable type of structure.

In one illustrative example, platform **110** is an aircraft, and structure **108** is a phased array antenna system. In this illustrative example, the phased array
 25 antenna is associated with the aircraft by being integrated into one or more other structures of the aircraft. For example, the phased array antenna may be integrated into a wing, a stabilizer, a skin panel, or a door of the aircraft.

Deformation **106** of structure **108** is any change in shape **112** of structure **108** from reference shape **114** of structure **108**. In one illustrative example,

reference shape **114** is the shape of structure **108** without any loads or pressure being applied to structure **108**.

When one or more loads and/or pressure is applied to structure **108**, structure **108** may deform such that shape **112** of structure **108** changes from
 5 reference shape **114** to deformed shape **116**. The loads and/or pressure applied to structure **108** may include, for example, without limitation, aerodynamic loads, gusts, vibrations in structure **108**, static loads, aero-acoustic loads, temperature-based loads, and/or other suitable types of loads and/or pressures.

Structure **108** may deform during operation of platform **110**. When structure
 10 **108** has deformed shape **116**, structure **108** may operate outside of selected tolerances. An identification of deformed shape **116** for structure **108** may be used to adjust group of control parameters **115** for structure **108**.

As used herein, a “group of” items means one or more items. For example, group of control parameters **115** means one or more control parameters **115**.
 15 Group of control parameters **115** may be adjusted to manage the performance of structure **108** such that structure **108** operates and performs within selected tolerances. In these illustrative examples, “adjusting” a group of parameters, such as group of control parameters **115** may include changing one, some, all, or none of the parameters in the group of parameters.

20 As one illustrative example, when platform **110** is an aircraft and structure **108** is a phased array antenna system integrated into the aircraft, the phased array antenna system may deform into deformed shape **116**, while the aircraft is in flight. When the phased array antenna system has deformed shape **116**, the phased array antenna system may operate outside of selected tolerances.

25 An identification of deformed shape **116** may be used to adjust a phase and/or amplitude of the phased array antenna system to electronically steer a beam formed by the phased array antenna system to compensate for deformation **106**, while platform **110** is in flight. When deformation **106** is electronically compensated in this manner, the phased array antenna system operates within selected
 30 tolerances during flight. In particular, this system operates within the selected

tolerances during flight even when the phased array antenna system has deformed shape **116**.

Heuristic model **104** can be trained to identify deformation **106** of structure **108**, thereby identifying deformed shape **116** of structure **108**. In these illustrative
5 examples, identifying deformation **106** of structure **108** may comprise estimating deformation **106** of structure **108** with a desired level of accuracy. In this manner, deformed shape **116** of structure **108** may be estimated with a desired level of accuracy.

As used herein, a “heuristic model”, such as heuristic model **104**, may be any
10 mathematical or computational model configured to learn, adapt, make decisions, find patterns in data, remember data, and/or process information in some other suitable manner to generate output data **118** in response to receiving input data **120**.

Heuristic model **104** may comprise any number of learning algorithms,
15 decision-making models, problem solving-models, computational algorithms, and/or other types of processes. In these illustrative examples, heuristic model **104** comprises at least one of a neural network, a learning-based algorithm, a regression model, a support vector machine, a data fitting model, a pattern recognition model, artificial intelligence (AI), and some other suitable type of
20 algorithm or model.

As used herein, the phrase “at least one of”, when used with a list of items, means different combinations of one or more of the listed items may be used and only one of each item in the list may be needed. For example, “at least one of item A, item B, and item C” may include, without limitation, item A or item A and item B.
25 This example also may include item A, item B, and item C, or item B and item C. In other examples, “at least one of” may be, for example, without limitation, two of item A, one of item B, and ten of item C; four of item B and seven of item C; and other suitable combinations.

As depicted in these examples, heuristic model **104** is configured to generate
30 output data **118** in response to receiving input data **120** based on group of

parameters **121**. Group of parameters **121** may include, for example, without limitation, biases, weights, coefficients, relationships, constants, constraints, and/or other suitable types of parameters. In one illustrative example, heuristic model **104** may include an equation comprising biases and weights configured to produce
5 output data **118** in response to receiving input data **120**.

In these illustrative examples, trainer **102** is configured to train heuristic model **104** to estimate deformation **106** of structure **108** with a desired level of accuracy. Estimating deformation **106** of structure **108** with a desired level of accuracy means estimating deformation **106** such that a difference between the
10 estimated deformation of structure **108** and the actual deformation of structure **108** is within selected tolerances.

Trainer **102** may be implemented using hardware, software, or a combination of both in these examples. For example, trainer **102** may be implemented in computer system **122**. Computer system **122** comprises a number of computers.
15 As used herein, a “number of” items means one or more items. For example, a number of computers means one or more computers.

When more than one computer is present in computer system **122**, these computers are in communication with each other. The different computers in computer system **122** may be located on platform **110**, on structure **108**, and/or
20 remote to platform **110**.

In one illustrative example, heuristic model **104** generates output data **118** in the form of estimated deformation data **124** in response to receiving input data **120** in the form of input strain data **126**. Estimated deformation data **124** defines the estimated deformed shape for structure **108** based on input strain data **126**.

25 As used herein, “deformation data”, such as estimated deformation data **124**, comprises a plurality of estimated deformation measurements. A “plurality of” items, as used herein, means two or more items. For example, a plurality of estimated deformation measurements means two or more estimated deformation measurements.

In these depicted examples, a deformation measurement is a measurement of the deflection of a point on structure **108** from the location of the point when structure **108** has reference shape **114**, to the location of the point when structure **108** has deformed shape **116**. As used herein, the “deflection” of a point on structure **108** is the distance between the point when the structure **108** has reference shape **114** and the point when the structure **108** has deformed shape **116**. This deflection of the point may be also referred to as a displacement of the point.

In these illustrative examples, the measurement of the deflection of the point may be in units of length. Units of length include, for example, without limitation, inches, feet, centimeters, millimeters, and other types of units of length. Of course, in other illustrative examples, the measurement of the deflection of the point may be in angular units. Angular units include, for example, without limitation, radians, degrees, and other types of angular units.

Further, as used herein, “strain data”, such as input strain data **126**, comprises a plurality of strain measurements. A strain measurement is a measurement of the deflection of a point on structure **108** from the location of the point when structure **108** has reference shape **114** to the location of the point when structure **108** has deformed shape **116**, normalized relative to a reference length. A strain measurement does not have any units and may be represented as a percentage, a fraction, or a parts-per-notation (ppn).

Heuristic model **104** may receive input strain data **126** in a number of different ways. As one illustrative example, input strain data **126** may be received as strain data **128** generated by sensor system **130**. Sensor system **130** is associated with structure **108**. In some illustrative examples, a portion of sensor system **130** may be associated with platform **110**.

Sensor system **130** comprises plurality of sensors **132** configured to generate strain data **128**. Strain data **128** comprises a plurality of strain measurements generated by plurality of sensors **132**, respectively. A sensor in plurality of sensors **132** may comprise at least one of, for example, a strain gauge, a

fiber-optic sensor, a piezoelectric sensor, a transducer, or some other suitable type of sensor configured to generate strain measurements.

In some illustrative examples, input data **120** may also include additional input data **133** in addition to input strain data **126**. Additional input data **133** may
 5 include any data that may affect output data **118** generated by heuristic model **104** based on input strain data **126**. In particular, additional input data **133** may include any data about conditions that may affect deformation **106** of structure **108** while platform **110** operates.

For example, additional input data **133** may include environmental data such
 10 as, for example, measurements of environmental conditions that may affect deformation **106** of structure **108** and/or strain data **128**. This environmental data may include, for example, temperature data, humidity data, and/or other suitable types of data. In some cases, additional input data **133** may include data from an inertial measurement unit (IMU) attached to platform **110**, position data, altitude
 15 data, velocity data, acceleration data, and/or other suitable types of data.

In these illustrative examples, trainer **102** trains heuristic model **104** using plurality of training cases **136** selected for training heuristic model **104**. As used herein, a “training case”, such as a training case in plurality of training cases **136** is a particular state for structure **108** in which data about structure **108**, when structure
 20 **108** is in this particular state, is used to train heuristic model **104**. The particular state for structure **108** may be, for example, a particular deformed shape for structure **108**. However, in some cases, the particular state for structure **108** may be a selected amount of loading and/or pressure being applied to structure **108**.

Trainer **102** identifies training deformation data and training strain data for
 25 each training case in plurality of training cases **136**. Training case **140** is an example of one of plurality of training cases **136**. Further, trainer **102** identifies training deformation data **142** and training strain data **144** for training case **140**.

Trainer **102** sends training deformation data **142** and training strain data **144**
 to heuristic model **104**. Heuristic model **104** uses training deformation data **142** and
 30 training strain data **144** to adjust group of parameters **121** for heuristic model **104**.

Group of parameters **121** are adjusted such that heuristic model **104** is capable of generating estimated deformation data **124** for structure **108** with a desired level of accuracy based on input strain data **126**. In these illustrative examples, trainer **102** trains heuristic model **104** using plurality of training cases **136** and an iterative
5 process.

The training deformation data and training strain data identified for each training case in plurality of training cases **136** may be identified in a number of different ways in training environment **100**. For example, training environment **100** may be a laboratory, a testing facility, a wind tunnel, or some other type of training
10 environment in which the training deformation data and the training strain data can be generated. In some cases, training environment **100** may be the actual environment in which platform **110** operates. In this manner, the training deformation data and the training strain data may be gathered and collected in any number of different ways.

15 In one illustrative example, plurality of actuators **146** are used to deform structure **108** according to plurality of training cases **136**. For example, plurality of actuators **146** may be used to cause structure **108** to deform in a manner corresponding to training case **140**. More specifically, plurality of actuators **146** may be used to apply a plurality of selected loads to plurality of points **148** on
20 structure **108** to cause plurality of points **148** to deflect in a manner that causes structure **108** to have the deformed shape corresponding to training case **140**.

Of course, in other illustrative examples, some other type of system may be used to cause structure **108** to deform in a manner corresponding to plurality of training cases **136**. Depending on the implementation, structure **108** may be
25 deformed for the purposes of training with structure **108** separated from platform **110**. In some illustrative examples, platform **110** may be operated with structure **108** associated with platform **110** to cause structure **108** to deform according to plurality of training cases **136**.

When structure **108** has been deformed according to a particular training
30 case, training deformation data and training strain data for that training case are

identified. The training deformation data and the training strain data may be referred to as a training data set, in some illustrative examples. The training deformation data may be identified in a number of different ways. As one illustrative example, trainer **102** may identify the training deformation data using imaging data
5 **150** received from imaging system **152**.

Imaging system **152** comprises any number of components configured to generate imaging data **150** from which a plurality of deformation measurements can be identified. For example, imaging system **152** may comprise an optical imaging system, a laser imaging system, an infrared imaging system, or some other suitable
10 type of imaging system. In some illustrative examples, imaging data **150** may include a plurality of deformation measurements for use as the training deformation data.

Further, strain data **128** generated by sensor system **130** when structure **108** is deformed according to a particular training case may be used as the training
15 strain data for that training case. Of course, in other illustrative examples, sensor system **130** may generate other sensor data in addition to and/or in place of strain data **128**. Trainer **102** may use this other sensor data to identify the training strain data.

In these illustrative examples, the number of training cases in plurality of
20 training cases **136** may be selected by the operator. New training cases may be added to plurality of training cases **136** at any point in time such that heuristic model **104** can adapt to this new data.

Further, in some cases, trainer **102** may identify training environmental data for a training case, such as training case **140**, to train heuristic model **104**. This
25 training environmental data may be identified in a number of different ways. For example, historical environmental data and/or test environmental data may be used. This training environmental data may be used to train heuristic model **104** such that estimated deformation data **124** may be generated with the desired level of accuracy based on input strain data **126** when structure **108** is operated in different
30 types of environmental conditions.

Once heuristic model **104** has been trained within training environment **100**, heuristic model **104** can be used in structure **108** to manage the performance of structure **108** during operation of platform **110**. For example, when structure **108** is a phased array antenna, heuristic model **104** may be used in a processor unit
 5 associated with the phased array antenna. Estimated deformation data **124** generated by heuristic model **104** during operation of platform **110** may be used to adjust group of control parameters **115** for structure **108**.

In these illustrative examples, group of control parameters **115** are adjusted to increase the performance of structure **108** to a desired level of performance
 10 when structure **108** has deformed shape **116**. The performance of structure **108** may be evaluated using group of performance parameters **154** for structure **108**. When structure **108** is a phased array antenna, group of performance parameters **154** may include, for example, without limitation, peak sidelobe ratio (PSLR), gain loss, beam steering angle deviation, and/or other types of suitable performance
 15 parameters.

Estimated deformation data **124** may be used to calculate values for adjusting group of control parameters **115**. Group of control parameters **115** may be adjusted based on these values until group of performance parameters **154** indicates that structure **108** has the desired level of performance when structure
 20 **108** has deformed shape **116**. In this manner, estimated deformation data **124** is used to adjust group of control parameters **115** to compensate for deformation **106** of structure **108** such that structure **108** maintains a desired level of performance.

In these illustrative examples, estimated deformation data **124** may be identified for structure **108** and used to adjust group of control parameters **115** for
 25 structure **108** during operation of platform **110** in substantially real-time. These processes being performed in “substantially real-time” means that these processes are performed without any unintentional delays. In some cases, in “substantially real-time” may mean immediately.

For example, without limitation, in response to structure **108** deforming from
 30 reference shape **114**, heuristic model **104** is used to generate estimated

deformation **124** for this deformation immediately. Estimated deformation data **124** may then be used to immediately control structure **108** by adjusting group of control parameters **115** to compensate for this deformation. In this manner, any change in a level of performance of structure **108** in response to the deformation of structure
5 **108** may be reduced, and in some cases, prevented.

In this manner, the different illustrative embodiments provide a method and apparatus for identifying deformation **106** of structure **108** and managing the performance of structure **108** based on this estimation. Further, the different illustrative embodiments provide a method and apparatus for training heuristic
10 model **104** to generate estimated deformation data **124** for structure **108** with a desired level of accuracy in response to receiving input data **120**.

The illustration of training environment **100** in **Figure 1** is not meant to imply physical or architectural limitations to the manner in which an illustrative embodiment may be implemented. Other components in addition to or in place of the ones illustrated may be used. Some components may be optional. Also, the blocks are presented to illustrate some functional components. One or more of these blocks may be combined, divided, or combined and divided into different blocks when implemented in an illustrative embodiment.
15

For example, in some cases, heuristic model **104** may comprise a plurality of
20 neural networks. Each neural network may be configured to generate estimated deformation data **124** for a particular point on structure **108**. In these cases, each neural network may be trained to generate an estimated deformation measurement for the particular point on structure **108** based on one or more input strain measurements at or near the particular point on structure **108**.

25 Further, each training case for each neural network may comprise one or more training strain measurements and one training deformation measurement at the particular point. The training deformation measurement may be identified using a sensor at the particular point on structure **108**.

With reference now to **Figure 2**, an illustration of a training environment is
30 depicted in accordance with an illustrative embodiment. In this illustrative

embodiment, training environment **200** is an example of one implementation for training environment **100** in **Figure 1**. As depicted, computer system **202**, support system **204**, actuator system **206**, imaging system **208**, and sensor system **210** are present in training environment **200**.

5 Computer system **202** may be an example of one implementation for computer system **122** in **Figure 1**. A heuristic model, such as heuristic model **104** in **Figure 1**, may be trained using computer system **202**. In particular, the heuristic model may be trained using a trainer, such as, for example, trainer **102** in **Figure 1**, implements in computer system **202**.

10 As depicted, support system **204** is configured to hold and support structure **211**. In this illustrative example, structure **211** is phased array antenna **212**. Support system **204** supports and holds phased array antenna **212**, while actuator system **206** applies a plurality of loads to phased array antenna **212** for selected training cases. As depicted, actuator system **206** comprises plurality of actuators
 15 **214** positioned relative to a plurality of points on phased array antenna **212**. Plurality of actuators **214** is configured to apply a plurality of selected loads to the plurality of points on phased array antenna **212** to cause phased array antenna **212** to deform in a manner corresponding to a particular training case. In these illustrative examples, applying a selected load to a point on phased array antenna
 20 **212** causes that point to be deflected from a reference position of that point by a selected amount.

 Imaging system **208** is used to generate imaging data of phased array antenna **212**. In this illustrative example, imaging system **208** comprises plurality of cameras **216**. The imaging data generated by plurality of cameras **216** may be
 25 used to identify a plurality of deformation measurements at the plurality of points on phased array antenna **212**. In this illustrative example, each deformation measurement may be a deflection of a corresponding point on phased array antenna **212** in a direction substantially perpendicular to phased array antenna **212**.

 For example, a trainer, such as trainer **102** in **Figure 1**, may identify
 30 deformation measurements for phased array antenna **212** using the imaging data

generated by plurality of cameras **216**. These deformation measurements provide an indication of the deformed shape of phased array antenna **212**.

Further, sensor system **210** generates a plurality of strain measurements for phased array antenna **212**. Sensor system **210** comprises a plurality of strain
 5 gauges (not shown in this view) embedded into phased array antenna **212**. The plurality of strain measurements generated by sensor system **210** and the plurality of deformation measurements identified using imaging system **208** are sent to computer system **202** for processing. A trainer, such as trainer **102** in **Figure 1**, uses these different deformation measurements and strain measurements to train a
 10 heuristic model to estimate the deformation of phased array antenna **212** with a desired level of accuracy based on strain data input into the heuristic model. The trainer may also use other information such as, for example, environmental data, to train the heuristic model.

The illustration of training environment **200** in **Figure 2** is not meant to imply
 15 physical or architectural limitations to the manner in which an illustrative embodiment may be implemented. Other components in addition to or in place of the ones illustrated may be used. Some components may be optional.

Further, the different components shown in **Figure 2** may be combined with components in **Figure 1**, used with components in **Figure 1**, or a combination of the
 20 two. Additionally, some of the components in **Figure 2** may be illustrative examples of how components shown in block form in **Figure 1** can be implemented as physical structures.

With reference now to **Figure 3**, an illustration of a plurality of sensors associated with a phased array antenna is depicted in accordance with an
 25 illustrative embodiment. In this illustrative example, phased array antenna **300** is an example of one implementation for phased array antenna **212** in **Figure 2**. Further, phased array antenna **300** is an example of one implementation for structure **108** in **Figure 1**.

Phased array antenna **300** has an array of antenna elements located within
 30 portion **302** of phased array antenna **300**. Plurality of sensors **304** are positioned at

plurality of points **306** on phased array antenna **300** in this depicted example. As depicted, a portion of plurality of sensors **304** are located within portion **302** of phased array antenna **300** and another portion of plurality of sensors **304** are located outside of portion **302** of phased array antenna **300**.

5 Plurality of sensors **304** may take the form of, for example, without limitation, a plurality of strain gauges. Each strain gauge is configured to generate a strain measurement at the point on phased array antenna **300** at which the strain gauge is located. For example, sensor **308** at point **310** within portion **302** of phased array antenna **300** is configured to generate a strain measurement at point **310**.

10 In this manner, plurality of sensors **304** generates a plurality of strain measurements that form strain data for use as input strain data for a heuristic model, such as heuristic model **104** in **Figure 1**. In particular, the strain measurements generated by plurality of sensors **304** are an example of strain data **128** in **Figure 1** that may be used as input strain data **126** for heuristic model **104** in **Figure 1**. Further, the strain measurements generated by plurality of sensors **304** may be used to train heuristic model **104** in **Figure 1**.

With reference now to **Figure 4**, an illustration of a table of estimated deformation data is depicted in accordance with an illustrative embodiment. In this illustrative example, table **400** includes point identifiers **402**, training case **404**,
20 training case **406**, training case **408**, training case **410**, and training case **412**.

Point identifiers **402** identify the points on a structure for which estimated deformation measurements **413** are generated by a heuristic model, such as heuristic model **104** in **Figure 1**, that has been trained by, for example, trainer **102** in **Figure 1**. In this illustrative example, the points identified by point identifiers **402**
25 are a selected combination of points from plurality of points **306** on phased array antenna **300** in **Figure 3**.

Training case **404**, training case **406**, training case **408**, training case **410**, and training case **412** each correspond to a particular deformed shape for phased array antenna **300**. For each of these training cases, the sensors in plurality of
30 sensors **304** in **Figure 3** positioned at the points identified in point identifiers **402**

generate strain measurements for these points when phased array antenna **300** is deformed into a deformed shape corresponding to the training case. These strain measurements are input into the heuristic model to generate estimated deformation measurements **413** for these same points.

5 With reference now to **Figure 5**, an illustration of a table of actual deformation data is depicted in accordance with an illustrative embodiment. In this illustrative example, table **500** includes point identifiers **502**, training case **504**, training case **506**, training case **508**, training case **510**, and training case **512**.

10 Point identifiers **502** identify the points on a structure for which actual deformation measurements **513** are identified. Actual deformation measurements **513** are the deformation measurements identified for the points on the structure when the structure has actually been deformed. Actual deformation measurements **513** for these training cases may be identified using, for example, imaging data **150** generated by imaging system **152** in **Figure 1**.

15 In this illustrative example, the points identified in point identifiers **502** are a selected combination of points from plurality of points **306** on phased array antenna **300** in **Figure 3**. In particular, the points identified by point identifiers **502** are the same points identified by point identifiers **402** in **Figure 4**.

20 Training case **504**, training case **506**, training case **508**, training case **510**, and training case **512** are the same as training case **404**, training case **406**, training case **408**, training case **410**, and training case **412**, respectively.

25 Turning now to **Figure 6**, an illustration of a table of differences between estimated deformation measurements and actual deformation measurements is depicted in accordance with an illustrative embodiment. In this illustrative example, table **600** includes point identifiers **602**. In this illustrative example, point identifiers **602** identifies the same points identified by point identifiers **502** in **Figure 5** and point identifiers **402** in **Figure 4**.

30 Table **600** presents difference values **604** for training case **606**, training case **608**, training case **610**, training case **612**, and training case **614**. Training case **606**, training case **608**, training case **610**, training case **612**, and training case **614**

are the same as training case **404**, training case **406**, training case **408**, training case **410**, and training case **412**, respectively, in **Figure 4**. Further, training case **606**, training case **608**, training case **610**, training case **612**, and training case **614** are the same as training case **504**, training case **506**, training case **508**, training case **510**, and training case **512**, respectively, in **Figure 5**.

Difference values **604** are the differences between estimated deformation measurements **413** in **Figure 4** and actual deformation measurements **513** in **Figure 5**. In this illustrative example, difference values **604** indicate that estimated deformation measurements **413** have the desired level of accuracy.

10 With reference now to **Figure 7**, an illustration of a process for managing the performance of a structure in the form of a flowchart is depicted in accordance with an illustrative embodiment. The process illustrated in **Figure 7** may be implemented using trainer **102**, heuristic model **104**, and structure **108** in **Figure 1**.

The process begins by training a heuristic model to generate estimated deformation data for a structure with a desired level of accuracy based on input strain data for the structure (operation **700**). The structure may be, for example, structure **108** in **Figure 1**. The structure may be configured for association with a platform, such as platform **110** in **Figure 1**. The structure may or may not be associated with the platform when the training data needed to train the heuristic model is collected.

20 Thereafter, the process identifies strain data generated by a sensor system associated with the structure during operation of the platform (operation **702**). In operation **702**, the structure is associated with the platform and may experience loading and/or pressure applied to the structure during operation of the platform. Further, in this illustrative example, the sensor system comprises a plurality of strain gauges attached to and/or embedded within the structure.

The process then generates estimated deformation data for the structure during operation of the platform based on the strain data generated by the sensor system (operation **704**). The strain data generated by the sensor system forms the input strain data for the heuristic model.

The process then adjusts a group of control parameters for the structure using the estimated deformation data for the structure to increase a performance of the structure to a desired level of performance (operation **706**), with the process terminating thereafter. As one illustrative example, when the structure is a phased
 5 array antenna, the estimated deformation data is used to adjust a phase and/or an amplitude for electronically steering a beam formed by the phased array antenna. For example, the estimated deformation data may be input into a compensation algorithm for the phased array antenna.

With reference now to **Figure 8**, an illustration of a process for training a
 10 heuristic model in the form of a flowchart is depicted in accordance with an illustrative embodiment. The process illustrated in **Figure 8** may be used to implement operation **700** in **Figure 7**. Further, this process may be implemented using trainer **102** in **Figure 1**.

The process begins by identifying training deformation data for each training
 15 case in a plurality of training cases (operation **800**). Each training case in the plurality of training cases corresponds to at least one of a particular deformed shape for a structure, such as structure **108** in **Figure 1**, and a selected amount of loading and/or pressure to be applied to the structure. In operation **800**, the training deformation data may be identified using, for example, imaging data **150** generated
 20 by imaging system **152** in **Figure 1**.

The process then identifies training strain data for each training case in the plurality of training cases (operation **802**). In operation **802**, the training strain data may be identified using, for example, strain data generated by a sensor system associated with the structure, such as, for example, strain data **128** generated by
 25 sensor system **130** associated with structure **108** in **Figure 1**.

Thereafter, the process adjusts a group of parameters for the heuristic model using the training deformation data and the training strain data for each case in the plurality of training cases such that the heuristic model is trained to generate estimated deformation data for the structure with a desired level of accuracy based
 30 on input strain data for the structure (operation **804**), with the process terminating

thereafter. In particular, operation **804** may be performed such that the heuristic model generates estimated deformation data for the structure with the desired level of accuracy during the operation of the platform with which the structure is associated.

5 With reference now to **Figure 9**, an illustration of a process for training a heuristic model in the form of a flowchart is depicted in accordance with an illustrative embodiment. The process illustrated in **Figure 9** may be used to implement operation **700** in **Figure 7**. Further, this process may be a more detailed process of the process described in **Figure 8**.

10 The process begins by selecting a training case from a plurality of training cases (operation **900**). In this illustrative example, each training case in the plurality of training cases specifies a particular deformed shape for the structure. The process then deforms the structure such that the structure has the deformed shape specified by the selected training case (operation **902**).

15 Thereafter, the process identifies training deformation data for the structure having the deformed shape specified by the selected training case (operation **904**). Operation **904** may be performed using, for example, an imaging system. The training deformation data identified in operation **904** comprises a plurality of deformation measurements identified for a plurality of points on the structure.

20 The process also identifies training strain data for the structure having the deformed shape specified by the selected training case (operation **906**). Operation **906** may be performed using a sensor system associated with the structure. The sensor system comprises a plurality of sensors. Each sensor generates a strain measurement for a particular point on the structure at which the sensor is
25 positioned. In this manner, training strain data comprises a plurality of strain measurements for a plurality of points on the structure.

 In this illustrative example, the plurality of deformation measurements in the training deformation data and the plurality of strain measurements in the training strain data are generated for a same plurality of points on the structure. In this
30 manner, each strain measurement generated at a point on the structure

corresponds to a deformation measurement generated at the same point on the structure.

Next, the process selects one combination of strain measurements from the training strain data (operation **908**). As used herein, a “combination of strain
5 measurements” is a selection of one or more of the plurality of strain measurements generated by the plurality of sensors in the sensor system. The combination of strain measurements does not include more than one strain measurement from a particular sensor in the sensor system. In this manner, a selection of a combination of strain measurements corresponds to a selection of a combination of sensors in
10 the sensor system. The combination of strain measurements selected may include one, some, or all of the strain measurements.

The process then uses the selected combination of strain measurements and a corresponding combination of deformation measurements in the training deformation data to train the heuristic model (operation **910**). In operation **910**, the
15 heuristic model uses the selected combination of strain measurements and the corresponding combination of deformation measurements to adjust a group of parameters for the heuristic model. The group of parameters adjusted determines the estimated deformation data that is generated by the heuristic model based on certain input strain data.

20 Thereafter, the process inputs the selected combination of strain measurements into the heuristic model to generate estimated deformation data (operation **912**). The process determines whether the estimated deformation data has a desired level of accuracy (operation **914**). In operation **914**, the determination may be made based on whether a difference between the estimated deformation
25 data generated by the heuristic model and the actual deformation data indicated in the training deformation data is within selected tolerances.

If the estimated deformation data does not have the desired level of accuracy, the process adjusts the group of parameters for the heuristic model (**916**) and then returns to operation **912**. With reference again to operation **914**, if the
30 estimated deformation data has the desired level of accuracy, the process stores

the selected combination of strain measurements, the corresponding combination of deformation measurements, and the values for the group of parameters (operation **918**).

5 The process then determines whether any additional unprocessed combinations of strain measurements are present (operation **920**). If any additional unprocessed combinations of strain measurements are present, the process returns to operation **908** as described above to select a new unprocessed combination of strain measurements.

10 Otherwise, the process determines whether any additional training cases are present in the plurality of training cases (operation **922**). If any additional unprocessed training cases are present, the process returns to operation **900** as described above. Otherwise, the process terminates. In this manner, the process described in **Figure 1** trains the heuristic model to generate estimated deformation data for the structure with a desired level of accuracy using the plurality of training cases.

15 With reference now to **Figure 10**, an illustration of a process for identifying a configuration of sensors for use on a structure in the form of a flowchart is depicted in accordance with an illustrative embodiment. The process described in **Figure 10** may be implemented to select a number of sensors from plurality of sensors **132** in sensor system **130** for structure **108** in **Figure 1** and a configuration for these selected sensors.

20 The process begins by identifying the estimated deformation data generated by the heuristic model based on each selected combination of strain measurements for each training case in the plurality of training cases for the heuristic model (operation **1000**). The process then uses the estimated deformation data generated based on each selected combination of strain measurements for each training case in the plurality of training cases to adjust a group of control parameters for the structure (operation **1002**).

25 Thereafter, the process identifies the combination of strain measurements with the minimum number of strain measurements needed for the heuristic model to

generate estimated deformation data for the structure with the level of accuracy needed to provide a desired level of performance for the structure when the estimated deformation data is used to adjust the group of control parameters for the structure (operation **1004**), with the process terminating thereafter. For example, a
5 compensation algorithm may use the estimated deformation data generated by the heuristic model to adjust the group of control parameters for the structure such that the structure has a desired level of performance.

The estimated deformation data has the desired level of accuracy when a difference between a group of performance parameters for the structure based on
10 adjustments to the group of control parameters, identified using the estimated deformation data, and the group of performance parameters for the structure based on adjustments to the group of control parameters, identified using actual deformation data, are within selected tolerances. In operation **1004**, the process determines which combination of strain measurements, that leads to the heuristic
15 model generating estimated deformation data with the desired level of accuracy, has the minimum number of sensors.

The flowcharts and block diagrams in the different depicted embodiments illustrate the architecture, functionality, and operation of some possible implementations of apparatuses and methods according to an illustrative
20 embodiment. In this regard, each block in the flowcharts or block diagrams may represent a module, segment, function, and/or a portion of an operation or step. For example, one or more of the blocks may be implemented as program code, in hardware, or as a combination of the two. When implemented in hardware, the hardware may, for example, take the form of integrated circuits that are
25 manufactured or configured to perform one or more operations in the flowcharts or block diagrams.

In some alternative implementations of an illustrative embodiment, the function or functions noted in the blocks may occur out of the order noted in the figures. For example, in some cases, two blocks shown in succession may be
30 executed substantially concurrently, or the blocks may sometimes be performed in

the reverse order, depending upon the functionality involved. Also, other blocks may be added in addition to the illustrated blocks in a flowchart or block diagram.

With reference now to **Figures 11-14**, illustrations of comparisons between graphs for control parameters are depicted in accordance with an illustrative embodiment. In **Figures 11-14**, each pair of graphs compares adjustments made to a control parameter for a phased array antenna using estimated deformation data and actual deformation data.

The estimated deformation data may be generated using, for example, heuristic model **104** in **Figure 1**. The estimated deformation data is generated by the heuristic model using strain data generated by a sensor system associated with the phased array antenna. In **Figures 11-14**, the values of the control parameters are presented in the different graphs with respect to the number of sensors in the sensor system associated with the phased array antenna.

With reference now to **Figure 11**, an illustration of a comparison of graphs for the peak sidelobe ratio of a phased array antenna is depicted in accordance with an illustrative embodiment. Graph **1100** has horizontal axis **1104** and vertical axis **1106**. Graph **1102** has horizontal axis **1108** and vertical axis **1110**.

Both horizontal axis **1104** and horizontal axis **1108** represent a number of points on the phased array antenna for which estimated deformation measurements and actual deformation measurements are identified. Both vertical axis **1106** and vertical axis **1110** represent the peak sidelobe ratio, in decibels, selected for the phased array antenna.

However, curve **1112** in graph **1100** identifies the peak sidelobe ratio when estimated deformation data generated by a trained heuristic model is used to adjust the phase and/or amplitude for the phased array antenna. Curve **1114** in graph **1102** identifies the peak sidelobe ratio when actual deformation data is used to adjust the phase and/or amplitude for the phased array antenna.

As depicted, these curves indicate that the peak sidelobe ratio selected for the phased array antenna based on the estimated deformation data is within selected tolerances of the peak sidelobe ratio selected for the phased array

antenna based on the actual deformation data. In other words, the peak sidelobe ratio for the phased array antenna, when the phased array antenna is electronically compensated using the estimated deformation data, and the peak sidelobe ratio for the phased array antenna when the phased array antenna is electronically compensated using the actual deformation data may be substantially equal within selected tolerances.

With reference now to **Figure 12**, an illustration of a comparison of graphs for a reduction in gain is depicted in accordance with an illustrative embodiment. In this illustrative example, graph **1200** has horizontal axis **1204** and vertical axis **1206**. Graph **1202** has horizontal axis **1208** and vertical axis **1210**.

Both horizontal axis **1204** and horizontal axis **1208** represent a number of sensors in the sensor system associated with the phased array antenna. Both vertical axis **1206** and vertical axis **1210** represent the reduction in gain for the phased array antenna, in decibels.

However, curve **1212** in graph **1200** identifies the reduction in gain when estimated deformation data generated by a trained heuristic model is used to adjust the phase and/or amplitude for the phased array antenna. Curve **1214** in graph **1202** identifies the reduction in gain when actual deformation data is used to adjust the phase and/or amplitude for the phased array antenna.

As depicted, these curves indicate that the reduction in gain for the phased array antenna based on the estimated deformation data is within selected tolerances of the reduction in gain for the phased array antenna based on the actual deformation data. In other words, the reduction in gain for the phased array antenna when the phased array antenna is electronically compensated using the estimated deformation data and the reduction in gain for the phased array antenna when the phased array antenna is electronically compensated using the actual deformation data may be substantially equal within selected tolerances.

With reference now to **Figure 13**, an illustration of a comparison of graphs for phase is depicted in accordance with an illustrative embodiment. In this

illustrative example, graph **1300** has horizontal axis **1304** and vertical axis **1306**. Graph **1302** has horizontal axis **1308** and vertical axis **1310**.

Both horizontal axis **1304** and horizontal axis **1308** represent a number of sensors in the sensor system associated with the phased array antenna. Both
5 vertical axis **1306** and vertical axis **1310** represent the phase selected for the phased array antenna, in degrees.

However, curve **1312** in graph **1300** identifies the phase when estimated deformation data generated by a trained heuristic model is used to adjust the phase for the phased array antenna. Curve **1314** in graph **1302** identifies the phase when
10 actual deformation data is used to adjust the phase for the phased array antenna. As depicted, these curves indicate that the phase selected for the phased array antenna based on the estimated deformation data is within selected tolerances of the phase selected for the phased array antenna based on the actual deformation data.

15 With reference now to **Figure 14**, an illustration of a comparison of graphs for beam steering angle deviation is depicted in accordance with an illustrative embodiment. In this illustrative example, graph **1400** has horizontal axis **1404** and vertical axis **1406**. Graph **1402** has horizontal axis **1408** and vertical axis **1410**.

Both horizontal axis **1404** and horizontal axis **1408** represent a number of
20 sensors in the sensor system associated with the phased array antenna. Both vertical axis **1406** and vertical axis **1410** represent the beam steering angle deviation for the phased array antenna, in degrees.

However, curve **1412** in graph **1400** identifies the beam steering angle deviation when estimated deformation data generated by a trained heuristic model
25 is used to adjust the phase and/or amplitude for the phased array antenna. Curve **1414** in graph **1402** identifies the beam steering angle deviation when actual deformation data is used to adjust the phase and/or amplitude for the phased array antenna.

As depicted, these curves indicate that the beam steering angle deviation for
30 the phased array antenna based on the estimated deformation data is within

selected tolerances of the beam steering angle deviation for the phased array antenna based on the actual deformation data. In other words, the beam steering angle deviation for the phased array antenna when the phased array antenna is electronically compensated using the estimated deformation data, and the beam steering angle deviation for the phased array antenna when the phased array antenna is electronically compensated using the actual deformation data may be substantially equal within selected tolerances.

The illustrations of graphs **1100** and **1102** in **Figure 11**, graphs **1200** and **1202** in **Figure 12**, graphs **1300** and **1302** in **Figure 13**, and graphs **1400** and **1402** in **Figure 14** are not meant to imply physical or architectural limitations to the manner in which an illustrative embodiment may be implemented. The data presented in these graphs is with respect to only one possible implementation for a structure, a sensor system associated with that structure, and a heuristic model used to estimate deformation of the structure.

Turning now to **Figure 15**, an illustration of a data processing system is depicted in accordance with an illustrative embodiment. Data processing system **1500** may be used to implement computer system **122** in **Figure 1** and/or computer system **202** in **Figure 2**. In this illustrative example, data processing system **1500** includes communications framework **1502**, which provides communications between processor unit **1504**, memory **1506**, persistent storage **1508**, communications unit **1510**, input/output (I/O) unit **1512**, and display **1514**. In these examples, communications frame work **1502** may be a bus system.

Processor unit **1504** serves to execute instructions for software that may be loaded into memory **1506**. Processor unit **1504** may be a number of processors, a multi-processor core, or some other type of processor, depending on the particular implementation. Further, processor unit **1504** may be implemented using a number of heterogeneous processor systems in which a main processor is present along with secondary processors on a single chip. As another illustrative example, processor unit **1504** may be a symmetric multi-processor system containing multiple processors of the same type.

Memory **1506** and persistent storage **1508** are examples of storage devices **1516**. A storage device is any piece of hardware that is capable of storing information, such as, for example, without limitation, data, program code in functional form, and/or other suitable types of information either on a temporary basis and/or a permanent basis. Storage devices **1516** may also be referred to as computer readable storage devices in these examples. Memory **1506**, in these illustrative examples, may be, for example, a random access memory or any other suitable volatile or non-volatile storage device. Persistent storage **1508** may take various forms, depending on the particular implementation.

For example, persistent storage **1508** may contain one or more components or devices. For example, persistent storage **1508** may be a hard drive, a flash memory, a rewritable optical disk, a rewritable magnetic tape, or some combination of the above. The media used by persistent storage **1508** also may be removable. For example, a removable hard drive may be used for persistent storage **1508**.

Communications unit **1510**, in these examples, provides for communications with other data processing systems or devices. In these examples, communications unit **1510** is a network interface card. Communications unit **1510** may provide communications through the use of physical and/or wireless communications links.

Input/output unit **1512** allows for input and output of data with other devices that may be connected to data processing system **1500**. For example, input/output unit **1512** may provide a connection for user input through a keyboard, a mouse, and/or some other suitable input device. Further, input/output unit **1512** may send output to a printer. Display **1514** provides a mechanism to display information to a user.

Instructions for the operating system, applications, and/or programs may be located in storage devices **1516**, which are in communication with processor unit **1504** through communications framework **1502**. In these illustrative examples, the instructions are in a functional form on persistent storage **1508**. These instructions may be loaded into memory **1506** for execution by processor unit **1504**. The

processes of the different embodiments may be performed by processor unit **1504** using computer implemented instructions, which may be located in a memory, such as memory **1506**.

These instructions are referred to as program code, computer usable
 5 program code, or computer readable program code that may be read and executed by a processor in processor unit **1504**. The program code in the different embodiments may be embodied on different physical or computer readable storage media, such as memory **1506** or persistent storage **1508**.

Program code **1518** is located in a functional form on computer readable
 10 media **1520** that is selectively removable and may be loaded onto or transferred to data processing system **1500** for execution by processor unit **1504**. Program code **1518** and computer readable media **1520** form computer program product **1522** in these illustrative examples. In one example, computer readable media **1520** may be computer readable storage media **1524** or computer readable signal media
 15 **1526**. Computer readable storage media **1524** may include, for example, an optical or magnetic disk that is inserted or placed into a drive or other device that is part of persistent storage **1508** for transfer onto a storage device, such as a hard drive, that is part of persistent storage **1508**. Computer readable storage media **1524** also may take the form of a persistent storage, such as a hard drive, a thumb drive, or a
 20 flash memory, that is connected to data processing system **1500**. In some instances, computer readable storage media **1524** may not be removable from data processing system **1500**. In these examples, computer readable storage media **1524** is a physical or tangible storage device used to store program code **1518** rather than a medium that propagates or transmits program code **1518**. Computer
 25 readable storage media **1524** is also referred to as a computer readable tangible storage device or a computer readable physical storage device. In other words, computer readable storage media **1524** is a media that can be touched by a person.

Alternatively, program code **1518** may be transferred to data processing system **1500** using computer readable signal media **1526**. Computer readable
 30 signal media **1526** may be, for example, a propagated data signal containing

program code **1518**. For example, computer readable signal media **1526** may be an electromagnetic signal, an optical signal, and/or any other suitable type of signal. These signals may be transmitted over communications links, such as wireless communications links, optical fiber cable, coaxial cable, a wire, and/or any other
5 suitable type of communications link. In other words, the communications link and/or the connection may be physical or wireless in these illustrative examples.

In some illustrative embodiments, program code **1518** may be downloaded over a network to persistent storage **1508** from another device or data processing system through computer readable signal media **1526** for use within data
10 processing system **1500**. For instance, program code stored in a computer readable storage medium in a server data processing system may be downloaded over a network from the server to data processing system **1500**. The data processing system providing program code **1518** may be a server computer, a client computer, or some other device capable of storing and transmitting program
15 code **1518**.

The different components illustrated for data processing system **1500** are not meant to provide architectural limitations to the manner in which different embodiments may be implemented. The different illustrative embodiments may be implemented in a data processing system including components in addition to or in
20 place of those illustrated for data processing system **1500**. Other components shown in **Figure 15** can be varied from the illustrative examples shown. The different embodiments may be implemented using any hardware device or system capable of running program code. As one example, the data processing system may include organic components integrated with inorganic components and/or may
25 be comprised entirely of organic components excluding a human being. For example, a storage device may be comprised of an organic semiconductor.

In another illustrative example, processor unit **1504** may take the form of a hardware unit that has circuits that are manufactured or configured for a particular use. This type of hardware may perform operations without needing program code

to be loaded into a memory from a storage device to be configured to perform the operations.

For example, when processor unit **1504** takes the form of a hardware unit, processor unit **1504** may be a circuit system, an application specific integrated circuit (ASIC), a programmable logic device, or some other suitable type of hardware configured to perform a number of operations. With a programmable logic device, the device is configured to perform the number of operations. The device may be reconfigured at a later time or may be permanently configured to perform the number of operations. Examples of programmable logic devices include, for example, a programmable logic array, a field programmable logic array, a field programmable gate array, and other suitable hardware devices. With this type of implementation, program code **1518** may be omitted because the processes for the different embodiments are implemented in a hardware unit.

In still another illustrative example, processor unit **1504** may be implemented using a combination of processors found in computers and hardware units. Processor unit **1504** may have a number of hardware units and a number of processors that are configured to run program code **1518**. With this depicted example, some of the processes may be implemented in the number of hardware units, while other processes may be implemented in the number of processors.

In another example, a bus system may be used to implement communications framework **1502** and may be comprised of one or more buses, such as a system bus or an input/output bus. Of course, the bus system may be implemented using any suitable type of architecture that provides for a transfer of data between different components or devices attached to the bus system.

Additionally, a communications unit may include a number of more devices that transmit data, receive data, or transmit and receive data. A communications unit may be, for example, a modem or a network adapter, two network adapters, or some combination thereof. Further, a memory may be, for example, memory **1506**, or a cache, such as found in an interface and memory controller hub that may be present in communications framework **1502**.

Below are aspects, variants, instances, and examples of illustrations disclosed in the text and the figures above. In one aspect, a method is disclosed for identifying deformation of a structure **108**, the method including: identifying training deformation data **142** for the structure **108** for each training case in a plurality of training cases **136**, wherein the training deformation data **142** is configured for use by a heuristic model **108** to increase an accuracy of output data **118** generated by the heuristic model **104**; identifying training strain data **144** for the structure **108** for the each training case in the plurality of training cases **136**, wherein the training strain data **144** is configured for use by the heuristic model **104** to increase the accuracy of the output data **118** generated by the heuristic model **104**; and adjusting a group of parameters **121** for the heuristic model **104** using the training deformation data **142** and the training strain data **144** for the each training case in the plurality of training cases **136** such that the heuristic model **104** is trained to generate estimated deformation data **124** for the structure **108** based on input strain data **126** in which the estimated deformation data **124** has a desired level of accuracy.

In one variant, the method further includes generating strain data **128** for the structure **108** using a sensor system **130** associated with the structure **108** during operation of a platform **110** when the structure **108** is associated with the platform **110**. In another variant, the method further includes: generating the estimated deformation data **124** for the structure **108** using the heuristic model **104** and the strain data **128** as the input strain data **126** for the heuristic model **104**. In yet another variant, the method includes wherein the step of generating the estimated deformation data **124** for the structure **108** using the heuristic model **104** and the strain data **128** as the input strain data **126** for the heuristic model **104** includes: generating the estimated deformation data **124** for the structure **108** using the heuristic model **104**, the strain data **128** as the input strain data **126** for the heuristic model **104**, and additional input data **133** for the heuristic model **104**.

In one instance, the method further includes: adjusting a group of control parameters **115** for the structure **108** using the estimated deformation data generated by the heuristic model **104** such that the structure **108** has a desired level of performance during the operation of the platform **110**. In another instance,
 5 the method includes wherein the step of adjusting the group of control parameters **115** for the structure **108** using the estimated deformation data **124** generated by the heuristic model **104** such that the structure **108** has the desired level of performance during the operation of the platform **110** includes: adjusting the group of control parameters **115** for the structure **108** to compensate for the deformation
 10 of the structure **108** during the operation of the platform **110** using the estimated deformation data **124** generated by the heuristic model **104**.

In one example, the method further includes: selecting a combination of sensors for the sensor system **130**, wherein the selected combination of sensors has a minimum number of sensors needed for the heuristic model **104** to generate
 15 the estimated deformation data **124** with the desired level of accuracy and for the structure **108** to have the desired level of performance during the operation of the platform **110** when the estimated deformation data **124** is used to adjust the group of control parameters **115**. In another example, the method includes wherein the step of identifying the training deformation data **142** for the structure **108** for the
 20 each training case in the plurality of training cases **136** includes: identifying the training deformation data **142** for the structure **108** for the each training case in the plurality of training cases **136** using imaging data **150** generated by an imaging system **152**, wherein the training deformation data **142** is configured for use by a heuristic model **104** to increase an accuracy of output data **118** generated by the
 25 heuristic model **104**.

In yet another example, the method includes wherein the step of identifying the training strain data **144** for the structure **108** for the each training case **136** in the plurality of training cases includes: identifying the training strain data **144** for the structure **108** for the each training case in the plurality of training cases **136** using a
 30 sensor system **130** associated with the structure **108**, wherein the training strain

data **144** is configured for use by the heuristic model **104** to increase the accuracy of the output data **118** generated by the heuristic model **104**.

In one variant, the method further includes: identifying training environmental data for the structure **108** for the each training case in the plurality of training cases **136**, wherein the training environmental data is configured for use by the heuristic model **104** to increase the accuracy of the output data **118** generated by the heuristic model **104**; and wherein the step of adjusting the group of parameters **121** for the heuristic model **104** using the training deformation data **142** and the training strain data **144** for the each training case in the plurality of training cases **136** includes: adjusting the group of parameters **121** for the heuristic model **104** using the training deformation data **142**, the training strain data **144**, and the training environmental data for the each training case in the plurality of training cases **136** such that the heuristic model **104** is trained to generate the estimated deformation data **124** for the structure **108** based on the input strain data **126** in which the estimated deformation data **124** has the desired level of accuracy.

In one variant, the method further includes: deforming the structure **108** into a deformed shape **118** corresponding to a training case in the plurality of training cases **136**; and generating strain data **128** for the structure **108** when the structure **108** has the deformed shape **116**. In another variant, the method includes wherein the step of deforming the structure **108** into the deformed shape **116** corresponding to the training case in the plurality of training cases **136** includes: applying a plurality of selected loads to a plurality of points **148** on the structure **108** such that the structure **108** deforms into the deformed shape **116** corresponding to the training case in the plurality of training cases **136**.

In one example, the method includes wherein the heuristic model **104** includes at least one of a neural network, a learning-based algorithm, a regression model, a support vector machine, a data fitting model, a pattern recognition model, and artificial intelligence. In another example, the method includes wherein the structure is a phased array antenna **212** configured for association with an aircraft and wherein the structure **108** deforms while the aircraft is in flight such that a

shape **112** of the phased array antenna **212** changes from a reference shape **114** to a deformed shape **116**.

In one aspect, a method is disclosed for managing a performance of a structure **108**, the method including:

- 5 identifying training deformation data **142** and training strain data **144** for the structure **108** for each training case in a plurality of training cases **136**, wherein the each training case is configured for use by a heuristic model **104** to increase an accuracy of output data **118** generated by the heuristic model **104** and wherein the structure **108** is configured for association with a platform **110**; adjusting a group of
- 10 parameters **121** for the heuristic model **104** using the training deformation data **142** and the training strain data **144** for the each training case in the plurality of training cases **136** such that the heuristic model **104** is trained to generate estimated deformation data **124** for the structure **108** based on input strain data **126** in which the estimated deformation data **124** has a desired level of accuracy;
- 15 generating strain data **128** for the structure **108** using a sensor system **130** associated with the structure **108** during operation of the platform **110** when the structure **108** is associated with the platform **110**; generating the estimated deformation data **124** for the structure **108** using the heuristic model **104** and the strain data **128** as the input strain data **126** for the heuristic model **104**; and
- 20 adjusting a group of control parameters **115** for the structure **108** using the estimated deformation data **124** generated by the heuristic model **104** such that the structure **108** has a desired level of performance during the operation of the platform **110**.

- In another variant, the method further includes: selecting a combination of
- 25 sensors for the sensor system **130** in which the combination of sensors selected has a minimum number of sensors needed for the heuristic model **104** to generate the estimated deformation data **124** with the desired level of accuracy and for the structure **108** to have the desired level of performance during the operation of the platform **110** when the estimated deformation data **124** is used to adjust the group
 - 30 of control parameters **115**.

In one aspect, an apparatus is disclosed including:
a heuristic model **104** configured to generate estimated deformation data **124** for a
structure **108** based on input strain data **126**; and a trainer **102** configured to
identify training deformation data **142** and training strain data **144** for each training
5 case in a plurality of training cases **136** and train the heuristic model **104** using the
training deformation data **142** and the training strain data **144** identified for the each
training case in the plurality of training cases **136** such that the heuristic model **104**
generates the estimated deformation data **124** for the structure **108** based on the
input strain data **126** in which the estimated deformation data **124** has a desired
10 level of accuracy.

In one variant, the apparatus includes wherein the trainer **102** is configured
to receive the training strain data **144** for the each training case in the plurality of
training cases **136** from a sensor system **130** associated with the structure **108** in
which the sensor system **130** includes a plurality of sensors positioned at a plurality
15 of points **148** on the structure **108** in which the plurality of sensors is configured to
generate a plurality of strain measurements for the plurality of points **148** on the
structure **108**. In still another variant, the apparatus includes wherein the heuristic
model **104** is configured to adjust a group of parameters **121** for the heuristic model
104 using the training deformation data **142** and the training strain data **144** for the
20 each training case in the plurality of training cases **136** such that the estimated
deformation data **124** generated by the heuristic model **104** based on the input
strain data **126** has the desired level of accuracy.

In yet another variant, the apparatus includes wherein the heuristic model
104 includes at least one of a neural network, a learning-based algorithm, a
25 regression model, a support vector machine, a data fitting model, a pattern
recognition model, and artificial intelligence. In one example, the apparatus
includes wherein the structure **108** is associated with a platform **110** and wherein
the estimated deformation data **124** generated by the heuristic model **104** is used to
adjust a group of control parameters **115** for the structure **108** during operation of

the platform **110** such that the structure **108** has a desired level of performance during the operation of the platform **110**.

The description of the different illustrative embodiments has been presented for purposes of illustration and description, and is not intended to be exhaustive or
5 limited to the embodiments in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. Further, different illustrative embodiments may provide different features as compared to other illustrative embodiments. The embodiment or embodiments selected are chosen and described in order to best explain the principles of the embodiments, the
10 practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A system for identifying deformation of a structure associated with a platform,
5 the system comprising:

at least one computer processor operably configured to:

10 execute a heuristic model configured to generate estimated deformation data in response to input strain data for the structure and a group of heuristic model control parameters, wherein the accuracy of the estimated deformation data is controlled by said group of heuristic model control parameters, wherein the at least one computer processor is configured to generate training strain data in response to
15 measurements received from a sensor system associate with the structure, wherein the heuristic model has been configured by the training strain data and corresponding training deformation data for the structure for each training case in a plurality of training cases, and wherein said group of heuristic model control parameters have been
20 adjusted based on the training strain data and training deformation data to configure the heuristic model to generate the estimated deformation data with a particular level of accuracy;

25 receive actual strain data for the structure, from the sensor system, during operation of the platform that causes deformation of the structure; and

apply said actual strain data as input strain data to the heuristic model to produce estimated deformation data signals, with the particular level

of accuracy, for use in controlling operational performance of the structure during the deformation of the structure.

- 5 2. The system of claim 1 further comprising the sensor system, the sensor system including a plurality of sensors positioned at a plurality of points on the structure wherein the plurality of sensors is configured to generate a plurality of strain measurements for the plurality of points on the structure.
- 10 3. The system of any one of claims 1 to 2 wherein the at least one computer processor is configured to:
- 15 adjust a group of structure control parameters for the structure in response to the estimated deformation data signals generated by the heuristic model such that the structure has a particular level of performance during the operation of the platform.
- 20 4. The system of claim 3 wherein the at least one computer processor is configured to adjust the group of structure control parameters to compensate for the deformation of the structure during the operation of the platform, based on the estimated deformation data signals generated by the heuristic model.
- 25 5. The system of any one of claims 1 to 4 wherein the structure includes a phased array antenna on an aircraft and wherein the phased array antenna deforms from a reference shape to a deformed shape in flight.
- 30 6. The system of claim 5 wherein the at least one computer processor is configured to:

identify a deformation of the phased array antenna; and

beam steer the phased array antenna to compensate for the deformation in substantially real-time, in response to the estimated deformation data signals.

- 5 **7.** The system of any one of claims **5** to **6** wherein the at least one computer processor is configured to:

electronically adjust at least one of a phase and an amplitude of the phased array antenna in response to deformation of the phased array antenna.

10

- 8.** The system of claim **3** wherein the at least one computer processor is configured to produce a group of performance parameters for the structure and to evaluate performance of the structure based on said group of performance parameters.

15

- 9.** The system of claim **8** wherein the structure includes a phased array antenna and the group of performance parameters includes at least one of: peak sidelobe ratio (PSLR), gain loss, and beam steering angle deviation.

- 20 **10.** The system of claim **9** wherein the at least one computer processor is configured to adjust the group of structure control parameters in response to the group of performance parameters such that the phased array antenna has the particular level of performance during the operation of the platform.

- 25 **11.** The system of any one of claims **1** to **10**, wherein the at least one computer processor is configured to select a combination of sensors of the sensor system such that the selected combination of sensors has a minimum number of sensors needed for the heuristic model to generate the estimated deformation data with the particular level of accuracy.

30

- 5
12. The system of any one of claims 1 to 11, wherein the at least one computer processor is configured to generate the training deformation data in response to imaging data from an imaging system.
- 10
13. The system of any one of claims 1 to 12 wherein the heuristic model comprises at least one of a neural network, a learning-based algorithm, a regression model, a support vector machine, a data fitting model, a pattern recognition model, and an artificial intelligence system.
- 15
14. The system of any one of claims 1 to 13 wherein the at least one computer processor is configured to identify training environmental data for the structure.
- 15
15. The system of claim 14 wherein the at least one computer processor is configured to adjust the group of heuristic model control parameters in response to the training deformation data, the training strain data, and the training environmental data.
- 20
16. The system of any one of claims 1 to 15 wherein the at least one computer processor is configured to apply additional input data to the heuristic model for use in producing said estimated deformation data signals.
- 25
17. The system of any one of claims 1 to 16, wherein the at least one computer processor generates said training strain data by generating strain data for the structure when the structure has a deformed shape.
- 30
18. The system of claim 17, wherein a plurality of selected loads are applied to a plurality of points on the structure such that the structure deforms into the deformed shape.

19. The system of any one of claims 1 to 18 wherein the at least one computer processor includes:

5 a trainer system processor for configuring the heuristic model based on the training strain data and corresponding training deformation data; and

10 a performance management processor associated with the platform for controlling operational performance of the structure during the deformation of the structure, in response to the heuristic model configured by the trainer system processor.

20. A system for identifying deformation of a structure associated with a platform, the system comprising:

15 a first computer operably configured to:

generate training strain data and training deformation data for the structure for each training case in a plurality of training cases;

20 configure a heuristic model to generate estimated deformation data in response to input strain data for the structure, the accuracy of the estimated deformation data being controlled by a group of heuristic model control parameters, wherein configuring the heuristic model comprises:

25 providing the training strain data and the training deformation data to the heuristic model; and

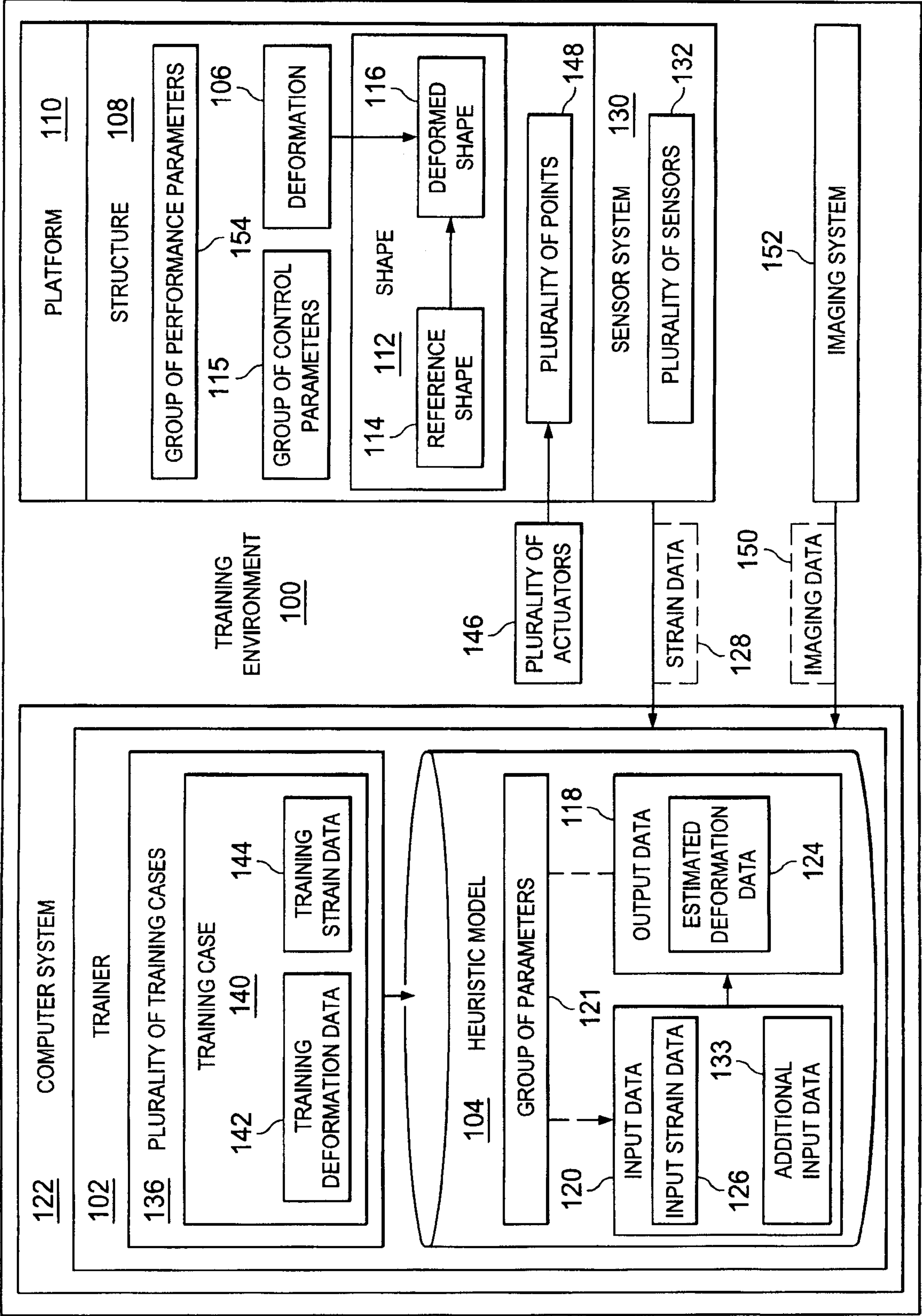
30 adjusting said group of heuristic model control parameters such that the heuristic model will, in response to the input strain data,

produce the estimated deformation data with a particular level of accuracy; and

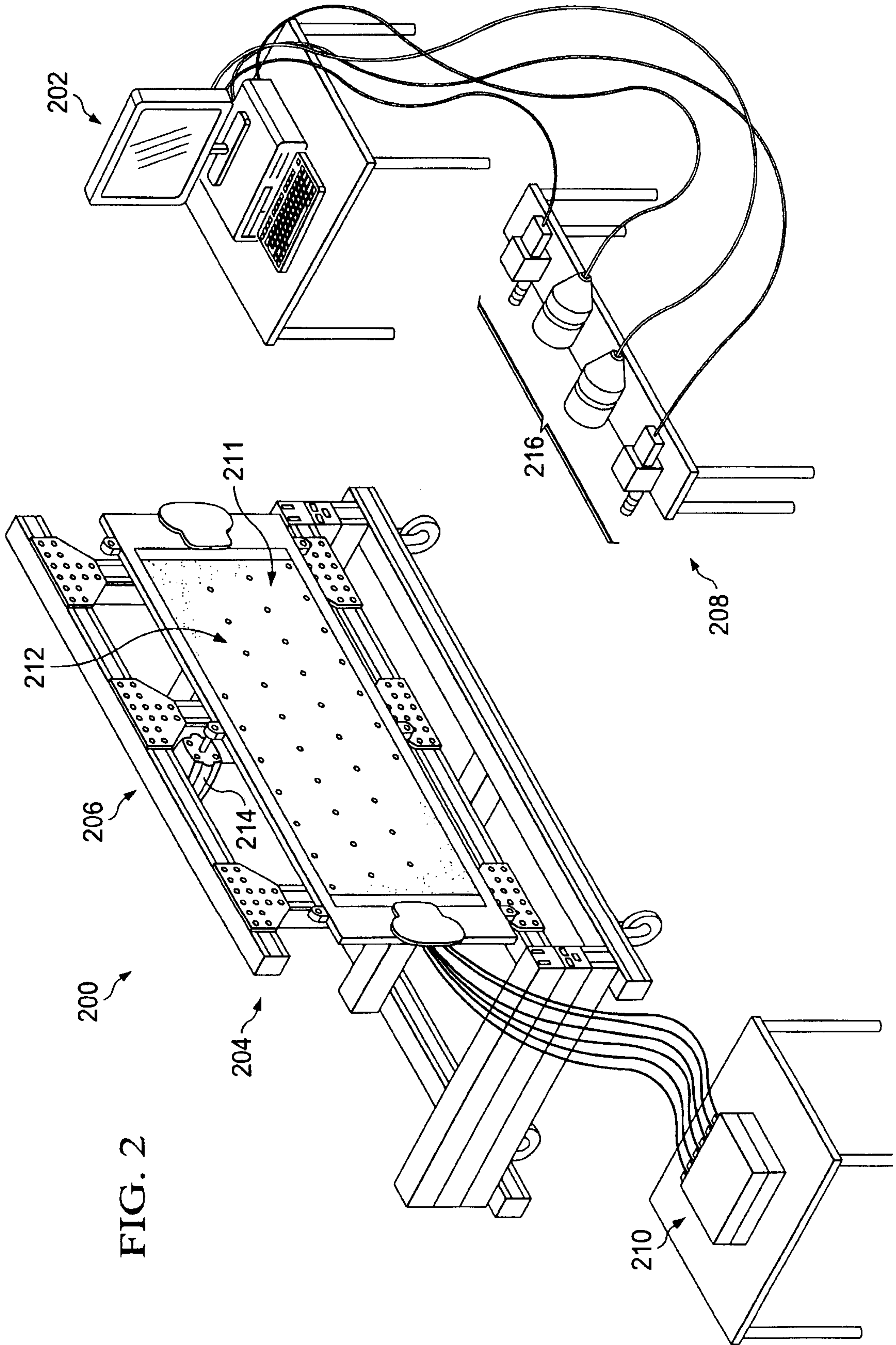
5 the system of any one of claims 1 – 19, wherein the heuristic model configured by the first computer is executed by said at least one processor.

10 **21.** The system of claim 20 wherein the first computer is part of a trainer system in a training environment, and the at least one processor is part of an aircraft, and the structure includes a phased array antenna of the aircraft.

FIG. 1



2/12



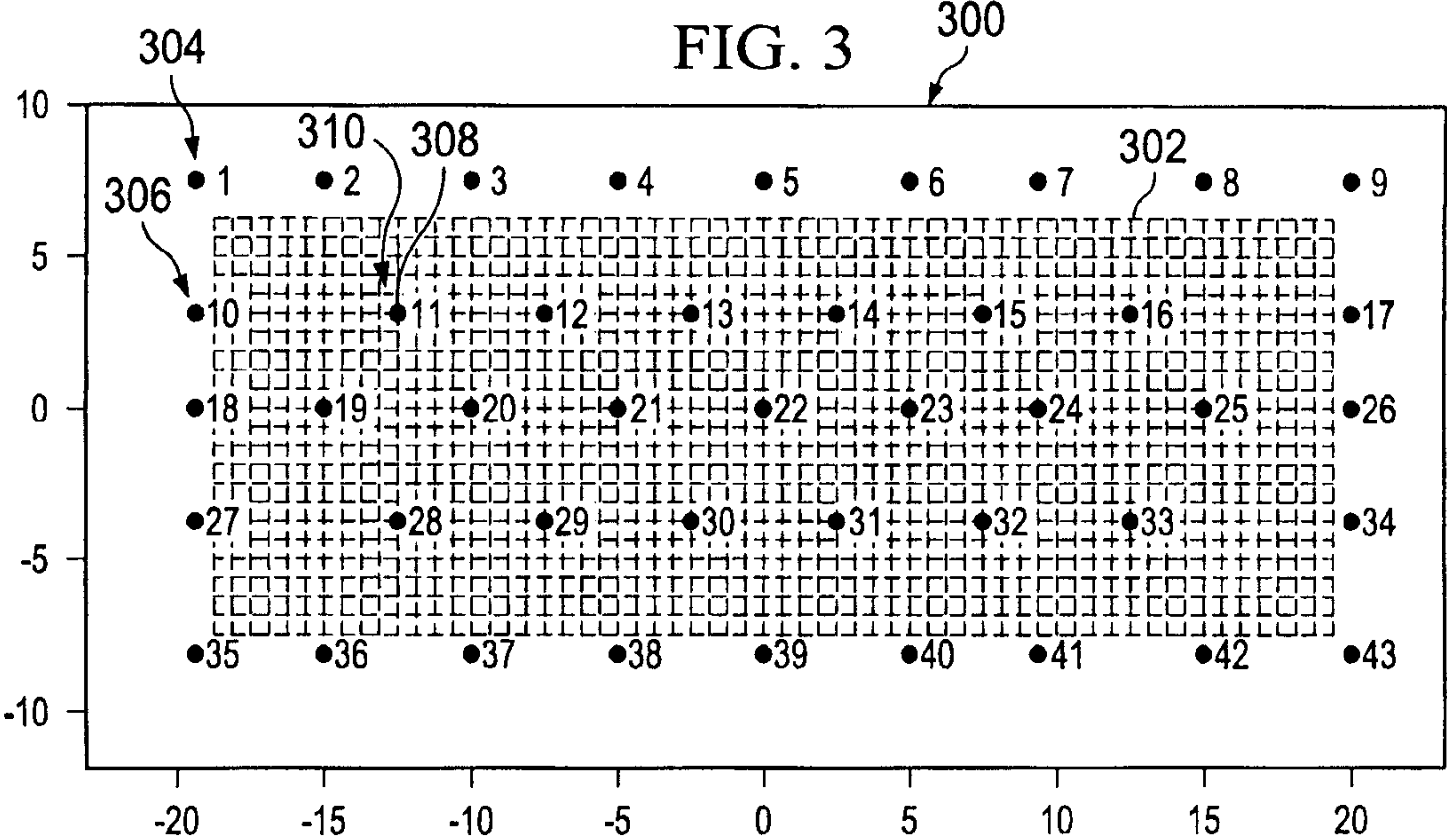


FIG. 4

400

ESTIMATED DEFORMATION MEASUREMENTS					
ID	SHAPE A	SHAPE B	SHAPE C	SHAPE D	SHAPE E
<u>402</u>	<u>404</u>	<u>406</u>	<u>408</u>	<u>410</u>	<u>412</u>
1	-0.0753	0.0187	-0.0133	0.0657	0.0963
5	-0.3329	-0.0940	0.1483	0.1784	0.3891
9	-0.0102	-0.0189	0.0103	0.0202	0.0308
11	-0.1868	0.0107	0.0093	0.1350	0.2276
16	-0.0904	-0.0577	0.0421	0.0561	0.1087
18	-0.1400	0.1281	-0.1456	0.1740	0.1866
22	-0.1712	-0.0415	0.0563	0.1014	0.2013
26	0.0906	-0.0510	-0.0611	-0.0114	-0.0882
28	-0.1633	0.0971	-0.1031	0.1687	0.2086
32	-0.0258	-0.0486	0.0090	0.0298	0.0381
35	-0.1993	0.2503	-0.3022	0.2925	0.2733
39	-0.0342	-0.0045	0.0019	0.0288	0.0449
43	0.2303	-0.0670	-0.1476	-0.0419	-0.2298

413

500 4/12

FIG. 5

ACTUAL DEFORMATION MEASUREMENTS					
ID	SHAPE A	SHAPE B	SHAPE C	SHAPE D	SHAPE E
<u>502</u>	<u>504</u>	<u>506</u>	<u>508</u>	<u>510</u>	<u>512</u>
1	-0.0773	0.0195	-0.0133	0.0656	0.0939
5	-0.3333	-0.0945	0.1496	0.1780	0.3866
9	-0.0131	-0.0186	0.0127	0.0212	0.0281
11	-0.1882	0.0100	0.0078	0.1362	0.2235
16	-0.0872	-0.0584	0.0456	0.0568	0.1150
18	-0.1427	0.1247	-0.1504	0.1739	0.1767
22	-0.1725	-0.0416	0.0577	0.1021	0.1996
26	0.0943	-0.0478	-0.0531	-0.0110	-0.0779
28	-0.1653	0.0945	-0.1079	0.1685	0.2013
32	-0.0244	-0.0489	0.0132	0.0305	0.0428
35	-0.2023	0.2444	-0.3139	0.2914	0.2577
39	-0.0351	-0.0056	0.0030	0.0293	0.0444
43	0.2360	-0.0668	-0.1396	-0.0471	-0.2101

513

600

FIG. 6

DIFFERENCE					
ID	SHAPE A	SHAPE B	SHAPE C	SHAPE D	SHAPE E
<u>602</u>	<u>606</u>	<u>608</u>	<u>610</u>	<u>612</u>	<u>614</u>
1	0.002	-0.001	0.000	0.000	0.002
5	0.000	0.000	-0.001	0.000	0.002
9	0.003	0.000	-0.002	-0.001	0.003
11	0.001	0.001	0.001	-0.001	0.004
16	-0.003	0.001	-0.003	-0.001	-0.006
18	0.003	0.003	0.005	0.000	0.010
22	0.001	0.000	-0.001	-0.001	0.002
26	-0.004	-0.003	-0.008	0.000	-0.010
28	0.002	0.003	0.005	0.000	0.007
32	-0.001	0.000	-0.004	-0.001	-0.005
35	0.003	0.006	0.012	0.001	0.016
39	0.001	0.001	-0.001	0.000	0.000
43	-0.006	0.000	-0.008	0.005	-0.020

604

5/12

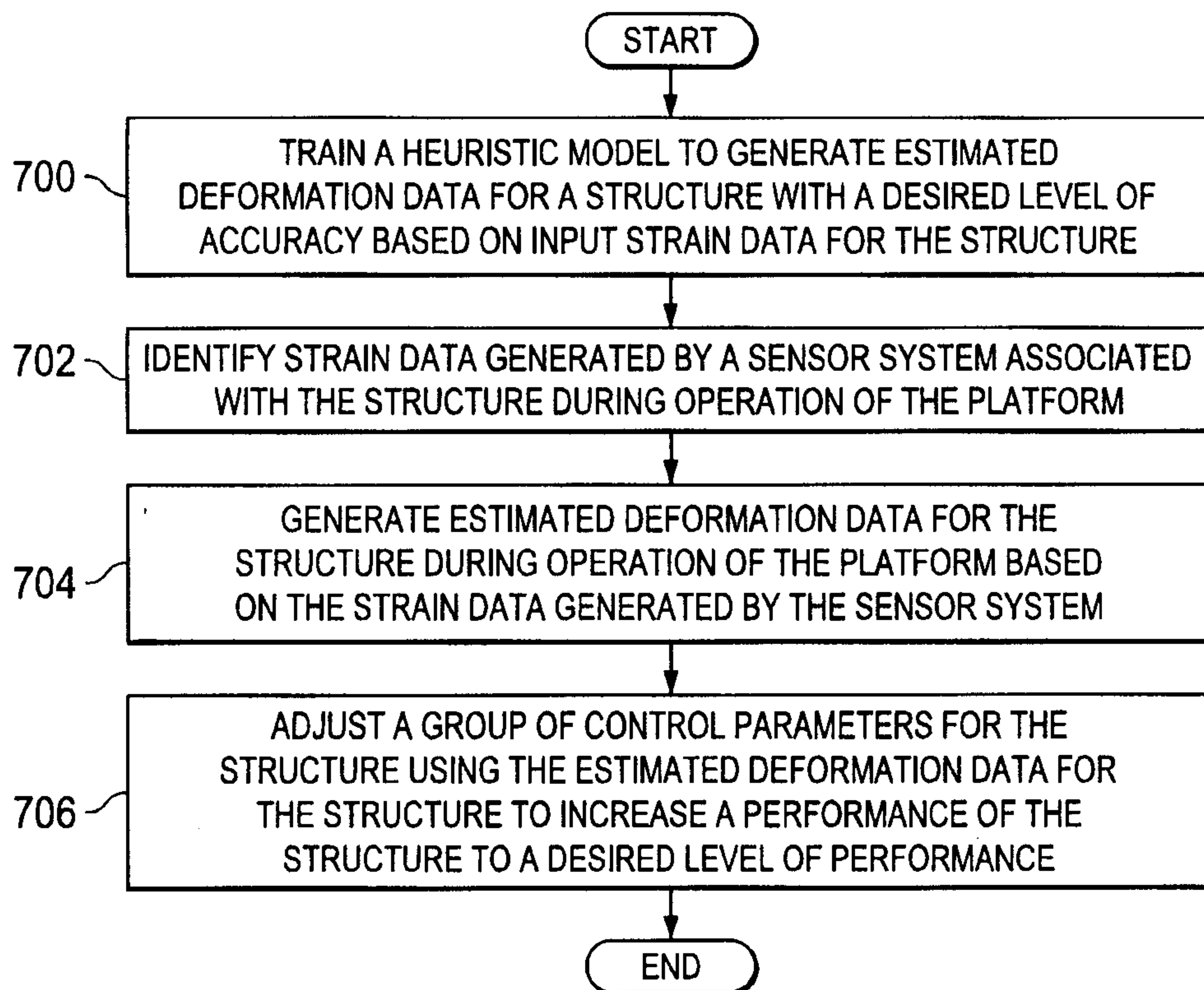


FIG. 7

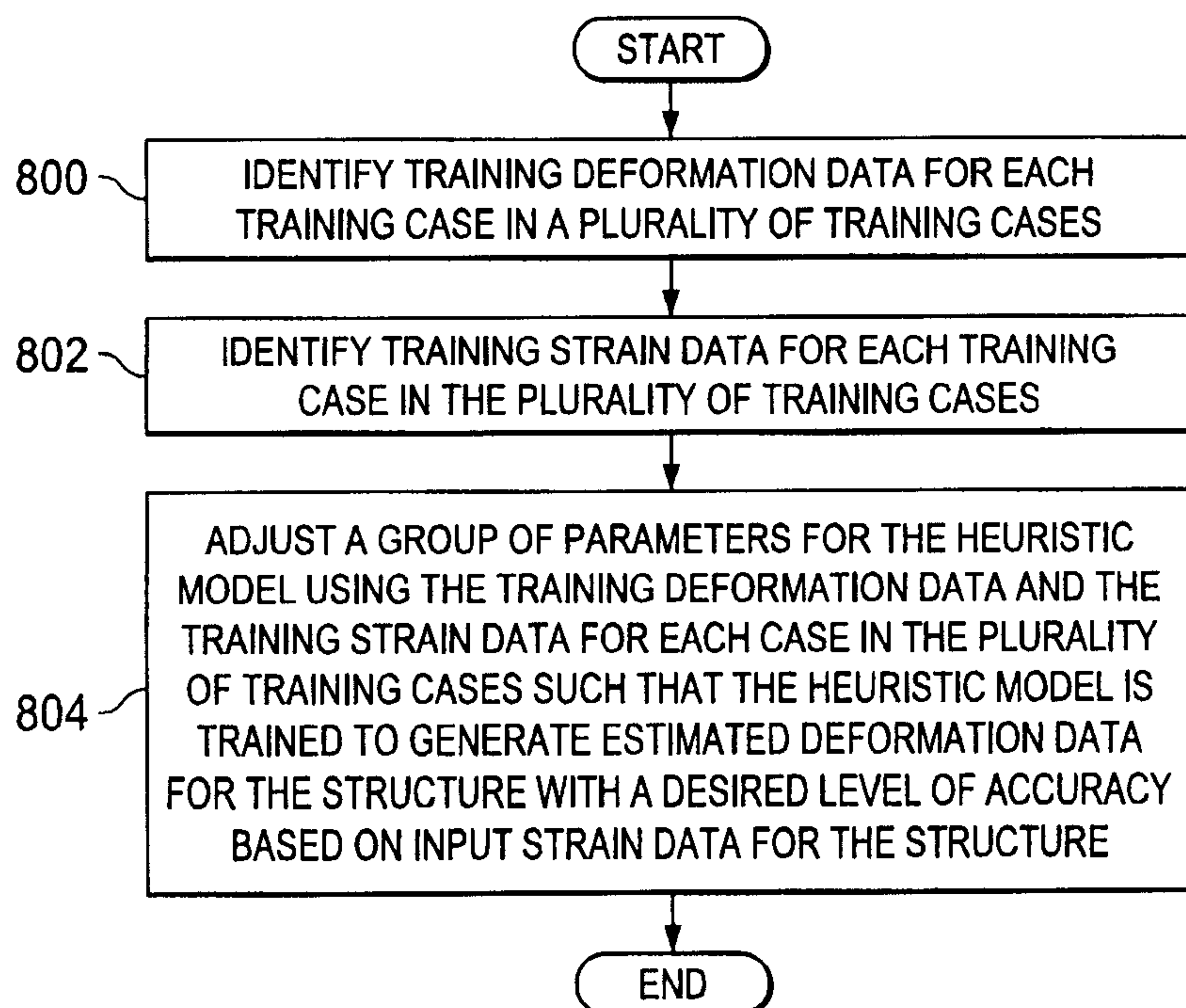
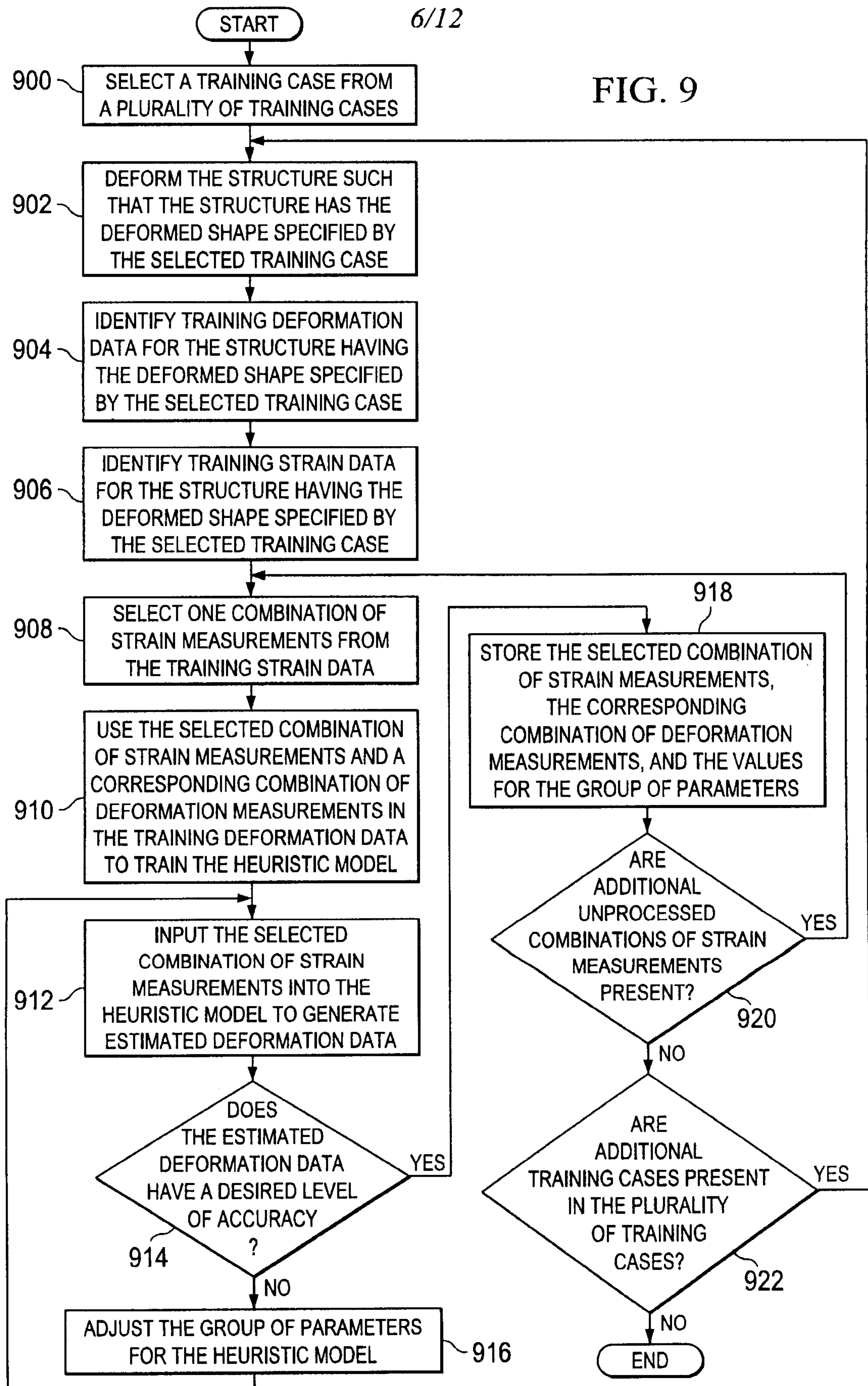


FIG. 8

6/12

FIG. 9



7/12

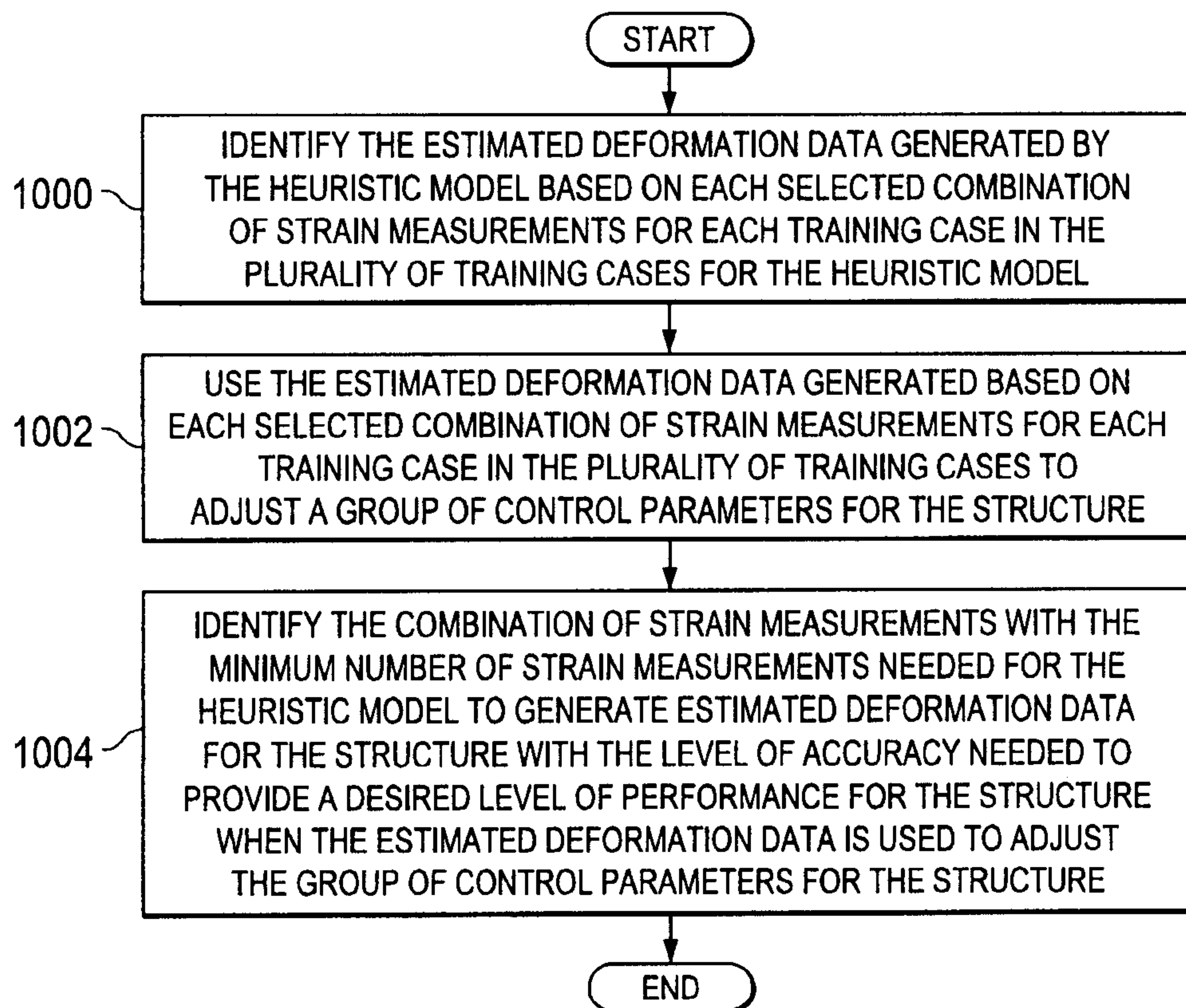


FIG. 10

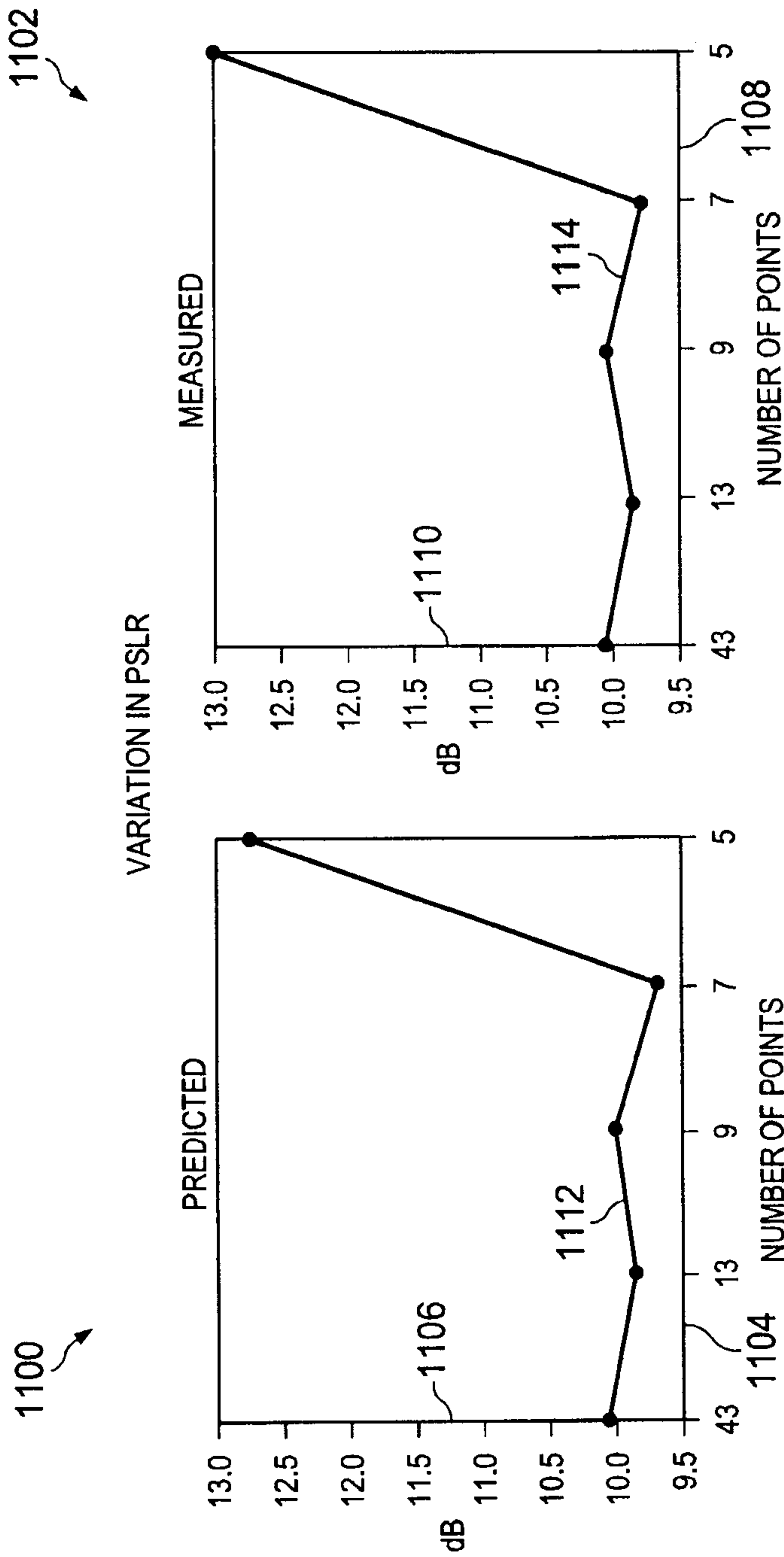


FIG. 11

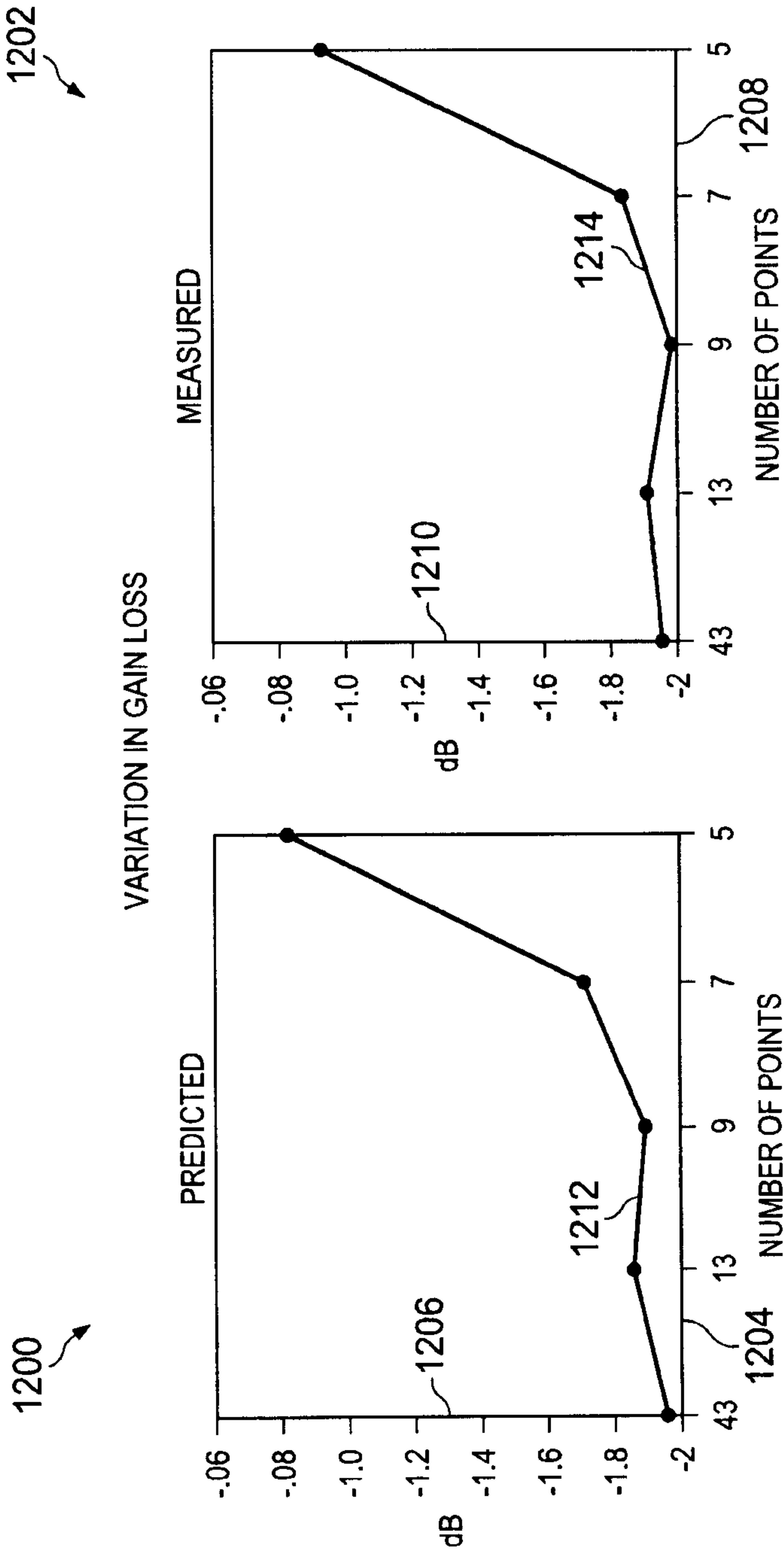


FIG. 12

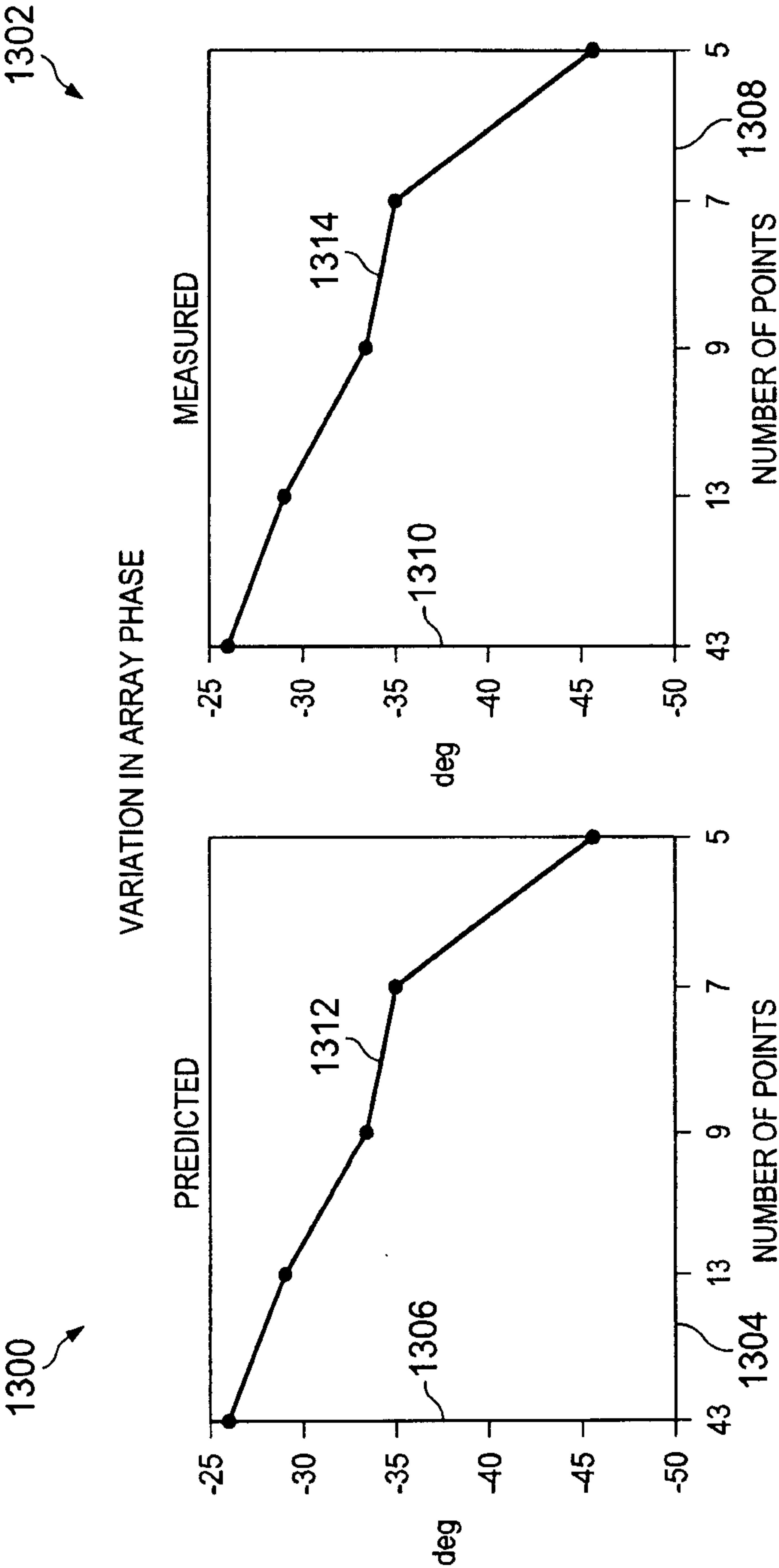


FIG. 13

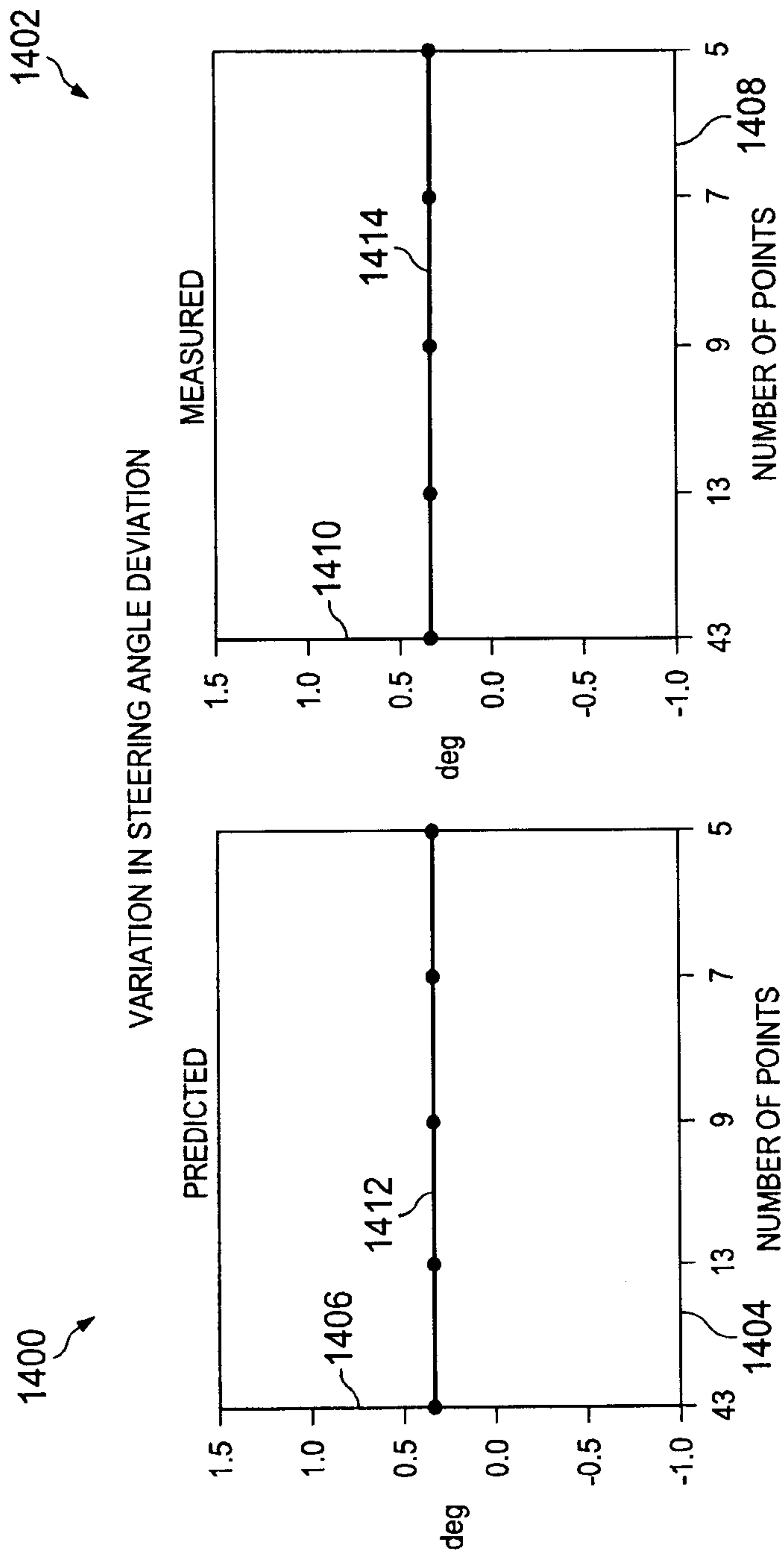


FIG. 14

12/12

