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(71) Applicant: **HALLIBURTON ENERGY SERVICES, INC.** [US/US]; 3000 N. Sam Houston Parkway E., Houston, Texas 77032 (US).

(72) Inventors: **ZHAO, Yiming**; 22400 Westheimer Pkwy, Apt 701, Katy, Texas 77450 (US). **ZALLUHOGLU, Umut**; 4475 Wilson Rd, Apt 3302, Humble, Texas 77396 (US).

(74) Agent: **BRYAN, Jason W.** et al.; 1000 Louisiana Street, Fifty-Third Floor, Houston, Texas 77002 (US).

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(57) Abstract: A method for controlling directional drilling including defining a cost function that includes at least one penalty condition associated with a control input. A controller is provided with a current position of the drilling tool and a reference position of a predetermined wellbore path. The controller determines an optimal trajectory for a curved path based on the cost function and the current position and reference position. The optimal trajectory originates from the current position and substantially intersects the reference position. As a result, the controller instructs the drilling tool to generate a wellbore path based on the optimal trajectory.

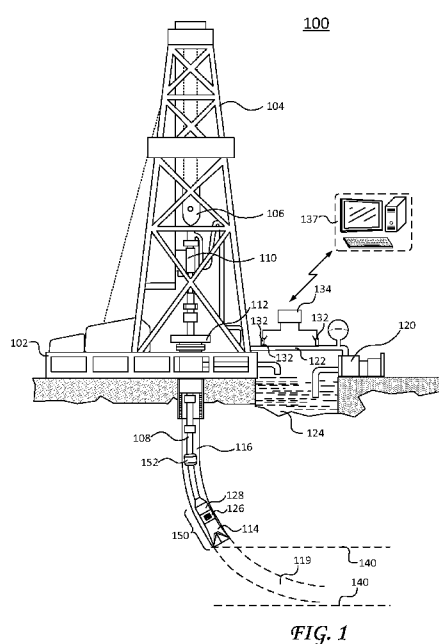


FIG. 1

OPTIMAL TRAJECTORY CONTROL FOR ROTARY STEERABLE SYSTEMS

CROSS-REFERENCE

[0001] The present application claims the benefit of U.S. Provisional Application No. 62/452,948, filed January 31, 2017, which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

[0002] The present technology generally pertains to directional drilling within subterranean earth formations, and more specifically, to directional drilling based on optimal drilling trajectories.

BACKGROUND

[0003] Directional drilling, or controlled steering, is commonly used to guide drilling tools in the oil, water, and gas industries to reach resources that are not located directly below a wellhead. Directional drilling particularly provides access to reservoirs where vertical access is difficult if not impossible. In general, directional drilling refers to steering a drilling tool according to a predefined well path plan, having target coordinates and drilling constraints, created by a multidisciplinary team (e.g., reservoir engineers, drilling engineers, geo-steerers, geologists, etc.) to optimize resource collection/discovery.

[0004] As the future of directional drilling moves toward exploiting complex reservoirs and difficult to reach resources, it becomes increasingly important for the drilling tool to follow these predefined path plans as closely as possible. Deviations from such pre-defined path plans may result in a waste of resources, damage the drilling tools, or even undermine the stability of earth formations surrounding a reservoir. Path tracking and guiding drilling tools along the predefined path plans often presents new challenges due, in part, physical and operational constraints of the drilling tools, characteristics of rock formations, complex well geometries, and the like.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] The embodiments herein may be better understood by referring to the following description in conjunction with the accompanying drawings in which like reference numerals indicate analogous, identical, or functionally similar elements. Understanding that these drawings depict only exemplary embodiments of the disclosure and are not therefore to be considered to be limiting of its scope, the principles herein are described and explained with additional specificity and detail through the use of the accompanying drawings in which:

[0006] FIG. 1 is a schematic diagram of a directional drilling environment, showing measurement while drilling (MWD) operations;

[0007] FIG. 2 is a schematic diagram control device for a directional drilling tool;

[0008] FIG. 3 is a schematic diagram of a three-dimensional (3D) wellbore environment, showing a directional drilling tool following a well path defined by a collection of waypoints;

[0009] FIG. 4A is a graph showing two-dimensional (2D) wellbore path divergences for directional drilling using attitude azimuth correction;

[0010] FIG. 4B is a graph showing 2D wellbore path divergences for directional drilling using attitude position correction;

[0011] FIG. 5 is a graph showing wellbore path convergence for directional drilling using a curvature-based feedback control loop, according to one embodiment of this disclosure;

[0012] FIG. 6 is a block diagram of a control loop system, in accordance with one or more embodiments of this disclosure;

[0013] FIG. 7 is a graph illustrating linear quadratic tracking technique, in accordance with the disclosure herein;

[0014] FIG. 8 is a flow chart illustrating a method for adjusting the trajectory of a directional drilling tool;

[0015] FIG. 9 is an exemplary graph illustrating a generated path, in accordance with the disclosure herein; and

[0016] FIG. 10 is an exemplary graph illustrating test results for finite horizon LQT control, in accordance with the disclosure herein.

DETAILED DESCRIPTION

[0017] Various embodiments of the disclosure are discussed in detail below. While specific implementations are discussed, it should be understood that this is done for illustration purposes only. A person skilled in the relevant art will recognize that other components and configurations may be used without parting from the spirit and scope of the disclosure. Additional features and advantages of the disclosure will be set forth in the description which follows, and in part will be obvious from the description, or can be learned by practice of the herein disclosed principles. The features and advantages of the disclosure can be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims. These and other features of the disclosure will become more fully apparent from the following description and appended claims, or can be learned by the practice of the principles set forth herein.

[0018] As used herein, the term “coupled” is defined as connected, whether directly or indirectly through intervening components, and is not necessarily limited to physical connections. The

term “substantially” is defined to be essentially conforming to the particular dimension, shape or other word that substantially modifies, such that the component need not be exact. For example, substantially rectangular means that the object in question resembles a rectangle, but can have one or more deviations from a true rectangle. The “position” of an object can refer to a placement of the object, location of the object, plane of the object, direction of the object, distance of the object, azimuth of the object, axis of the object, inclination of the object, horizontal position of the object, vertical position of the object, and so forth. Moreover, the “position” of an object can refer to the absolute or exact position of the object, the measured or estimated position of the object, and/or the relative position of the object to another object.

[0019] The present disclosure provides a control process for drilling a wellbore with a steerable drilling tool that substantially conforms to a planned well path. For example, this present disclosure describes directional drilling tools that employ a controller to correct for trajectory errors or discrepancies between a reference or target position on, or in the vicinity of, a predetermined wellbore path and its current position. The controller resolves such trajectory errors and substantially conforms its path to converge with the desired reference position by controlling and adjusting its position and attitude and employing a cost function to determine an optimal trajectory. The cost function can, for example, associate various penalty conditions which may be associated with a control input. For instance, the penalty conditions may penalize a variety of different control features which may include, but are not limited to, trajectory error, target error, and control effort. The controller can further assign different weights to the various penalty functions when minimizing the cost function to determine an optimal trajectory. Once the cost function is minimized and the optimal trajectory determined, the controller can instruct or implement changes to a steering system of a directional drilling tool. Moreover, the controller can employ a single loop continuous feedback process, in conjunction with the cost function, to continuously and iteratively identify the optimal trajectory.

[0020] FIG. 1 is a schematic diagram of a directional drilling environment, particularly showing a measurement-while-drilling (MWD) system 100, in which the presently disclosed optimal trajectory control techniques may be deployed. As depicted, the MWD system 100 includes a drilling platform 102 having a derrick 104 and a hoist 106 to raise and lower a drill string 108. Hoist 106 suspends a top drive 110 suitable for rotating drill string 108 and lowering drill string 108 through a well head 112. Notably, drill string 108 may include sensors or other instrumentation for detecting and logging nearby characteristics and conditions of the wellbore and surrounding earth formation.

[0021] In operation, top drive 110 supports and rotates drill string 108 as it is lowered through well head 112. In this fashion, drill string 108 (and/or a downhole motor) rotate a drill bit 114 coupled with a lower end of drill string 108 to create a borehole 116 through various formations. A pump 120 can circulate drilling fluid through a supply pipe 122 to top drive 110, down through an interior of drill string 108, through orifices in drill bit 114, back to the surface via an annulus around drill string 108, and into a retention pit 124. The drilling fluid can transport cuttings from wellbore 116 into pit 124 and helps maintain wellbore integrity. Various materials can be used for drilling fluid, including oil-based fluids and water-based fluids.

[0022] As shown, drill bit 114 forms part of a bottom hole assembly 150, which further includes drill collars (e.g., thick-walled steel pipe) that provide weight and rigidity to aid drilling processes. Detection tools 126 and a telemetry sub 128 are coupled to or integrated with one or more drilling collars.

[0023] Detection tools 126 may gather MWD survey data or other data and may include various types of electronic sensors, transmitters, receivers, hardware, software, and/or additional interface circuitry for generating, transmitting, and detecting signals (e.g., sonic waves, etc.), storing information (e.g., log data), communicating with additional equipment (e.g., surface equipment, processors, memory, clocks input/output circuitry, etc.), and the like. In particular, detection tools 126 can measure data such as position, orientation, weight-on-bit, strains, movements, borehole diameter, resistivity, drilling tool orientation, which may be specified in terms of a tool face angle (rotational orientation), and inclination angle (the slope), and compass direction, each of which can be derived from measurements by sensors (e.g., magnetometers, inclinometers, and/or accelerometers, though other sensor types such as gyroscopes, etc.).

[0024] Telemetry sub 128 communicates with detection tools 126 and transmits telemetry data to surface equipment (e.g., via mud pulse telemetry). For example, telemetry sub 128 can include a transmitter to modulate resistance of drilling fluid flow thereby generating pressure pulses that propagate along the fluid stream at the speed of sound to the surface. One or more pressure transducers 132 operatively convert the pressure pulses into electrical signal(s) for a signal digitizer 134. It is appreciated other forms of telemetry such as acoustic, electromagnetic, telemetry via wired drill pipe, and the like may also be used to communicate signals between downhole drilling tools and signal digitizer 134. Further, it is appreciated telemetry sub 128 can store detected and logged data for later retrieval at the surface when bottom hole assembly 150 is recovered.

[0025] Digitizer 134 converts the pressure pulses into a digital signal and sends the digital signal over a communication link to a computing system 137 or some other form of a data processing

device. In at least some embodiments, computer system 137 includes processing units to analyze collected data and/or perform other operations by executing software or instructions obtained from a local or remote non-transitory computer-readable medium. As shown, computer system 137 includes input device(s) (e.g., a keyboard, mouse, touchpad, etc.) as well as output device(s) (e.g., monitors, printers, etc.). These input/output devices provide a user interface that enables an operator to interact and communicate with the borehole assembly 150, surface/downhole directional drilling components, and/or software executed by computer system 137.

[0026] For example, computer system 137 enables an operator to select or program directional drilling options, review or adjust types of data collected, modify values derived from the collected data (e.g., measured bit position, estimated bit position, bit force, bit force disturbance, rock mechanics, etc.), adjust borehole assembly dynamics model parameters, generate drilling status charts, waypoints, a desired borehole path, an estimated borehole path, and/or to perform other tasks. In at least some embodiments, the directional drilling performed by borehole assembly 150 is based on a surface and/or downhole feedback loops, as discussed in greater detail below.

[0027] MWD system 100 also includes a controller 152 that instructs or steers bottom hole assembly 150 as drill bit 114 extends wellbore 116 along a desired path 119 (e.g., within one or more boundaries 140). The bottom hole assembly includes a steering system, such as steering vanes, bent stub, or rotary steerable system (RSS), thereby together with the drill bit 114 form a directional drilling tool. Controller 152 includes processors, sensors, and other hardware/software and which may communicate to components of the steering system. For instance with a RSS, the controller 152 applies a force to flex or bend a drilling shaft coupled to bottom hole assembly 150, or by steering pads on the outside of a non-rotating housing, imparts an angular deviation to a current the direction traversed by drill bit 114. Controller 152 can communicate real-time data with one or more components of bottom hole assembly 150 and/or surface equipment. In this fashion, controller 152 can analyze real-time data and generate steering signals according to, for example, optimal trajectory control techniques discussed herein. While controller 152 is shown and described as a single component that operates for a particular type of directional drilling, it is appreciated controller 152 may include any number of sub-components that collectively communicate and operate to perform the above discussed functions. Controller 152 represents an example component, which may further include various other types of steering mechanisms as well – e.g., steering vanes, a bent sub, and the like. It is further appreciated by those skilled in the art, the environment shown in FIG. 1 is provided for purposes of discussion only, not for purposes of limitation. The detection tools, drilling devices,

and optimal trajectory control techniques discussed herein may be suitable in any number of drilling environments.

[0028] As disclosed herein, the environment shown in FIG. 1 is provided for purposes of discussion only, not for purposes of limitation. The detection tools, drilling devices, and optimal trajectory control techniques discussed herein may be suitable in any number of drilling environments.

[0029] FIG. 2 is a block diagram of an exemplary device 200, which can represent or otherwise include components of controller 152. Device 200 is configured to perform the optimal trajectory control techniques discussed herein and communicates signals that steer or direct the drilling tool along a well path. In operation, device 200 communicates with one or more of the above-discussed borehole assembly 150 components and may also be configured to communicate with remote devices/systems such as computer system 137.

[0030] As shown, device 200 includes hardware and software components such as network interfaces 210, at least one processor 220, sensors 260 and a memory 240 interconnected by a system bus 250. Network interface(s) 210 include mechanical, electrical, and signaling circuitry for communicating data over communications links, which may include wired or wireless communication links. Network interfaces 210 are configured to transmit and/or receive data using a variety of different communication protocols. For example, device 200 can use network interface 210 to communicate with one or more of the above-discussed borehole assembly 150 components and/or communicate with remote devices/systems such as computer system 137.

[0031] Processor 220 represents a digital signal processor (e.g., a microprocessor, a microcontroller, or a fixed-logic processor, etc.) configured to execute instructions or logic to perform tasks in a wellbore environment. Processor 220 may include a general purpose processor, special-purpose processor (where software instructions are incorporated into the processor), a state machine, application specific integrated circuit (ASIC), a programmable gate array (PGA) including a field PGA, an individual component, a distributed group of processors, and the like. Processor 220 typically operates in conjunction with shared or dedicated hardware, including but not limited to, hardware capable of executing software and hardware. For example, processor 220 may include elements or logic adapted to execute software programs and manipulate data structures 245, which may reside in memory 240.

[0032] Sensors 260 typically operate in conjunction with processor 220 to perform wellbore measurements, and can include special-purpose processors, detectors, transmitters, receivers, and the like. In this fashion, sensors 260 may include hardware/software for generating,

transmitting, receiving, detecting, logging, and/or sampling magnetic fields, seismic activity, and/or acoustic waves.

[0033] Memory 240 comprises a plurality of storage locations that are addressable by processor 220 for storing software programs and data structures 245 associated with the embodiments described herein. An operating system 242, portions of which are typically resident in memory 240 and executed by processor 220, functionally organizes the device by, *inter alia*, invoking operations in support of software processes and/or services executing on device 200. These software processes and/or services may comprise an illustrative “optimal trajectory control” process/service 244, as described herein. Note that while process/service 244 is shown in centralized memory 240, some embodiments provide for these processes/services to be operated in a distributed computing network.

[0034] It will be apparent to those skilled in the art that other processor and memory types, including various computer-readable media, may be used to store and execute program instructions pertaining to the optimal trajectory control techniques described herein. Also, while the description illustrates various processes, it is expressly contemplated that various processes may be embodied as modules configured to operate in accordance with the techniques herein (e.g., according to the functionality of a similar process). Further, while some processes or functions may be described separately, those skilled in the art will appreciate the processes and/or functions described herein may be performed as part of a single process. In addition, the disclosed processes and/or corresponding modules may be encoded in one or more tangible computer readable storage media for execution, such as with fixed logic or programmable logic (e.g., software/computer instructions executed by a processor, and any processor may be a programmable processor, programmable digital logic such as field programmable gate arrays or an ASIC that comprises fixed digital logic. In general, any process logic may be embodied in processor 220 or computer readable medium encoded with instructions for execution by processor 220 that, when executed by the processor, are operable to cause the processor to perform the functions described herein.

[0035] FIG. 3 is a schematic diagram of a 3D wellbore environment 300, showing a drilling tool 305 as it creates a wellbore path that substantially follows a predetermined well path 310. Predetermined wellbore path 310 can be described as three-dimensional (3D) path in an earth formation and defined by a collection of waypoints. Generally, each waypoint can correspond to a position in the 3D space, and possibly, higher order information about the path at the specified location. For example, in this context, a 3D waypoint may take the form of: $x_i, y_i, z_i, x'_i, y'_i, z'_i, x''_i, y''_i, z''_i, \dots$ and so on. Where x'_i, y'_i, z'_i represent first derivatives of the

predetermined wellbore path with respect to a path length coordinate associated with the predetermined wellbore path, and x_i'', y_i'', z_i'' represent second derivatives of the predetermined wellbore path with respect to the path length coordinate associated with the predetermined wellbore path. Notably, attitude information, which can include inclination and azimuth, is typically defined as part of the predetermined wellbore path, or it may also be inferred based on known interpolation schemes for smoothly interpolating multiple waypoints. In addition, x_i'', y_i'', z_i'' may be optionally included as part of the definition of a waypoint.

[0036] For example, as shown, predetermined well path 310 is defined by a collection of waypoints, labeled as $[x_1, y_1, z_1]$; $[x_2, y_2, z_2]$; ... $[x_6, y_6, z_6]$. Notably, each waypoint may include higher order information (e.g., derivatives) such as a steering angle or attitude angle ϕ (e.g., labeled as “ ϕ_1 ” through “ ϕ_6 ”). Wellbore environment 300 represents an ideal environment where drilling tool 305 creates a stable wellbore path that accurately tracks predetermined well path 310. In real-world environments, however, the wellbore path may be subject to various instabilities, disturbances, noise, faults, and the like, which may require path correction or adjustment in order to minimize path divergence or deviation.

[0037] Various control techniques may be employed to adjust and conform a current wellbore path of a drilling tool to a planned well path. One example of these control techniques includes an attitude control, which attempts to control a drilling tool's attitude (inclination and azimuth) to minimize wellbore path divergence from the predetermined wellbore path. However, when a predetermined wellbore path is described by a tool attitude (including inclination and azimuth), and only attitude control is applied for and path correction/convergence on tool attitude relative to the predetermined wellbore path, the actual drilled wellbore path can deviate considerably from the planned well path.

[0038] FIGS. 4A and 4B provide graphs 401 and 402, respectively, showing well path divergences caused by attitude azimuth correction (graph 401) and attitude inclination or position correction (graph 402). Here, graph 401 illustrates an intended or target well path 405a (dashed line), defined by “target” waypoints $[x_{1t}, y_{1t}]$, $[x_{2t}, y_{2t}]$, and $[x_{3t}, y_{3t}]$, and an actual wellbore path 405b (solid line) created or traversed by the drilling tool, defined by actual waypoints $[x_1, y_1]$, $[x_2, y_2]$, and $[x_3, y_3]$. In operation, the drilling tool may include a controller (e.g., a hardware/software) that performs path tracking and steers the drilling tool through waypoints for an intended well path as it creates an actual wellbore path.

[0039] As shown, in FIG. 4A, the controller applies attitude azimuth correction or attitude hold that matches a current attitude for a position on actual wellbore path 405b to a target attitude (inclination) for a corresponding position on the intended well path 405a. In other words, the

controller employs an attitude hold that directs the drill tool to actual positions/actual waypoints so that the drilling tool has the same attitude (inclination) as the corresponding target waypoint (e.g., the inclination of drilling tool at waypoint $[x_1, y_1]$ is the same as the target inclination at waypoint $[x_{1t}, y_{1t}]$). Although such attitude hold control ensures attitude convergence between the actual wellbore path and the intended well path, deviations may be present or even increase depending on distances traversed and a complexity of the predetermined wellbore path.

[0040] In FIG. 4B, graph 402 illustrates deviations between an intended well path 410a (dashed line) and an actual wellbore path 410b (solid line) when the controller applies position hold controls. Here, both well path 410a and wellbore path 410b are defined by the same waypoints $[x_1, y_1]$, $[x_2, y_2]$, and $[x_3, y_3]$. In operation, the controller steers the drilling tool along the same waypoints of both paths and matches the target position for each target waypoint. As shown, actual well path 410b represents a position hold control, which directs the drill tool to traverse the target waypoints. While such position hold controls ensure wellbore path 410b substantially traverses each target waypoint, such position hold controls may create oscillating behavior and divergences between intended well path 410a and wellbore path 410b. This oscillation may be caused, in part, by differences between an actual steering angles (labeled as “ ϕ_1 ” through “ ϕ_3 ”) of the drill tool and target steering angles (labeled as “ ϕ_{1t} ” through “ ϕ_{6t} ”) at each waypoint.

[0041] The optimal trajectory control techniques described herein support simultaneous adjustment of a drilling tool's position and attitude and drives both position and attitude toward optimal trajectory convergence using a single closed control loop. For example, the optimal trajectory control techniques may describe drilling tool trajectories using a cost function, where certain control features (e.g., trajectory errors, target errors, control efforts, instantaneous state errors, and the like) are penalized when calculating an optimal trajectory (e.g., optimally reducing the cost function). In this fashion, the optimal trajectory control techniques disclosed herein can efficiently and optimally control or steer drilling systems such as a rotary steerable system, in a wellbore environment.

[0042] In addition, as discussed in greater detail below, the optimal trajectory control techniques further describe a well path or a wellbore path for the drilling tool in terms of a curved path. More specifically, a 3D well path can be projected into two perpendicular planes, and represented by a unique curve in each plane. Therefore, without loss of generality, the optimal trajectory control techniques herein may control the evolution of wellbore in a 2D plane and establish a desired convergence in the 2D plane. Convergence in the 3D space logically follows. For example, the following kinematic equation can represent an arbitrary evolution of wellbore

in a 2D plane with Cartesian coordinates (x and y), where s is a path length coordinate (e.g., a curvilinear coordinate defined along the wellbore path), ϕ is a steering angle, and κ is the curvature. When x and y define a vertical plane, ϕ may be interpreted as inclination when $\phi \in [0, \pi]$. Notably, in the following Equations 1-3, $\phi \in (-\infty, \infty)$, and the equations can generate arbitrary path with continuous first derivatives in the x - y plane.

$$x'(s) = \cos(\phi(s)) \quad (1)$$

$$y'(s) = \sin(\phi(s)) \quad (2)$$

$$\phi'(s) = \kappa(s) \quad (3)$$

[0043] In this fashion, equations 1-3 can uniquely identify a curvature $\kappa(s)$ for a curved wellbore path or a curved convergence path as a function of a current position and attitude. Preferably, a drilling tool controller (e.g., controller 152, device 200, etc.) continuously computes and adjusts curvature values $\kappa(s)$ in a state feedback control law, and operatively steers the drilling tool based on the curvature values as it generates a curved wellbore path (e.g., by adjusting an appropriate amount of RSS force and bending, etc.).

[0044] For example, the state feedback control law may take the form of Equations 4 and 5:

$$\kappa(s) = SFB(x(s), y(s), x'(s), y'(s), x_d, y_d, x'_d, y'_d) \quad (4)$$

$$\kappa(s) = SFB(x(s), y(s), x'(s), y'(s), x_d, y_d, x'_d, y'_d, x''_d, y''_d, \dots) \quad (5)$$

Where the curvature value $\kappa(s)$ represents a curvature of a curved path between a current location and a target waypoint that satisfies both position and slope constraints.

[0045] FIG. 5 illustrates a graph 500 that shows path convergence for a drilling tool, from a current position $[x_0, y_0]$ to a target or desired position $[x_d, y_d]$. In particular, graph 500 provides a deflection beam 505 that represents a curved convergence path for directing drill tool 510 from its current position $[x_0, y_0]$ to a desired position $[x_d, y_d]$ while also providing simultaneous attitude (e.g., derivatives of position) convergence such that drill tool 510 traverses desired position $[x_d, y_d]$ at a desired orientation or attitude ϕ_d . A current orientation of drill tool 510 at current position $[x_0, y_0]$ is represented ϕ , and derivatives of x and y positions are specified according to Equation 6:

$$x'(0) = \cos \phi, y'(0) = \sin \phi \quad (6)$$

Where a desired location and attitude (waypoint) are represented by x_d, y_d, x'_d, y'_d

[0046] Curved convergence path 505 intersects current position $[x_0, y_0]$ (tangent to current attitude ϕ) and the desired position $[x_d, y_d]$ at (at the desired orientation ϕ_d). For purposes of illustration and discussion herein, assume the tangent direction of the path at $[x_d, y_d]$ is parallel to the x axis (i.e., $\phi_d = 0$). However, for non-parallel tangents, another set of $\tilde{x} - \tilde{y}$ coordinates may be determined by rotating the original x - y system to ensure a parallel relation. The

coordinate transform may be performed from x - y to $\tilde{x}$ - $\tilde{y}$ to establish equivalent boundary conditions at current and target positions in the $\tilde{x}$ - $\tilde{y}$ domain.

[0047] In certain instances, when x is very close proximity or distance to x_d and y and y' has not converged to a desired value, a large or steep curvature value is needed for path convergence with respect to both position and attitude. Preferably, however, when x is sufficiently close to x_d (e.g., x is within a threshold distance from x_d) the current target waypoint may be assigned to a “next” target waypoint on the planned path. For example, the next or subsequent waypoint on the planned path may be selected when x (a current position) is within a threshold distance of x_d and/or a curvature value for the drilling tool to pass proximate (or through) x_d is above/below a threshold tolerance, and the like. Alternatively (or in addition), the “next” target waypoint may continuously move along the planned path as the drill tool moves forward to avoid any steep curvatures and minimize potential oscillations.

[0048] With respect to three dimension (3D) coordinates, the waypoint can be selected based on Equations 7 and 8:

$$s_c = \min_s \left[\left(x_c - x_p(s) \right)^2 + \left(y_c - y_p(s) \right)^2 + \left(z_c - z_p(s) \right)^2 \right]^{\frac{1}{2}} \quad (7)$$

$$[x_p(s_c + \tau), y_p(s_c + \tau), z_p(s_c + \tau)] \quad (8)$$

Where $X_c = (x_c, y_c, z_c)$ is the current position, and $[x_p(s), y_p(s), z_p(s)]$ defines the planned path, s is depth, and s_c denotes the depth at which the position of the well plan is closest to the current position.

[0049] Notably, equation 8 identifies a target position $[x_p, y_p, z_p]$, and derivatives of the target position correspond to a target attitude. If a curvature value for a curved path from the current position to the target position is larger than a threshold, τ is increased. Equations 7 and 8 may be iteratively calculated as the drilling tool moves forward.

[0050] Collectively, the above discussed curved convergence paths may be incorporated into a state feedback control law where curvature calculations describe and solve for curvature values of a curved convergence path that satisfies position constraints and slope constraints between a current position and a target waypoint (e.g., a desired position).

[0051] For example, in operation, drilling tool 510 can include a controller (e.g., controller 152, devices 200, etc.) which executes a state feedback control law that continuously determines curvature values for the curved convergence path and provide control inputs (e.g., curvature-based inputs) based on the curvature values to a force controller or bending controller, which, in turn, steers drilling tool 510.

[0052] With respect to the state feedback control law, FIG. 6 provides a block diagram one embodiment of an optimal state feedback system 600, which employs optimal trajectory control process 244. As shown, system 600 illustrates various drilling tool components as well as communication signals exchanged therebetween.

[0053] In particular, system 600 includes an optimal mode controller 620 and a rotary steerable system 640, which collectively operate to monitor and adjust a current trajectory of a drilling tool and minimize trajectory errors (with respect to a reference trajectory). Notably, although optimal mode controller 620 and rotary steerable system 640 are shown as individual and independent components, such components may form part of a larger control system. Generally, optimal mode controller 620 receives a reference trajectory 610 as well as an actual trajectory 650 of the drilling tool (e.g., from a feedback loop 625). Reference trajectory 610 can be communicated to optimal mode controller 620 from any number of the components, hardware, and/or software illustrated, for example, by the directional drilling environment shown in FIG. 1. Moreover, as discussed, reference trajectory 610 represents an intended or target trajectory based on a predetermined drilling path for the drilling tool, which can be defined by one or more waypoints or positions. These waypoints can be stationary and/or they may be continuously and dynamically updated to track the predetermined wellbore path as the drilling tool extends the wellbore. Actual trajectory 650 is continuously measured by the drilling tool and may be represented by one or more of an inclination, azimuth, and/or a drilled depth.

[0054] Optimal mode controller 620 iteratively and continuously analyzes and compares actual trajectory 650 and reference trajectory 610, determines deviations there-between, determines appropriate control adjustments, and generates a control input signal 630. The iterative and continuous operations by optimal mode controller 620 results in a continuously changing control input signal 630 corresponding to a continuously converging (or substantially converging) curved path between actual trajectory 650 and reference trajectory 610. Optimal mode controller 620 further transmits control input signal 630 to rotary steerable system 640 for course correction, which cause rotary steerable system 640 to adjust the current or current trajectory 650 of the drilling tool, as discussed above.

[0055] As discussed above, optimal mode controller 620 employs a state feedback control law to iteratively and continuously adjust the trajectory of the drilling tool based on deviations between reference trajectory 610 and actual trajectory 650. This state feedback control law may further incorporate a cost function, where certain control features (e.g., trajectory errors, target errors, control efforts, instantaneous state errors, and the like) are penalized when calculating an optimal trajectory (e.g., optimally reducing the cost function).

[0056] In this context, a trajectory of the directional drilling tool can be expressed by a set of differential equations as set out below, starting with Equation 12.

$$x'(t) = A(t)x(t) + B(t)u(t) \quad (12)$$

where $x(t) \in \mathbb{R}^n$ is the state vector used to define the tool trajectory, $A(t) \in \mathbb{R}^{n \times n}$ is the state matrix, $B(t) \in \mathbb{R}^{n \times m}$ is the input matrix, and $u(t) \in \mathbb{R}^m$ is the input vector.

[0057] A reference trajectory $r(t)$ represents a projected trajectory (e.g., reference trajectory 610) for the directional drilling tool with respect to a specific position on a predetermined wellbore path. The reference trajectory can be in the form of one waypoint, or several distinct waypoints. Further, in some embodiments of this disclosure, the optimal control algorithm can be developed such that the trajectory of the tool passes through the each of the waypoints or, in the alternative, passes within close vicinity of each waypoint. For example, the control algorithm can determine an updated path that is determined to be more desirable than a current trajectory of the directional drilling tool.

[0058] The cost function can be described as follows:

$$J = \phi(x(t_1), t_1) + \int_{t_0}^{t_1} L(x(t), u(t), t) dt \quad (13)$$

where J is a total cost, $\phi(x(t_1), t_1)$ is a terminal cost or penalty on a final state error (e.g., a penalty corresponding to missing a target waypoint), $L(x(t), u(t), t)$ is a running cost, denoted the Lagrangian function, $x(t)$ is a state vector or trajectory of the drilling tool, $u(t)$ is a control input, t_0 is an initial time and t_1 is a final time or terminal time up to which cost is measured (e.g., point of nearest approach to the target waypoint).

[0059] Equation 13 represents a cost function, whose performance index is minimized by solving for $u(t)$. Notably, the cost function set forth by Equation 13 is further subject to the following state equation:

$$x'(t) = A(t)x(t) + B(t)u(t) \quad (14)$$

[0060] Notably, additional state constraints may also be incorporated in an optimal trajectory control system, which may be represented by Equation 15, below.

$$\psi(x(t_1), t_1) = 0 \quad (15)$$

[0061] Moreover, additional boundary conditions may also be included, such as boundary conditions represented by equations 16 and 17, below.

$$\lambda^T|_{t_0} dx(t_0) - H|_{t_0} dt_0 = 0 \quad (16)$$

$$\left(\frac{\partial \phi}{\partial x} + \frac{\partial \psi^T}{\partial x} v - \lambda \right) \Big|_{t_1} dx(t_1) + \left(\frac{\partial \phi}{\partial t} + \frac{\partial \psi^T}{\partial t} v + H \right) \Big|_{t_1} dt_1 = 0 \quad (17)$$

where λ and ν are Lagrange multipliers, and $H = H(x(t), u(t), t)$ is a Hamiltonian function that describes a dynamic system in terms of momentum and space-time coordinates equal to a total energy of a system, as defined by Equation 18, below.

$$H(x(t), u(t), t) = L(x(t), u(t), t) + \lambda^T x'(t) \quad (18)$$

[0062] For the above equations, $u(t)$ represents a control input defined by a vector at any given time (t) satisfying cost function, which provides an optimal solution (e.g., control input 630), based on the constraints and performance criteria as set above.

[0063] In addition, the Lagrangian function $L = L(x(t), u(t), t)$ contains penalty factors or values which can be configured to assign a different weight when minimizing the control input $u(t)$ and minimizing the errors in trajectory state vector $x(t)$. For example, if the trajectory state vector $x(t)$ is set to include the position, attitude, and curvature of the trajectory, then simultaneous minimization of the error of each of the variables (as described above) can be achieved by adjusting the penalty factors as defined in the Lagrangian function.

[0064] Once a solution for the cost function is determined, the optimal trajectory for the rotary steerable system can be computed and control information provided by the controller to steer the drilling tool. As this is conducted on a continual basis with the actual position provided via feedback loop, the controller adjusts the steerable system of a drilling tool to an updated (and optimal) path. This feedback control input $u_{RSS}(t)$ provided to the steerable system (such as an RSS) can be expressed as a function of the actual trajectory (namely the trajectory state vector) $x(t)$, the reference trajectory $r(t)$, and the control input $u(t)$, as shown in Equation 19.

$$u_{RSS}(t) = f(x(t), r(t), u(t), t) \quad (19)$$

[0065] Accordingly, with solution of the cost function and implementation of penalty factors, an optimal trajectory is determined with reduced errors for control input to a directional drilling tool. The feedback control input can then be implemented on the rotary steerable system in the form of the adjustment to the steering system, such as by either a force on one or more pads or the adjustment of the eccentricity of a shaft, as described above.

Finite-Horizon Linear Quadratic Tracker

[0066] In addition to the above, a particular implementation of penalty factors may be employed for optimal control with the development of finite-horizon linear quadratic tracker (LQT) logic in accordance with Equations 20 and 21, shown below.

$$L = \frac{1}{2} (x(t) - r(t))^T Q (x(t) - r(t)) + \frac{1}{2} u^T(t) R u(t) \quad (20)$$

$$\phi = \frac{1}{2} (x(t_1) - r(t_1))^T P (x(t_1) - r(t_1)) \quad (21)$$

wherein the $Q(t) \in \mathbb{R}^{n \times n}$, $R(t) \in \mathbb{R}^{m \times m}$, and $P \in \mathbb{R}^{n \times n}$ matrices satisfy $P = P^T \geq 0$, $Q(t) = Q^T(t) \geq 0$, and $R = R^T(t) > 0$. As such, $Q(t)$ penalizes divergences from the reference trajectory, $R(t)$ penalizes the control input, and P penalizes the final state error. The time span can be defined as $t_{span} = [t_0, t_1]$, where t_0 represents the initial time and t_1 represents the final time (as described above). Thus, the finite-horizon LQT problem can result in a vector input as shown in Equation 22,

$$u(t) = -K(t)x(t) + R^{-1}(t)B^T(t)v(t) \quad (22)$$

wherein the Kalman gain is defined as $K(t) = R^{-1}(t)B^T(t)S(t)$. Then, $S(t) \in \mathbb{R}^{n \times n}$ can be obtained by solving the Riccati equation, shown below as Equation 23, where the boundary condition is set as $S(t_1) = P$.

$$S'(t) = -S(t)A(t) + A^T(t)S(t) + S(t)B(t)R^{-1}(t)B^T(t)S(t) - Q(t) \quad (23)$$

In addition, $v(t) \in \mathbb{R}^n$ can be obtained by solving Equation 24, below, where the boundary condition is set as $v(t_1) = P$.

$$v'(t) = -(A(t) - B(t)K(t))^T v(t) - Q(t)r(t) \quad (24)$$

[0067] FIG. 7 illustrates an exemplary wellbore 700 under LQT control. Specifically, wellbore 710 illustrates a scenario wherein the P matrix is relatively higher than the Q and R matrices. Thus, penalization is focused on the final state effort. In order to minimize the final error, a sharp turn is required at the end, resulting in an unrealistically high curvature. In an alternative scenario, graph 720 corresponds to a scenario wherein the Q matrix is relatively higher than the R and P matrices. The resulting penalization for this scenario is mainly on the trajectory error. The scenario results in a path that is substantially a direct line between the two waypoints thereby providing a minimum overall trajectory error. However, way point succession of two lines having different slopes can cause the path to take a sharp corner, resulting in inefficiency. Finally, in another alternative scenario 730 the R matrix is relatively higher than the Q and P matrices; resulting on heavy penalization of the control effort. This scenario can allow for a minimized control input throughout the entire trajectory.

[0068] FIG. 8 illustrates a control feedback procedure 800 for adjusting the trajectory of a directional drilling tool using a controller (e.g., controller 620). Procedure 800 begins at step 810 and continues to step 820 where, as discussed above, a controller defines a cost function which includes at least one penalty associated with a control input. The penalty condition may reduce one or more of a trajectory error, a target error, and a control effort. The penalty condition and the value, or amount of the penalty, is selected to reduce or minimize the cost function. By reduction of the cost function convergence on a position and attitude is enhanced as a drilling tool tracks a trajectory downhole. As illustrated in step 830, the drilling tool detects an actual

(e.g., current) position and a reference position. The reference position may be indicative of a desired position and may include a way point nearby a predetermined wellbore path. The current position may be fed to the controller as part of a feedback loop. Based on the cost function, as well as the current and reference position, as shown in step 840, the controller determines an optimal trajectory for a curved path, thereby converging the actual and reference trajectory. The optimal trajectory enhances control because the cost function enables minimizing inefficiencies and improved convergence. In step 850, based on the determined optimal trajectory, a control input is implemented on the steering system to steer the tool. As this is an iterative process based on a feedback loop, the process can be repeated by returning to step 820. With each step of the process the difference between the current position and reference position may be reduced. Alternatively, the system may repeat by returning to step 830, if no redefinition of the cost function is required.

[0069] Certain steps within procedure 800 may be optional, and further, the steps shown in FIG. 8 are merely examples for illustration – certain other steps may be included or excluded as desired. Further, while a particular order of the steps is shown, this ordering is merely illustrative, and any suitable arrangement of the steps may be utilized without departing from the scope of the embodiments herein.

[0070] The following example is provided to illustrate the subject matter of the present disclosure. The example is not intended to limit the scope of the present disclosure and should not be so interpreted.

EXAMPLE

[0071] A finite-horizon LQT controller is developed for trajectory tracking in a two-dimensional (2-D) (x, y) plane. The state vectors are set as $x(t) = [x(t), \dot{x}(t)]^T$ and $y(t) = [y(t), \dot{y}(t)]^T$. The state and input matrices are then set as $A = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$; such that the above state equations can be expressed as Equations 25 and 26.

$$\dot{x}(t) = Ax(t) + Bu_x(t) \quad (25)$$

$$\dot{y}(t) = Ay(t) + Bu_y(t) \quad (26)$$

[0072] The reference trajectory was provided in the form of a series of discrete waypoints along the predetermined wellbore path for drilling. The reference trajectory is then expressed by Equations 27 and 28, below.

$$r_x(t) = [r_{x_1}(t) \quad r_{x_2}(t)]^T \quad (27)$$

$$r_y(t) = [r_{y_1}(t) \quad r_{y_2}(t)]^T \quad (28)$$

[0073] The waypoint $(r_{x_1}(t), r_{y_1}(t))$ can be considered a reference position, whereas the waypoint $(r_{x_2}(t), r_{y_2}(t))$ is an indicator of the reference attitude in the (x, y) plane. As shown in FIG. 9, for a predetermined wellbore path 900 having four waypoints 910 set based on previously selected penalization factors (such as optimization criteria), convergence in both position and attitude can be obtained by adjusting the control input to create an updated path, as shown by trajectory 920.

[0074] As shown in FIG. 5, the desired curvature of the path, $\kappa(t)$, can be fed back to the rotary steerable system in the form of a force or bending control in order to adjust and drive the tool along the updated path. The control input to the directional drilling tool can then be expressed as shown in Equation 29.

$$u_{RSS}(t) = \kappa(t) = \frac{x'(t)y''(t) - y'(t)x''(t)}{[(x'(t))^2 + (y'(t))^2]^{3/2}} \quad (29)$$

[0075] It should be noted that $x''(t) = u_x(t)$ and $y''(t) = u_y(t)$ are as defined by the state equation. Therefore, $u_{RSS}(t) = \kappa(t)$ can be expressed as Equation 30.

$$u_{RSS}(t) = \frac{x'(t)u_y(t) - y'(t)u_x(t)}{[(x'(t))^2 + (y'(t))^2]^{3/2}} \quad (30)$$

After the constraints are put into the control algorithm, the strength of the algorithm can be tested. In this example, the control algorithm is a finite-horizon LQT algorithm, as described above. Using the predetermined wellbore path 1000 as shown in FIG. 10, 30 simulations were conducted wherein a disturbance was added to the desired fed back curvature as $\kappa(t) + \Delta\kappa(t)$. The $\Delta\kappa(t)$ was allowed to randomly vary between $[-\kappa(t), +\kappa(t)]$, corresponding to a 100% disturbance in the control command. As such, the $\Delta\kappa(t)$ can result from multiple sources such as inaccuracy of the curvature generation control of the tool, inaccuracy in the state measurements, and inaccuracy of generated estimations. The results of the simulations are shown in FIG. 10, showing wellbore path 1000 having two waypoints 1010 and generated path vectors 1020. The results illustrate simultaneous convergence to a desired position and attitude can be achieved via the control techniques, despite strong disturbances and uncertainties throughout the drilling process.

[0076] STATEMENTS OF THE DISCLOSURE INCLUDE:

[0077] Statement 1: A method for directional drilling, including: defining a cost function that includes at least one penalty condition associated with a control input; detecting, via a controller of a drilling tool, a current position of the drilling tool and a reference position of a predetermined wellbore path; determining, via the controller, an optimal trajectory for a curved path based on the cost function, the optimal trajectory originates from the current position and

substantially intersects the reference position; and instructing, via the controller, the drilling tool to generate a wellbore path based on the optimal trajectory.

[0078] Statement 2: The method according to Statement 1: wherein the at least one penalty condition reduces at least one of a trajectory error, a target error, and a control effort.

[0079] Statement 3: The method according to any one of Statements 1-2: wherein determining the optimal trajectory further includes: selecting a value for the at least one penalty condition; and minimizing the cost function based on the at least one penalty condition.

[0080] Statement 4: The method according to any one of Statements 1-3: updating the optimal trajectory based on a change in at least one of a position or an attitude of the drilling tool.

[0081] Statement 5: The method according to any one of Statements Statement 1-4, wherein the reference position includes a waypoint substantially proximate a predetermined wellbore path.

[0082] Statement 6: The method according to any one of Statements Statement 1-5, further including: tracking, via the controller, the current position of the directional drilling tool based on an inclination, an azimuth, and a depth.

[0083] Statement 7: The method according to any one of Statements Statement 1-6, wherein instructing the directional drilling tool to generate an updated path further includes: providing the input vector to one of a force controller or a bending controller of the directional drilling tool and radially moving one or more pads or changing an eccentricity of a drill shaft.

[0084] Statement 8: The method according to any one of Statements Statement 1-7, wherein the cost function comprises a finite-horizon linear quadratic tracker logic.

[0085] Statement 9: A system including: a directional drilling tool disposed in a wellbore; at least one processor in communication in communication with the directional drilling tool; a non-transitory computer-readable storage medium configured to store instructions, the instructions, when executed by the at least one processor, cause the at least one processor to: define a cost function that includes at least one penalty condition associated with a control input; detect, via a controller of a drilling tool, a current position of the drilling tool and a reference position of a predetermined wellbore path; determine, via the controller, an optimal trajectory based on the cost function for a curved path that originates from the current position and substantially intersects the reference; and instruct, via the controller, the drilling tool to generate a wellbore path based on the optimal trajectory.

[0086] Statement 10: The system according to Statement 9, wherein the at least one penalty condition reduces at least one of a trajectory error, a target error, and a control effort.

[0087] Statement 11: The system according to any one of Statements 9-10, wherein the instructions, when executed by the at least one processor to determine the optimal trajectory,

further cause the processor to: select a value for at least one penalty condition; and minimize the cost function based on the at least one penalty condition.

[0088] Statement 12: The system according to any one of Statements 9-11, wherein the value of the at least one penalty condition is selected to minimize the cost function.

[0089] Statement 13: The system according to any one of Statements 9-12, wherein the non-transitory computer-readable storage medium stores further instructions, which when executed by the at least one processor, cause the at least one processor to: update the optimal trajectory based on a change in at least one of a position or an attitude of the drilling tool.

[0090] Statement 14: The system according to any one of Statements 9-13, wherein the reference position includes a waypoint substantially proximate a predetermined wellbore path.

[0091] Statement 15: The system according to any one of Statements 9-14, wherein the instructions to instruct the drilling tool to generate the wellbore path further cause the drilling tool to move one or more pads or change an eccentricity of a drill shaft based on the optimal trajectory.

[0092] Statement 16: The system according to any one of Statements 9-15, wherein the reference position includes a waypoint substantially proximate a predetermined wellbore path.

[0093] Statement 17: A tangible non-transitory computer-readable storage medium having instructions stored thereon which, when executed by one or more processors, cause the one or more processors to: define a cost function that includes at least one penalty condition associated with a control input; detect, via a controller of a drilling tool, a current position of the drilling tool and a reference position of a predetermined wellbore path; determine, via the controller, an optimal trajectory based on the cost function for a curved path that originates from the current position and substantially intersects the reference; and instruct, via the controller, the drilling tool to generate a wellbore path based on the optimal trajectory.

[0094] Statement 18: The tangible non-transitory computer-readable storage medium according to Statement 17, wherein the at least one penalty condition reduces at least one of a trajectory error, a target error, and a control effort.

[0095] Statement 19: The tangible non-transitory computer-readable storage medium according to any one of Statements 17-18, wherein the instructions, when executed by the one or more processors to determine the optimal trajectory, further causes the one or more processors to: select value for the at least one penalty condition; and minimize the cost function based on the at least one penalty condition.

[0096] Statement 20: The tangible non-transitory computer-readable storage medium according to any one of Statements 17-19, wherein the reference position includes a waypoint substantially

proximate a predetermined wellbore path, and wherein the instructions to instruct the drilling tool to generate the wellbore path further cause the drilling tool to move one or more pads or change an eccentricity of a drill shaft based on the optimal trajectory.

CLAIMS

WHAT IS CLAIMED IS:

1. A method for directional drilling, comprising:
 - defining a cost function that includes at least one penalty condition associated with a control input;
 - detecting, via a controller of a drilling tool, a current position of the drilling tool and a reference position of a predetermined wellbore path;
 - determining, via the controller, an optimal trajectory for a curved path based on the cost function, the optimal trajectory originates from the current position and substantially intersects the reference position; and
 - instructing, via the controller, the drilling tool to generate a wellbore path based on the optimal trajectory.
2. The method of claim 1, wherein the at least one penalty condition reduces at least one of a trajectory error, a target error, and a control effort.
3. The method of claim 1, wherein determining the optimal trajectory further comprises:
 - selecting a value for the at least one penalty condition; and
 - minimizing the cost function based on the at least one penalty condition.
4. The method of claim 1, further comprising:
 - updating the optimal trajectory based on a change in at least one of a position or an attitude of the drilling tool.
5. The method of claim 1, wherein the reference position includes a waypoint substantially proximate a predetermined wellbore path.
6. The method of claim 1, further comprising:
 - tracking, via the controller, the current position of the directional drilling tool based on an inclination, an azimuth, and a depth.
7. The method of claim 1, wherein instructing the directional drilling tool to generate an updated path further comprises:

providing the input vector to one of a force controller or a bending controller of the directional drilling tool; and

radially moving one or more pads or changing an eccentricity of a drill shaft based on the input vector.

8. The method of claim 1, wherein the cost function comprises a finite-horizon linear quadratic tracker logic.

9. A system comprising:

a directional drilling tool disposed in a wellbore;

at least one processor in communication with the directional drilling tool;

a non-transitory computer-readable storage medium configured to store instructions, the instructions, when executed by the at least one processor, cause the at least one processor to:

define a cost function that includes at least one penalty condition associated with a control input;

detect, via a controller of a drilling tool, a current position of the drilling tool and a reference position of a predetermined wellbore path;

determine, via the controller, an optimal trajectory based on the cost function for a curved path that originates from the current position and substantially intersects the reference; and

instruct, via the controller, the drilling tool to generate a wellbore path based on the optimal trajectory.

10. The system of claim 9, wherein the at least one penalty condition reduces at least one of a trajectory error, a target error, and a control effort.

11. The system of claim 9, wherein the instructions, when executed by the at least one processor to determine the optimal trajectory, further cause the processor to:

select a value for at least one penalty condition; and

minimize the cost function based on the at least one penalty condition.

12. The system of claim 9, wherein the value of the at least one penalty condition is selected to minimize the cost function.

13. The system of claim 9, wherein the non-transitory computer-readable storage medium stores further instructions, which when executed by the at least one processor, cause the at least one processor to:

update the optimal trajectory based on a change in at least one of a position or an attitude of the drilling tool.

14. The system of claim 9, wherein the reference position includes a waypoint substantially proximate a predetermined wellbore path.

15. The system of claim 9, wherein the instructions to instruct the drilling tool to generate the wellbore path further cause the drilling tool to move one or more pads or change an eccentricity of a drill shaft based on the optimal trajectory:.

16. The system of claim 9, wherein the cost function comprises a finite-horizon linear quadratic tracker logic.

17. A tangible non-transitory computer-readable storage medium having instructions stored thereon which, when executed by one or more processors, cause the one or more processors to:

define a cost function that includes at least one penalty condition associated with a control input;

detect, via a controller of a drilling tool, a current position of the drilling tool and a reference position of a predetermined wellbore path;

determine, via the controller, an optimal trajectory based on the cost function for a curved path that originates from the current position and substantially intersects the reference; and

instruct, via the controller, the drilling tool to generate a wellbore path based on the optimal trajectory.

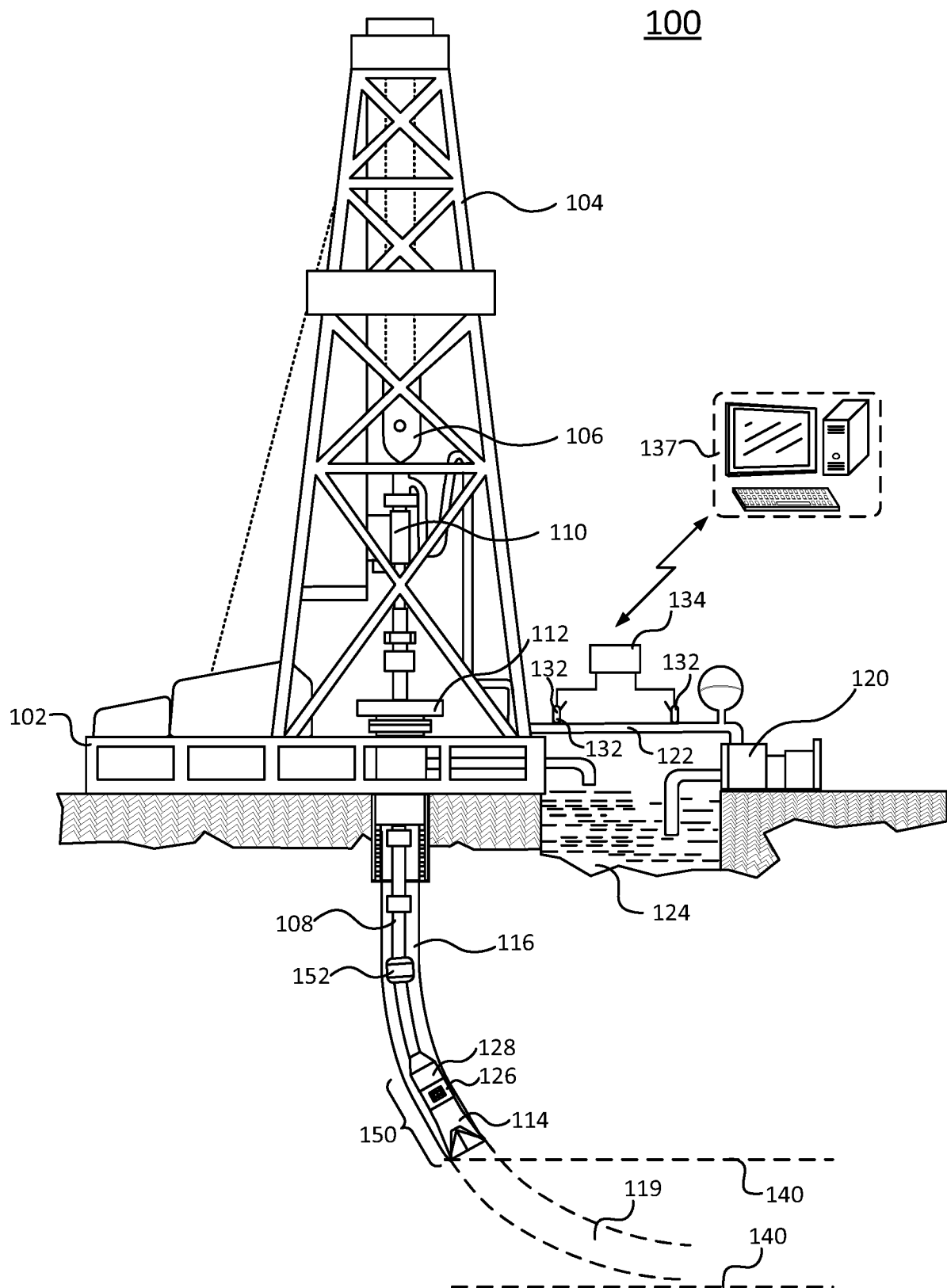
18. The tangible non-transitory computer-readable storage medium of claim 17, wherein the at least one penalty condition reduces at least one of a trajectory error, a target error, and a control effort.

19. The tangible non-transitory computer-readable storage medium of claim 17, wherein the instructions, when executed by the one or more processors to determine the optimal trajectory, further causes the one or more processors to:

- select value for the at least one penalty condition; and
- minimize the cost function based on the at least one penalty condition.

20. The tangible non-transitory computer-readable storage medium of claim 17, wherein the reference position includes a waypoint substantially proximate a predetermined wellbore path, and wherein the instructions, when executed by the processor to instruct the drilling tool to generate the wellbore path further cause the drilling tool to radially move one or more pads or change an eccentricity of a drill shaft based on the optimal trajectory.

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**FIG. 1**

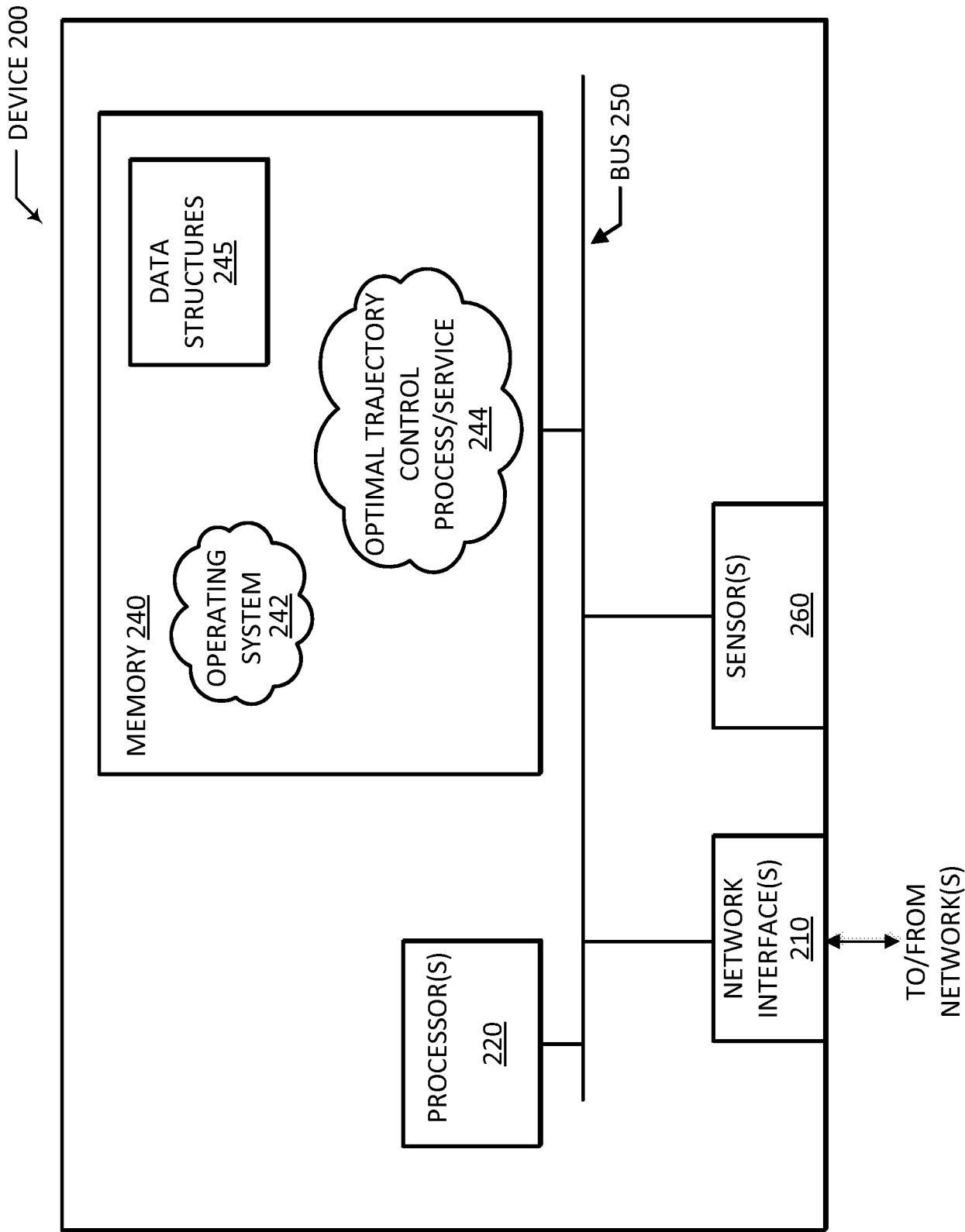


FIG. 2

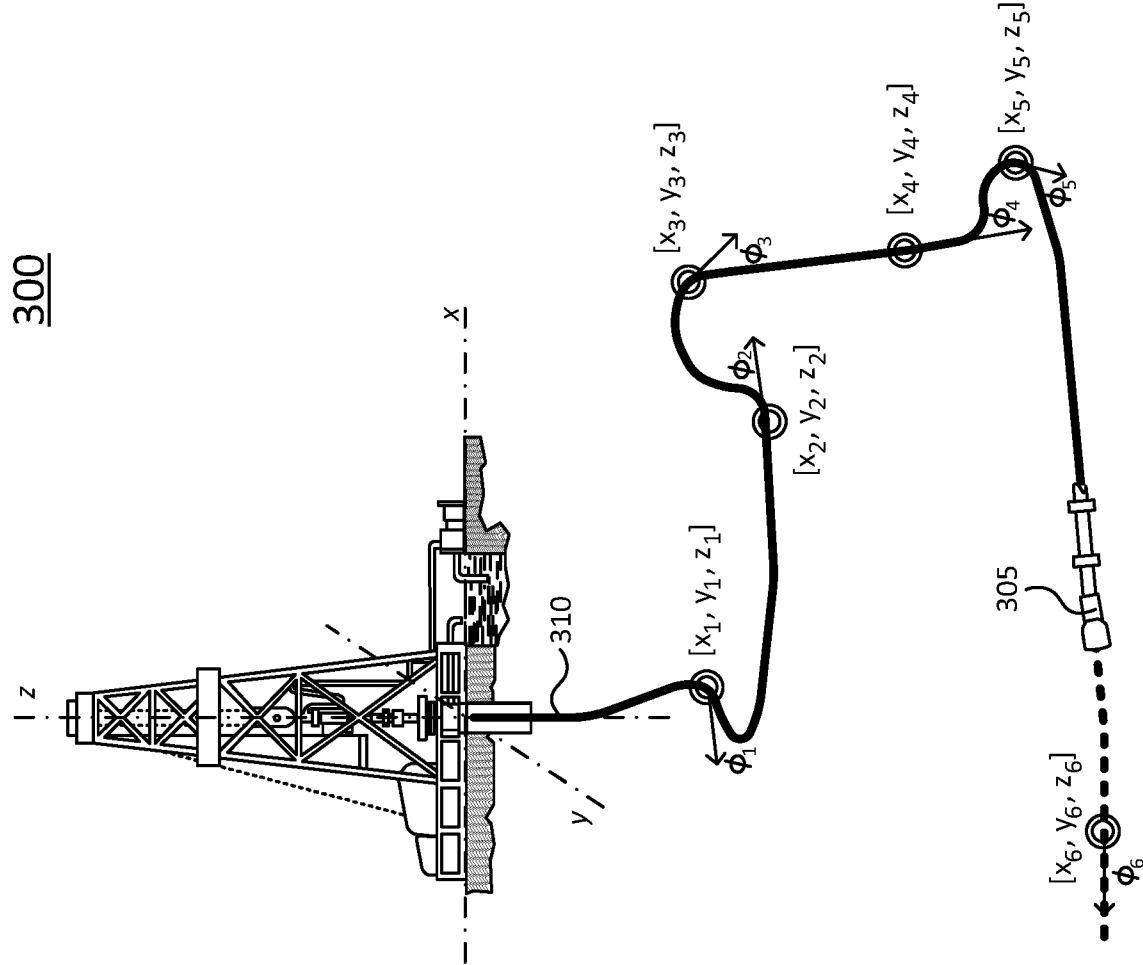


FIG. 3

401

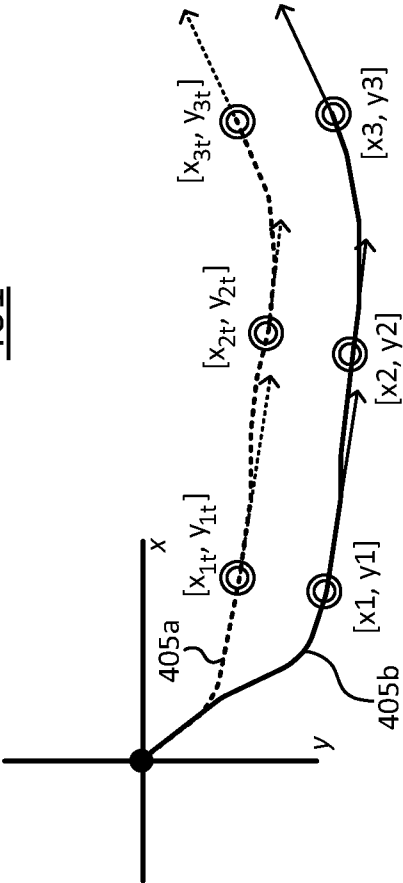


FIG. 4A

402

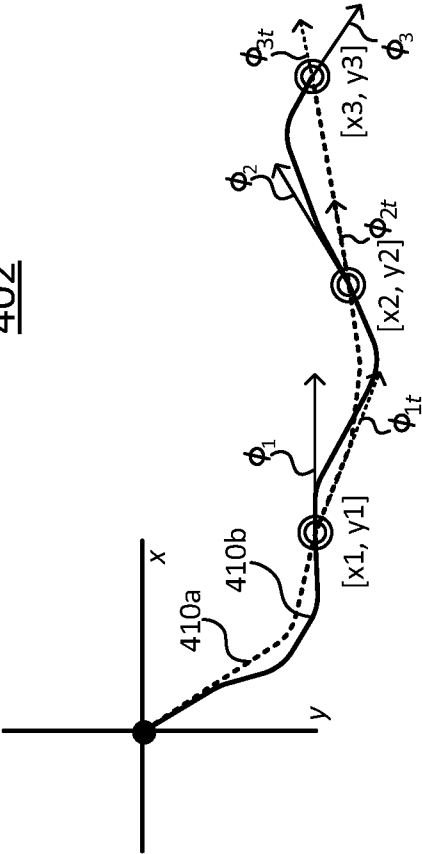
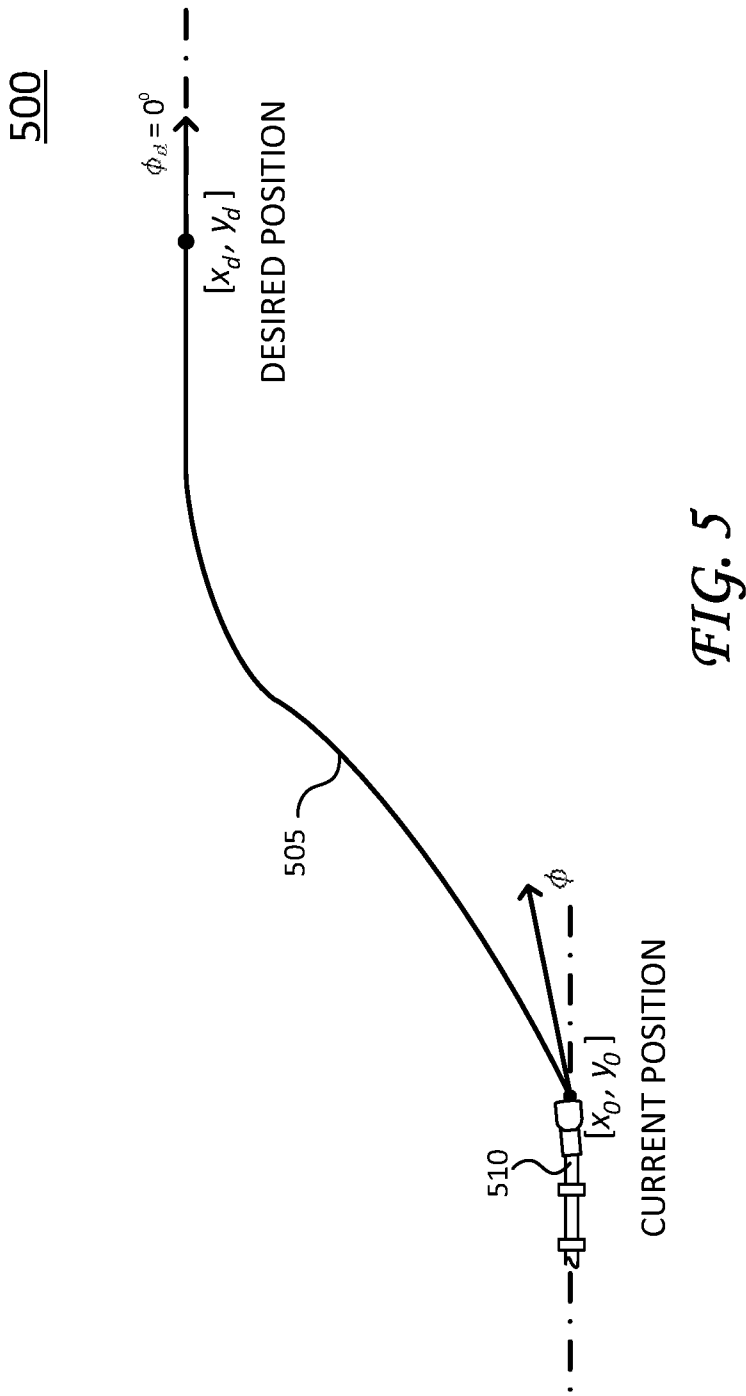


FIG. 4B



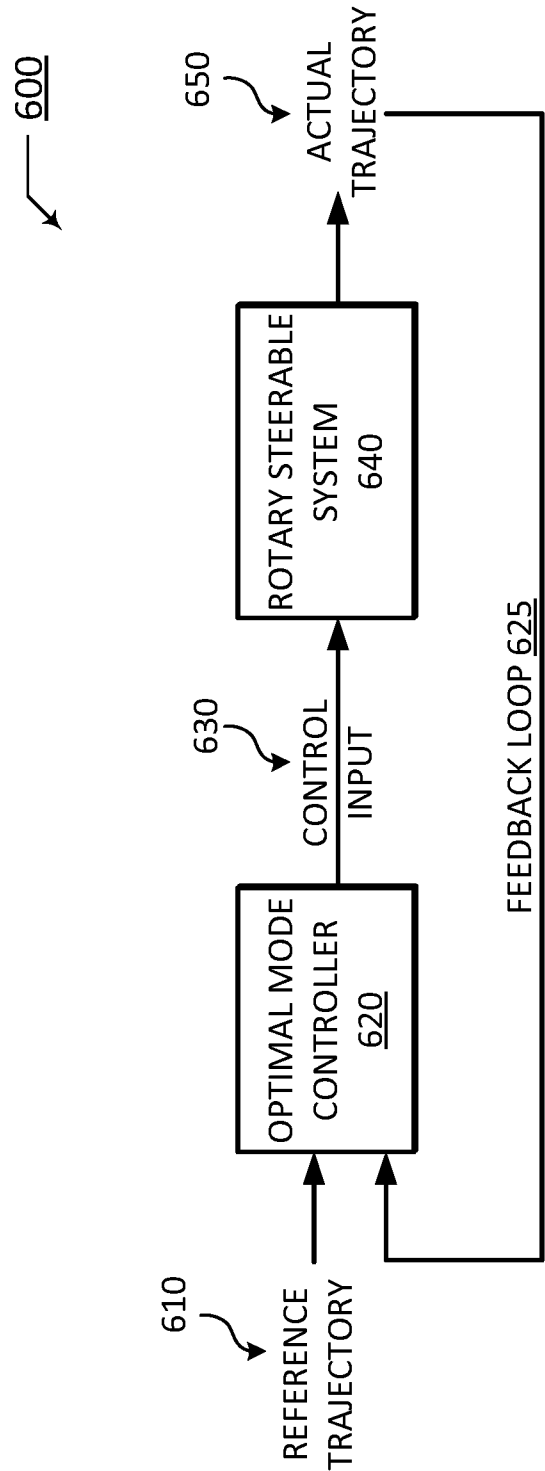
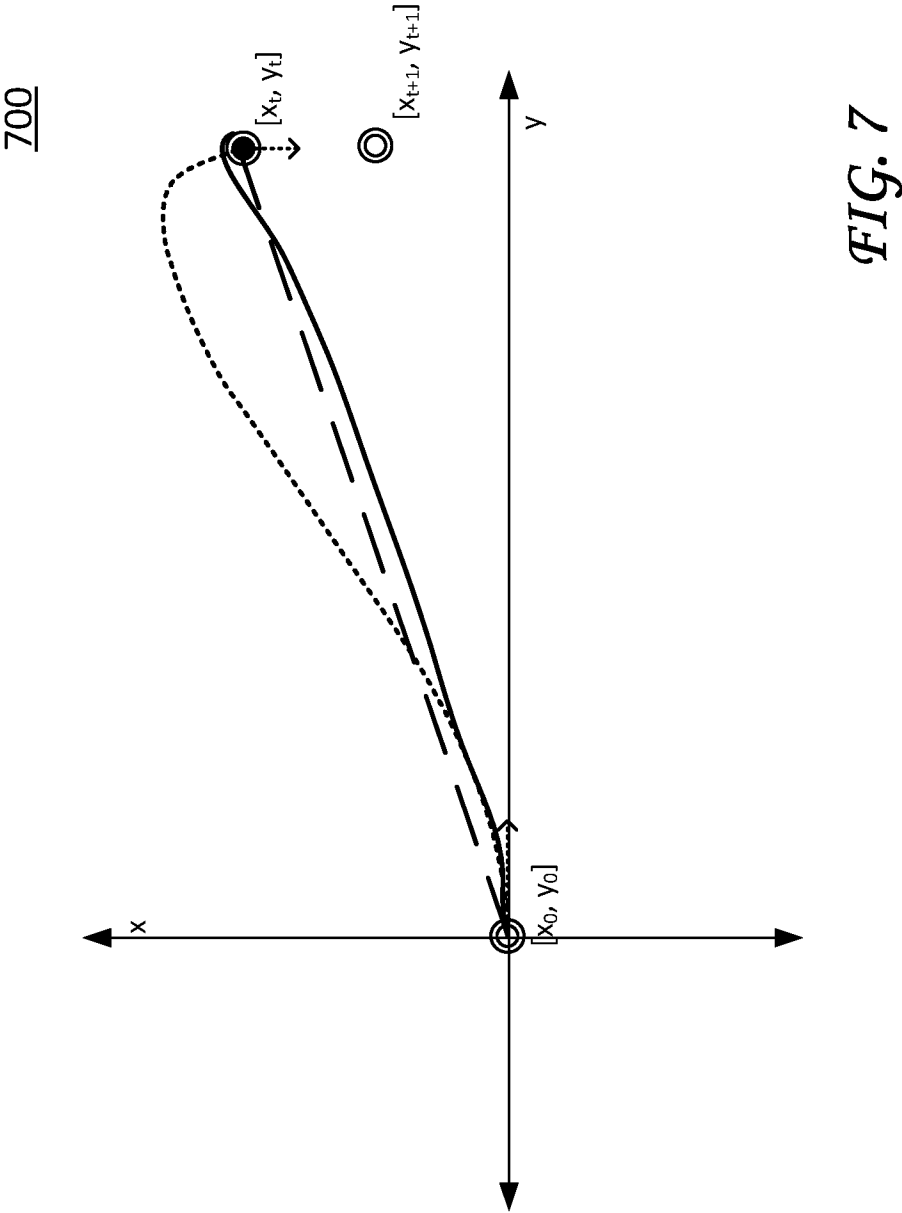


FIG. 6



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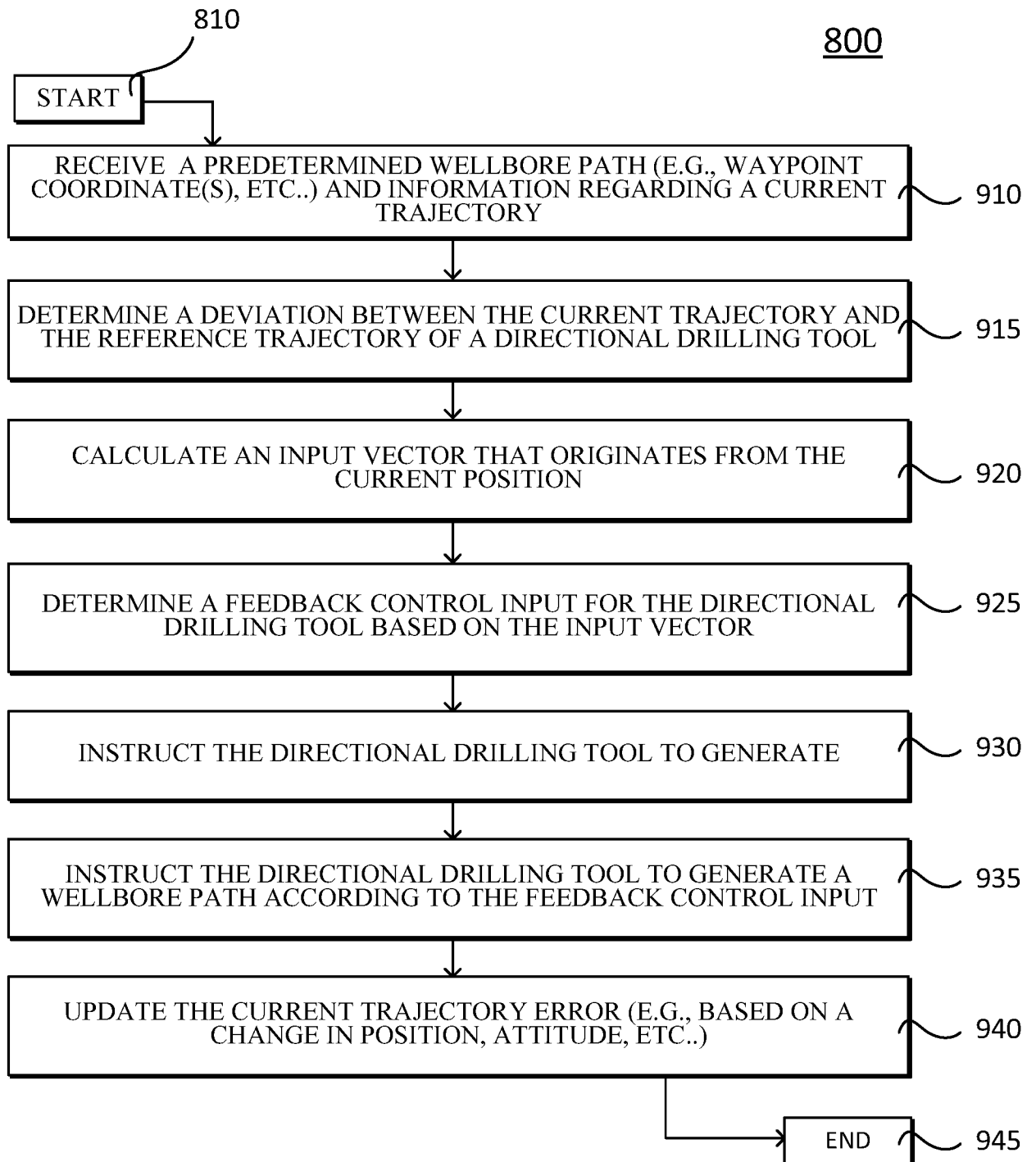


FIG. 8

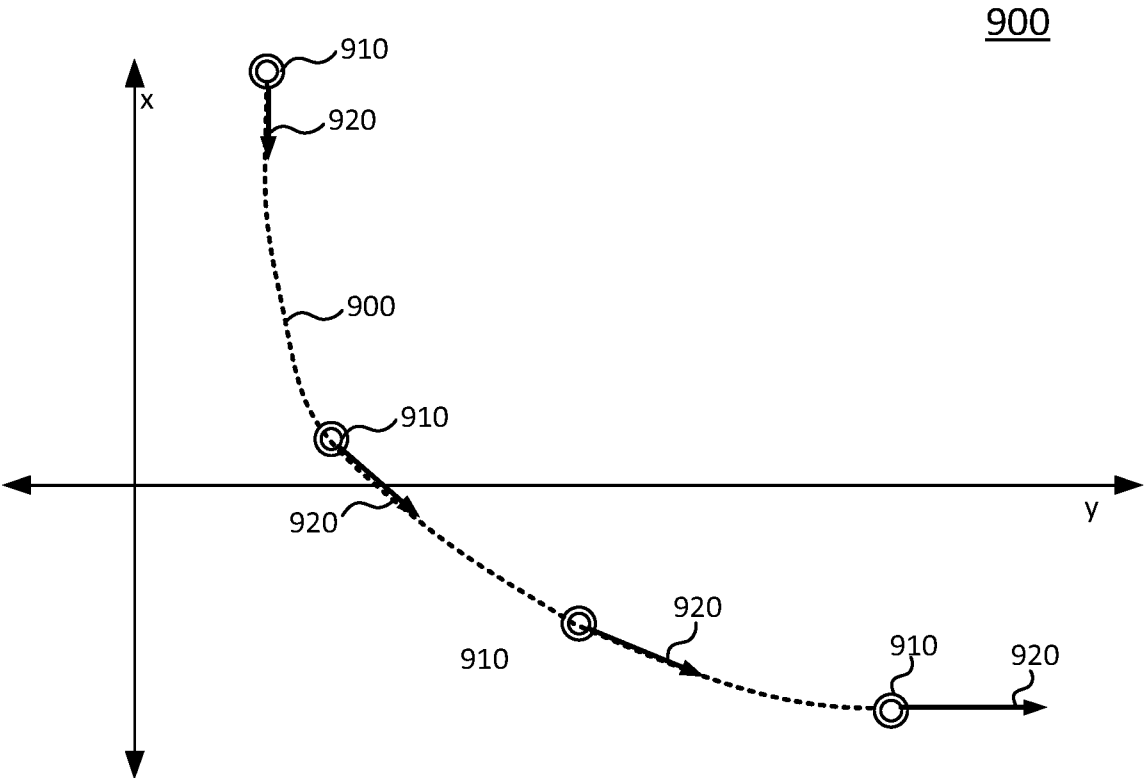


FIG. 9

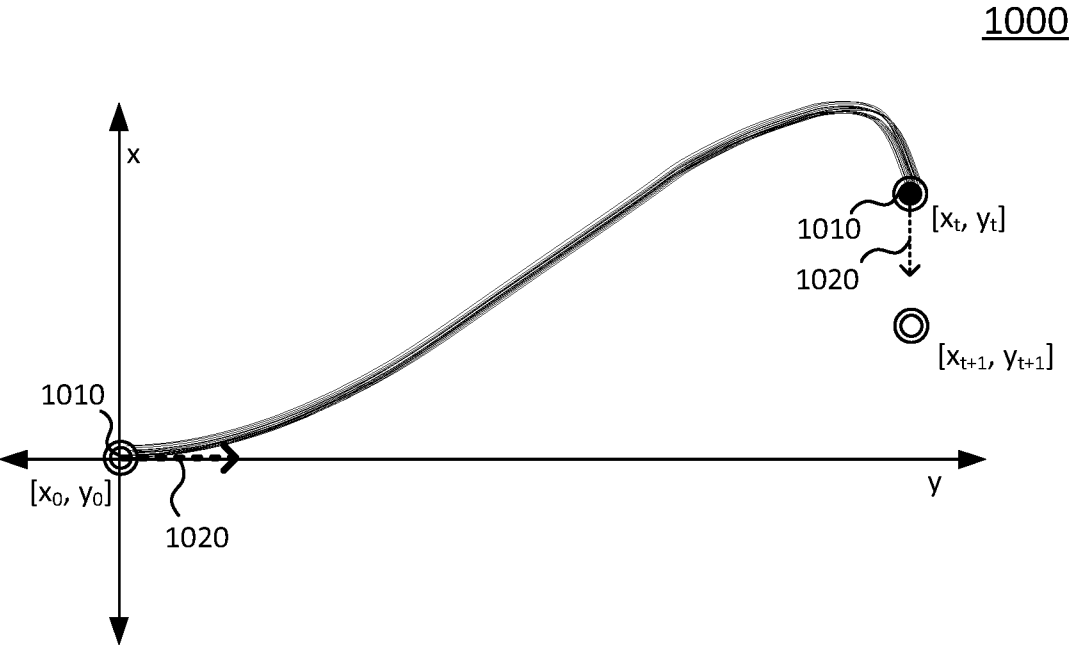


FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/069076**A. CLASSIFICATION OF SUBJECT MATTER****E21B 7/06(2006.01)i, E21B 44/00(2006.01)i**

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

E21B 7/06; G06F 19/00; E21B 43/00; E21B 47/02; E21B 44/00; G01V 9/00; G06Q 40/00; E21B 41/00

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: directional drilling, cost function, penalty condition, current position, reference position, error, waypoint, update, optimal trajectory

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2016-0186551 A1 (HALLIBURTON ENERGY SERVICES INC.) 30 June 2016 See paragraphs [0014]-[0020], [0025], [0059]-[0068] and figures 1, 6, 7.	1-20
A	US 2014-0305704 A1 (HUNT ADVANCED DRILLING TECHNOLOGIES, L.L.C.) 16 October 2014 See paragraphs [0043]-[0047] and figure 2A.	1-20
A	US 2010-0185395 A1 (PIROVOLOU et al.) 22 July 2010 See paragraphs [0028], [0035]-[0038] and figures 1, 4.	1-20
A	US 2013-0140037 A1 (SEQUEIRA, JR. et al.) 06 June 2013 See paragraphs [0085]-[0098] and figures 5-8.	1-20
A	US 2006-0151214 A1 (PRANGE et al.) 13 July 2006 See paragraphs [0052]-[0056], [0071]-[0073] and figures 4-8.	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

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International Application Division

Korean Intellectual Property Office

189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea



Facsimile No. +82-42-481-8578

Authorized officer

LEE, Se Gyoung

Telephone No. +82-42-481-8740



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