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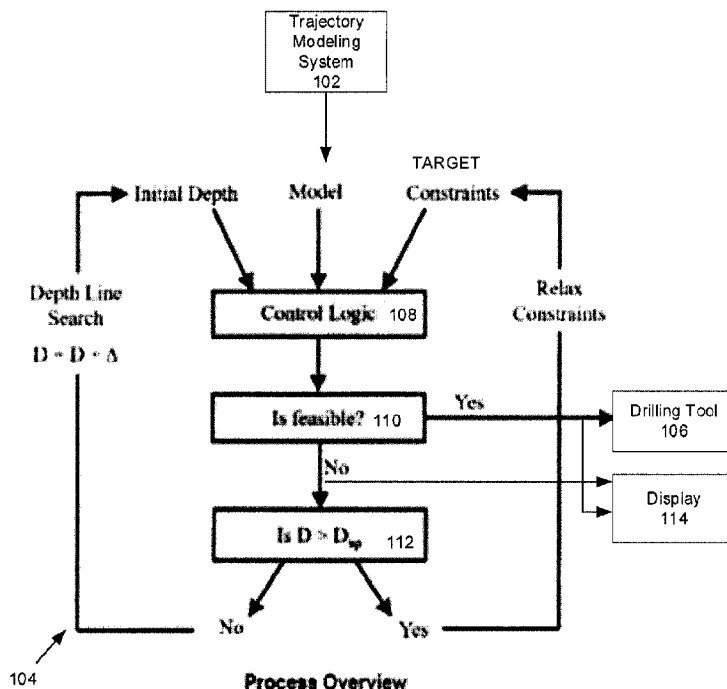
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(57) Abrégé/Abstract:

One or more wellbore trajectories and respective control inputs are determined which meet a wellbore trajectory model, a constraint, and a wellbore length. A wellbore trajectory and respective control input from the one or more wellbore trajectories and respective control inputs are then identified which minimize a cost function associated with the performance objective. The control input associated with this wellbore trajectory are output to a drilling system for drilling a wellbore.

ABSTRACT

One or more wellbore trajectories and respective control inputs are determined which meet a wellbore trajectory model, a constraint, and a wellbore length. A wellbore trajectory and respective control input from the one or more wellbore trajectories and respective control inputs are then identified which minimize a cost function associated with the performance objective. The control input associated with this wellbore trajectory are output to a drilling system for drilling a wellbore.

TOOL-SPECIFIC STEERING OPTIMIZATION TO HIT A TARGET

FIELD OF USE

[0001] The disclosure generally relates to the field of hydrocarbon production, and more particularly determining steering decisions for steering a downhole drilling tool to reach a set target in a geological formation to facilitate extraction of the hydrocarbon.

BACKGROUND

[0002] Drilling for hydrocarbons, such as oil and gas, typically involves operation of a drilling tool at underground depths that can reach down to thousands of feet below the surface. Such remote distances of the downhole drilling tool, combined with unpredictable downhole operating conditions and vibrational drilling disturbances, creates numerous challenges in accurately steering the drilling tool to reach a set target. Sensors, located at or near a bottom hole assembly (BHA), detect various conditions related to the drilling, such as position and angle of the drilling tool, characteristics of the rock formation, pressure, temperature, acoustics, and/or radiation. Such sensor measurement data is typically transmitted to the surface, where human operators analyze the data to steer the downhole drilling tool to reach a set target.

BRIEF DESCRIPTION OF THE DRAWINGS

[0002a] In accordance with one aspect, there is provided a method comprising receiving a performance objective for drilling a wellbore in a geologic formation, a wellbore trajectory model, an indication of wellbore length, and a constraint associated with drilling the wellbore, determining whether one or more first wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the wellbore length, if the one or more first wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the wellbore length, then identifying which wellbore trajectory and respective control input of the one or more first wellbore trajectories and respective control inputs minimizes a cost function associated with the performance objective, if the one or more first wellbore trajectories and respective control inputs does not meet the wellbore trajectory model, the constraint, and

the wellbore length, then adjusting the wellbore length, determining whether one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length, if the one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length, then identifying which wellbore trajectory and respective control input of the one or more second wellbore trajectories and respective control inputs minimizes the cost function associated with the performance objective, and outputting the control input associated with the wellbore trajectory of the one or more first wellbore trajectories or the one or more second wellbore trajectories that minimizes the cost function.

[0002b] In accordance with another aspect, there is provided a system comprising a wellbore trajectory modeling system comprising a wellbore trajectory model associated with a drilling system, and a device to receive a performance objective for drilling a wellbore in a geologic formation, the wellbore trajectory model, an indication of wellbore length, and a constraint associated with drilling the wellbore, determine whether one or more first wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the wellbore length, if the one or more first wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the wellbore length, then identify which wellbore trajectory and respective control input of the one or more first wellbore trajectories and respective control inputs minimizes a cost function associated with the performance objective, if the one or more first wellbore trajectories and respective control inputs does not meet the wellbore trajectory model, the constraint, and the wellbore length, then adjust the wellbore length, determine whether one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length, if the one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length, then identify which wellbore trajectory and respective control input of the one or more second wellbore trajectories and respective control inputs minimizes the cost function associated with the performance objective, and output the control inputs associated with the

wellbore trajectory of the one or more first wellbore trajectories or the one or more second wellbore trajectories that minimizes the cost function.

[0002c] In accordance with yet another aspect, there is provided one or more non-transitory machine-readable media comprising program code executable by a processor to perform the functions of receiving a performance objective for drilling a wellbore in a geologic formation, a wellbore trajectory model, an indication of wellbore length, and a constraint associated with drilling the wellbore, determining whether one or more first wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the wellbore length, if the one or more first wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the wellbore length, then identifying which wellbore trajectory and respective control input of the one or more first wellbore trajectories and respective control inputs minimizes a cost function associated with the performance objective, if the one or more first wellbore trajectories and respective control inputs does not meet the wellbore trajectory model, the constraint, and the wellbore length, then adjusting the wellbore length, determining whether one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length, if the one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length, then identifying which wellbore trajectory and respective control input of the one or more second wellbore trajectories and respective control inputs minimizes the cost function associated with the performance objective, and outputting the control inputs associated with the wellbore trajectory of the one or more first wellbore trajectories or the one or more second wellbore trajectories that minimizes the cost function.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] Aspects of the disclosure may be better understood by referencing the accompanying drawings.

[0004] FIG. 1 is a system for determining steering decisions for drilling a wellbore in a geological formation.

[0005] FIG. 2 illustrates this steering optimization in graphical form.

[0006] FIG. 3 illustrates details associated with an optimization system for solving a constrained optimization problem with respect to a given parameter to determine the steering decisions to reach a target.

[0007] FIG. 4A to C show various examples of performance of the optimization system in determining the steering decisions.

[0008] FIG. 5 is a schematic diagram of well apparatus for the determining steering decisions.

[0009] FIG. 6 is a block diagram of apparatus for determining the steering decisions.

[0010] The drawings are for purpose of illustrating example embodiments, but it is understood that the inventions are not limited to the arrangements and instrumentalities shown in the drawings.

DESCRIPTION

[0011] The description that follows includes example systems, methods, techniques, and program flows that embody aspects/embodiments of the disclosure. However, it is understood that this disclosure may be practiced without these specific details. For instance, this disclosure refers to determining steering decisions for steering a downhole drilling tool to reach a target in a geological formation in illustrative examples. Aspects of this disclosure can be applied to steering in other contexts as well. In other instances, well-known instruction instances, protocols, structures and techniques have not been shown in detail in order not to obfuscate the description.

Overview

[0012] A well plan is typically prepared before lateral drilling begins in a geological formation. The well plan defines steering decisions for a drilling tool so that a smooth wellbore trajectory is produced to a target in a geological formation. However, a majority of lateral drilling jobs requires frequent changes to targets after the lateral drilling begins. The original well plan is often disregarded when the new targets are set resulting in a wellbore being drilled which misses the set target or which reaches the set target via a longer path than necessary.

[0013] Embodiments described herein are directed to a control system for determining steering decisions as the drilling tool drills in the geological formation so that a wellbore being drilled reaches the target. Various inputs including (i) set target(s) in the geological formation, (ii) trajectory and operational constraints associated with drilling the wellbore, (iii) a wellbore trajectory model, and (iv) real time drilling data are input into a control system to determine the steering decisions. The wellbore trajectory model predicts a wellbore trajectory in the geological formation. The wellbore trajectory indicates curvature, attitude and/or position information of the wellbore which is used to steer the drilling tool to reach a target in the geological formation. The real time drilling data may include bottom hole assembly (BHA) geometry, steering inputs such as steering ratio and toolface, surveys of the geological formation, and continuous measurements of the geological formation. The set target(s) in the geological formation can be defined in terms of curvature, attitude and location. Constraints associated with the wellbore can be defined in terms of either operational parameters such as weight on bit (WOB), rate of penetration (ROP), or trajectory constraints (position, attitude, curvature). For instance, a position constraint can help dealing with collision avoidance and a curvature constraint can help with wellbore tortuosity, etc.

[0014] If the target is reachable, the control system determines the optimal steering decisions such as functions of toolface and steering ratio based on the wellbore trajectory model to reach the target. If the target is unreachable, the control system informs the user. In case the target is not reachable given the certain constraints, the control system suggests changes to the constraints so that the target will become reachable. As a by-product this control system also provides a resulting wellbore trajectory between the current bit position and the target which is displayed on a display screen.

[0015] The disclosed control system improves wellbore accuracy to the target, and as a result allows for increasing productions production of hydrocarbon. The disclosed control system also produces smooth steering decisions which reduces wellbore tortuosity and enables drilling longer laterals. Early warnings are also provided on whether a target can be reached, streamlining interactions between drilling and geology teams.

[0016] The description that follows includes example systems, apparatuses, and methods that embody aspects of the disclosure. However, it is understood that this disclosure may be practiced without these specific details. In other instances, well-known instruction instances, structures and techniques have not been shown in detail in order not to obfuscate the description.

Example Illustrations

[0017] FIG. 1 is a system for determining the steering decisions for drilling a wellbore in a geological formation. A wellbore may be associated an on-shore or off-shore well and the system 100 may be positioned downhole or at a surface of the geological formation. The system includes a trajectory modeling system 102, a steering decision system 104, and a drilling tool 106.

[0018] Data associated with drilling in the geological formation may be provided to a trajectory modeling system 102. The data may include one or more of bottom hole assembly (BHA) geometry, a drilling tool type, weight on bit (WOB), indication of measuring while drilling (MWD)/logging while drilling (LWD) components, and drill bit type. The trajectory modeling system may generate a wellbore trajectory model which predicts a wellbore trajectory based on given steering inputs such as steering ratio and toolface. The wellbore trajectory indicates curvature, attitude and/or position information of the wellbore which is used to steer the drilling tool to reach a target in the geological formation.

[0019] The wellbore trajectory model, an indication of a target, and operational/trajectory constraints may be input into the steering decision system 104. The target may be a position in the geological formation to reach. The target may be defined in curvature, attitude and/or location. The target can be given in terms of in 3D position, attitude and/or curvature (in absolute terms or relative to the current position, attitude or curvature). Additionally, or alternatively, the target can be given as a surface or volume to cross. In that case the relative position of the borehole to the “center” of the target can be an optimized parameter. In some examples, a target can be expanded to

more than one target to minimize a path through multiple targets defined as points, surfaces, or volumes. Other variations are also possible.

[0020] The operational/trajectory constraints may define limits to drilling operations and resulting wellbore. The operational/trajectory constraints may be in terms of operational parameters such as surveys of the geological formation, continuous measurements of the geological formation, weight on bit (WOB), toolface, rate of penetration (ROP), steering ratio or wellbore trajectory (position, attitude, curvature). For instance, a position constraint can help dealing with collision avoidance, curvature constraint can help with wellbore tortuosity, etc. An initial drill depth indicates an estimated distance to drill to reach the target determined based on the surveys and/or continuous measurements or defined as an external input. Alternatively, the initial distance to target can be calculated by a minimum curvature method. Further, a minimum curvature based wellbore trajectory can be generated and set as a reference for comparison with the wellbore trajectory actually being drilled.

[0021] A control system 108 (e.g., control logic) may have a processor and memory storing computer instructions which are executed to evaluate feasibility of reaching the target subject to the constraints, depth, and the trajectory model. The feasibility may be based on a desired offset between the wellbore trajectory and the target. The feasibility block 110 determines the feasibility. If reaching the target is feasible, then the steering decision system 104 outputs steering decisions to reach the target which are provided to the drilling tool 106. The steering decisions may be a control input into the drilling tool and be a function of a tool face and/or steering ratio. The drilling direction of the drilling tool 106 may be controlled based on the steering decisions. Additionally, the control system 104 may output a resulting wellbore trajectory on a display 114.

[0022] If reaching the target is infeasible, then the control system 104 may output a warning on the display 108, for example, to indicate the target is not reachable. Further, the control system 104 may relax the constraints until a feasible solution is obtained if the depth to drill D is greater than a threshold D_s at block 112. If the depth to drill is less than or equal to a threshold, then the drill depth may be increased by a delta amount and

feasibility of reaching the target subject to the constraints, drill depth, and the trajectory model is evaluated again. This process may continue until reaching the target is feasible or determined to be unfeasible.

[0023] FIG. 2 illustrates this steering optimization in graphical form. Given a current position 202 $[X_c, Y_c, Z_c]$ in 3 dimensions in a geological formation and attitude $[Inc_c, Azi_c]$ (inclination and azimuth) of the drilling tool, a wellbore shown by path 204 is to be drilled which reaches a target 206 in the geological formation for which Z_t (true vertical depth (TVD)), Inc_t and Azi_t are specified. In some cases, when the drilling tool location is uncertain, target true vertical depth (TVD) may be specified as the offset from current TVD. Also, in some cases, the target 206 can be defined not as a point but as a surface or volume to cross. In that case, constraints on the final position, attitude, or curvature of the wellbore at the target 206 are added. The steering decision system specifies one or more of the steering decisions to reach the target 206 via the path 204.

[0024] FIG. 3 illustrates details associated with an optimization system 300 of the controller system which solves a constrained optimization problem with respect to a given parameter to determine the steering decisions to reach the target. The given parameter to optimize can take a variety of forms. The parameter can be defined in terms of one or more of tortuosity, borehole length, limited change in downlink commands, time spent drilling, final offset from target, etc. or a weighted combination thereof.

[0025] The optimization system 300 includes inputs 302, a cost function 304 to minimize a given parameter associated with reaching the target, and outputs 306. The inputs 302 may include the constraints, initial depth, and trajectory model. The cost function may find a state such as output by the trajectory model and a control input based on tool face or steering ratio which minimizes the given parameter. The cost function 304 may have the following form and subject to the various constraints:

$$\min_{x,u} J(x(\xi), u(\xi))$$

$$\begin{aligned} \text{subject to } \dot{x}(\xi) &= f_s(x(\xi), u(\xi)) \\ g_i(x(\xi)) &\leq c_i, \quad i = 1, \dots, n \\ h_j(u(\xi)) &\leq d_j, \quad j = 1, \dots, m \\ p_k(x(\xi)) &= e_k, \quad k = 1, \dots, m \\ \xi &\in [MD_{start}, MD_{final}] \end{aligned}$$

[0026] where,

- ξ represents the measured depth. It takes values between MDstart, which is the current depth, and MDfinal which is the final depth when the target is reached. MDfinal-MDstart gives the borehole length required to reach the target, which is an input to the controller system as the initial depth.
- x is the state of the system output by the trajectory model, which can be a function of attitude (i.e., inclination and azimuth), curvature and/or position; and u is the control input, which is a function of toolface and steering ratio.
- J is the objective function of the problem, which is formulized such that the minimization of this value would result in the optimal performance of the system.
- f_s represents the trajectory model of the system, which is used to predict trajectory based on the current state and future steering decisions.
- g_i is a function of state, the inequality represents the state inequality constraints. These constraints can be used to put upper and lower bounds on the attitude, curvature, tortuosity, and/or position of the wellbore.
- h_j is a function of control input, the inequality represents the input constraints. These constraints can be used to bound the control inputs.

- p_k is a function of state, the equality represents the state equality constraints. These constraints can be used to specify state values at a certain depth.

[0027] To illustrate a steering optimization for reaching a target, consider a wellbore trajectory model which outputs a wellbore trajectory state comprising attitude and curvature, e.g.,

$$x = \begin{bmatrix} \theta \\ \kappa_\theta \\ \phi \\ \kappa_\phi \end{bmatrix} \quad \begin{array}{l} \bullet \text{ Inclination} \\ \bullet \text{ Inclination curvature} \\ \bullet \text{ Azimuth} \\ \bullet \text{ Azimuth curvature} \end{array}$$

[0028] The control inputs to the control system for controlling the drilling tool may be u_θ and u_ψ for inclination and pseudo-azimuth relatively. Pseudo-azimuth is the projection of azimuth onto the plane, which is perpendicular to inclination plane and include the tangent to the wellbore at the bit. This definition allows to represent steering ratio (SR) and toolface (TF) in terms of the control inputs, e.g.,

$$\begin{aligned} SR &= |u| = \sqrt{u_\theta^2 + u_\psi^2} \\ TF &= \arctan(u_\psi / u_\theta) \\ \psi &= \phi \sin(\theta) \end{aligned} \quad u = \begin{bmatrix} u_\theta \\ u_\psi \end{bmatrix}$$

[0029] Then, the steering optimization problem (e.g., determination of steering decisions) to hit a target which minimizes a distance to the target can be written as follows:

$$\begin{aligned}
& \min_{x,u} J_d(x) \\
& \text{s.t. } x_{k+1} = A_d x_k + B_d u_k + G_d \sin(\theta_0) + D_d \quad (1) \\
& lb \leq x_k \leq ub, \quad (2) \quad \sqrt{u_{\theta,k}^2 + u_{\phi,k}^2} \leq 1 \quad (3) \\
& x_n = x_T \quad (4) \\
& k = 1, \dots, n \\
& J_d(x) = \sum_{k=1}^N d_{sk}^2 = \sum_{k=1}^N (d_0 + \tau D_k (\theta - \theta_r))^2, \quad D_k = [1^{1 \times k} \quad 0^{1 \times (N-k)}]
\end{aligned}$$

[0030] where,

- J_d is the cost which is used to minimize offset from target where d_0 is the initial TVD offset from target.
- Equation (1) is the discretized system dynamics as a function of state where A_d is the system matrix, B_d is the control matrix, G_d and D_d are bias matrices based on gravity and other external effects, respectively.
- Equation (2) is the state constraints, which can be used to bound curvature and to bound attitude along the trajectory between lower and upper bounds.
- Equation (3) ensures that the steering ratio is between 0 and 1.
- Equation (4) ensures that the state at the final depth satisfies target specifications

[0031] Other variations of the control system are also possible. For example, the constrained optimization problem may be formulated as a free final depth control problem where the final depth is also a parameter which is optimized (as part of the cost function). As another example, similar to the free final depth problem, the constrained optimization problem can be formulized as a fixed or free final time problem where the time and depth are related via rate of penetration (ROP) which can be selected as an

optimization parameter. The objective can be set as such that the target is achieved with minimum control change (change in attitude). In one embodiment, bisection method can be used as the search algorithm for solving the constrained optimization problem or any minimum/root-finding algorithm.

[0032] FIG. 4A to C show various examples of performance of the control system in reaching the target based on solving the steering optimization problem which minimizes an offset to the target. The disclosed control system is used to determine steering decisions which allow for reaching the target in a minimum feasible depth. In general, the depth can be part of the cost function to minimize. In some examples, an optimal solution is achieved where the depth required is nearly half of the well known minimum curvature trajectory result and satisfying the tight operational bounds on the curvature.

[0033] FIG. 4A shows that the control system is able to optimize the wellbore trajectory in 600 feet while the minimum curvature method takes 1200 feet.

[0034] FIG. 4B shows the inclination angle and azimuth are stable.

[0035] FIG. 4C shows the curvature of the trajectory is within bounds.

[0036] FIG. 5 is a schematic diagram of well system 500 for determining steering decisions for a drilling tool in a geological formation to reach a target. The well system 500 includes a drill bit 502 disposed on a drill string 504 of the well system 500 for drilling a wellbore 506 in a subsurface formation 508. While wellbore 506 is shown extending generally vertically into the subsurface formation 508, the principles described herein are also applicable to wellbores that extend at an angle through the subsurface formation 508, such as horizontal and slanted wellbores. For example, the wellbore can be angled vertically followed by a low inclination angle, high inclination angle or horizontal placement of the well. It should further be noted that a land-based operation is depicted, but those skilled in the art will readily recognize that the principles described herein are equally applicable to subsea operations that employ floating or sea-based platforms and rigs, without departing from the scope of the disclosure.

[0037] The well system 500 may further include a drilling platform 510 that supports a derrick 512 having a traveling block 514 for raising and lowering drill string 504. Drill string 504 may include, but is not limited to, drill pipe and coiled tubing, as generally known to those skilled in the art. A kelly 516 may support drill string 504 as it may be lowered through a rotary table 518. The drill bit 502 may crush or cut rock, be attached to the distal end of drill string 504 and be driven either by a downhole motor and/or via rotation of drill string 504 from the surface 520. Without limitation, drill bit 502 may include, roller cone bits, PDC bits, natural diamond bits, any hole openers, reamers, coring bits, and the like. As drill bit 502 rotates, it may create and extend wellbore 506 that penetrates various subterranean formations. A pump 522 may circulate drilling fluid through a feed pipe 524 to kelly 516, downhole through interior of drill string 504, through orifices in drill bit 502, back to surface 520 via annulus 526 surrounding drill string 504, and into a retention pit 528.

[0038] Drill bit 502 may be just one piece of the drill string 504 that may include one or more drill collars 530 and one or a plurality of logging tools 534 such as logging-while-drilling (LWD) or measuring-while-drilling (MWD) tools for measuring, processing, and storing information such as the surveys and continuous measurements used to determine the depth to drill. It will also be understood that more than one logging tool 534 (i.e., one or more LWD and/or MWD module) can be employed. Logging tool 534 may be arranged to communicate with a computing system 536. Computing system 536 may include a processing unit 538, a monitor 540, an input device 542 (e.g., keyboard, mouse, etc.), computer media (e.g., optical disks, magnetic disks), and the wellbore trajectory model 550. The computing system 536 can store code representative of the steering decision system described herein for determining steering decisions to reach the target in the geological formation. Computing system 536 may act as a data acquisition system and possibly a data processing system that analyzes information from logging tool 534. Any suitable technique may be used for transmitting signals from logging tool 534 to the computing system 536 residing on the surface 520. As illustrated, a communication link 544 (which may be wired or wireless, for example) may be provided that may transmit data from logging tool 534 to the computing system 536.

Communication link 544 may implement one or more of various known drilling telemetry techniques such as mud-pulse, acoustic, electromagnetic, etc.

[0039] FIG. 6 is a block diagram of apparatus 600 (e.g., the computing system) for determining the steering decisions to reach the target in the geological formation. The apparatus 600 may be located at a surface of a formation or downhole. In the case that the apparatus 600 is downhole, the apparatus 600 may be rugged, unobtrusive, can withstand the temperatures and pressures in situ at the wellbore.

[0040] The apparatus 600 includes a processor 602 (possibly including multiple processors, multiple cores, multiple nodes, and/or implementing multi-threading, etc.). The apparatus 600 includes memory 604. The memory 604 may be system memory (e.g., one or more of cache, SRAM, DRAM, zero capacitor RAM, Twin Transistor RAM, eDRAM, EDO RAM, DDR RAM, EEPROM, NRAM, RRAM, SONOS, PRAM, etc.) or any one or more of the above already described possible realizations of machine-readable media.

[0041] The apparatus 600 may also include a persistent data storage 606. The persistent data storage 606 can be a hard disk drive, such as magnetic storage device. The apparatus 600 also includes a bus 608 (e.g., PCI, ISA, PCI-Express, NuBus, etc.). Coupled to the bus 608 is a network interface 610 which facilitates communication with the logging tool to receive the continuous measurements and surveys from the logging tool and send steering decisions to actuators associated with steering the drill bit to reach a target in the geological formation. The persistent data storage 606 may provide and/or access to data described above for determining steering decisions to reach the target in the geological formation. The apparatus 600 may have the steering decision system 612 for determining steering decisions to reach the target in the geological formation based on the data and the wellbore trajectory model 618.

[0042] Further, the apparatus 600 may comprise a display 614. The display 614 may comprise a computer screen or other visual device. The display 614 may provide feasibility information on whether a target can be reached and/or a trajectory of the wellbore. In the case that the apparatus 600 is located downhole, the display 616 may not

be coupled to the bus 608, and instead the network interface 610 may be used to provide the feasibility information to the display located on the surface. Additionally, the display 614 may convey alerts 616. The formation processing module 612 may generate the alerts 616 relating whether the target is reachable. The alerts 616 may be visual in nature but they may also comprise audible alerts output by an audio output device (e.g., speaker).

[0043] The flowcharts are provided to aid in understanding the illustrations and are not to be used to limit scope of the claims. The flowcharts depict example operations that can vary within the scope of the claims. Additional operations may be performed; fewer operations may be performed; the operations may be performed in parallel; and the operations may be performed in a different order. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by program code. The program code may be provided to a processor of a general purpose computer, special purpose computer, or other programmable machine or apparatus.

[0044] As will be appreciated, aspects of the disclosure may be embodied as a system, method or program code/instructions stored in one or more machine-readable media. Accordingly, aspects may take the form of hardware, software (including firmware, resident software, micro-code, etc.), or a combination of software and hardware aspects that may all generally be referred to herein as a “circuit,” “module” or “system.” The functionality presented as individual modules/units in the example illustrations can be organized differently in accordance with any one of platform (operating system and/or hardware), application ecosystem, interfaces, programmer preferences, programming language, administrator preferences, etc.

[0045] Any combination of one or more machine readable medium(s) may be utilized. The machine readable medium may be a machine readable signal medium or a machine readable storage medium. A machine readable storage medium may be, for example, but not limited to, a system, apparatus, or device, that employs any one of or combination of electronic, magnetic, optical, electromagnetic, infrared, or semiconductor

technology to store program code. More specific examples (a non-exhaustive list) of the machine readable storage medium would include the following: a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a portable compact disc read-only memory (CD-ROM), an optical storage device, a magnetic storage device, or any suitable combination of the foregoing. In the context of this document, a machine readable storage medium may be any tangible medium that can contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device. A machine readable storage medium is not a machine readable signal medium.

[0046] A machine readable signal medium may include a propagated data signal with machine readable program code embodied therein, for example, in baseband or as part of a carrier wave. Such a propagated signal may take any of a variety of forms, including, but not limited to, electro-magnetic, optical, or any suitable combination thereof. A machine readable signal medium may be any machine readable medium that is not a machine readable storage medium and that can communicate, propagate, or transport a program for use by or in connection with an instruction execution system, apparatus, or device.

[0047] Program code embodied on a machine readable medium may be transmitted using any appropriate medium, including but not limited to wireless, wireline, optical fiber cable, RF, etc., or any suitable combination of the foregoing.

[0048] Computer program code for carrying out operations for aspects of the disclosure may be written in any combination of one or more programming languages, including an object oriented programming language such as the Java® programming language, C++ or the like; a dynamic programming language such as Python; a scripting language such as Perl programming language or PowerShell script language; and conventional procedural programming languages, such as the "C" programming language or similar programming languages. The program code may execute entirely on a stand-alone machine, may execute in a distributed manner across multiple machines, and may

execute on one machine while providing results and or accepting input on another machine.

[0049] The program code/instructions may also be stored in a machine readable medium that can direct a machine to function in a particular manner, such that the instructions stored in the machine readable medium produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block or blocks.

[0050] While the aspects of the disclosure are described with reference to various implementations and exploitations, it will be understood that these aspects are illustrative and that the scope of the claims is not limited to them. In general, techniques for steering a downhole drilling tool to reach a set target in a geological formation to facilitate extraction of the hydrocarbon as described herein may be implemented with facilities consistent with any hardware system or hardware systems. Many variations, modifications, additions, and improvements are possible.

[0051] Plural instances may be provided for components, operations or structures described herein as a single instance. Finally, boundaries between various components, operations and data stores are somewhat arbitrary, and particular operations are illustrated in the context of specific illustrative configurations. Other allocations of functionality are envisioned and may fall within the scope of the disclosure. In general, structures and functionality presented as separate components in the example configurations may be implemented as a combined structure or component. Similarly, structures and functionality presented as a single component may be implemented as separate components. These and other variations, modifications, additions, and improvements may fall within the scope of the disclosure.

[0052] As used herein, the term “or” is inclusive unless otherwise explicitly noted. Thus, the phrase “at least one of A, B, or C” is satisfied by any element from the set {A, B, C} or any combination thereof, including multiples of any element.

CLAIMS

1. A method comprising:

receiving a performance objective for drilling a wellbore in a geologic formation, a wellbore trajectory model, an indication of wellbore length, and a constraint associated with drilling the wellbore;

determining whether one or more first wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the wellbore length;

if the one or more first wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the wellbore length, then identifying which wellbore trajectory and respective control input of the one or more first wellbore trajectories and respective control inputs minimizes a cost function associated with the performance objective;

if the one or more first wellbore trajectories and respective control inputs does not meet the wellbore trajectory model, the constraint, and the wellbore length, then adjusting the wellbore length;

determining whether one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length;

if the one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length, then identifying which wellbore trajectory and respective control input of the one or more second wellbore trajectories and respective control inputs minimizes the cost function associated with the performance objective; and

outputting the control input associated with the wellbore trajectory of the one or more first wellbore trajectories or the one or more second wellbore trajectories that minimizes the cost function.

2. The method of claim 1, further comprising if one or more second wellbore trajectories and respective control inputs does not meet the wellbore trajectory model, the constraint, and the adjusted wellbore length, then adjusting the constraint;

determining whether one or more third wellbore trajectories and respective control inputs meets the wellbore trajectory model, the adjusted constraint, and the adjusted wellbore length; and

if the one or more third wellbore trajectories and respective control inputs meets the wellbore trajectory model, the adjusted constraint, and the adjusted wellbore length, then identifying which

wellbore trajectory and respective control input of the one or more third wellbore trajectories and respective control inputs minimizes the cost function associated with the performance objective; and

outputting the control input associated with the wellbore trajectory of the one or more third wellbore trajectories that minimizes the cost function.

3. The method of claim 1, wherein the performance objective is to minimize a distance between a target in the geologic formation and the wellbore and wherein operations to determine whether one or more first wellbore trajectories and respective control inputs meet the wellbore trajectory model, the constraint, and the wellbore length and to identify which wellbore trajectory and respective control input of the one or more first wellbore trajectories and respective control inputs minimizes the cost function associated with the performance objective are performed simultaneously.

4. The method of claim 3, wherein the cost function receives as an input a plurality of states along a given wellbore trajectory and a respective control input for the plurality of states and provides an indication of the distance.

5. The method of claim 1, wherein the constraint limits a trajectory of the wellbore and the control inputs to predetermined values.

6. The method of claim 1, wherein adjusting the wellbore length comprises increasing the wellbore length by a predetermined depth.

7. The method of claim 1, further comprising repeatably adjusting the wellbore length by different amounts until the one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length.

8. A system comprising:

a wellbore trajectory modeling system comprising a wellbore trajectory model associated with a drilling system; and

a device to:

receive a performance objective for drilling a wellbore in a geologic formation, the wellbore trajectory model, an indication of wellbore length, and a constraint associated with drilling the wellbore;

determine whether one or more first wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the wellbore length;

if the one or more first wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the wellbore length, then identify which wellbore trajectory and respective control input of the one or more first wellbore trajectories and respective control inputs minimizes a cost function associated with the performance objective;

if the one or more first wellbore trajectories and respective control inputs does not meet the wellbore trajectory model, the constraint, and the wellbore length, then adjust the wellbore length;

determine whether one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length;

if the one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length, then identify which wellbore trajectory and respective control input of the one or more second wellbore trajectories and respective control inputs minimizes the cost function associated with the performance objective; and

output the control inputs associated with the wellbore trajectory of the one or more first wellbore trajectories or the one or more second wellbore trajectories that minimizes the cost function.

9. The system of claim 8, further comprising the device to:

adjust the constraint, if one or more second wellbore trajectories and respective control inputs does not meet the wellbore trajectory model, the constraint, and the adjusted wellbore length;

determine whether one or more third wellbore trajectories and respective control inputs meets the wellbore trajectory model, the adjusted constraint, and the adjusted wellbore length; and

if the one or more third wellbore trajectories and respective control inputs meets the wellbore trajectory model, the adjusted constraint, and the adjusted wellbore length, then identify which wellbore trajectory and respective control input of the one or more third wellbore trajectories and respective control inputs minimizes the cost function associated with the performance objective; and

output the control input associated with the wellbore trajectory of the one or more third wellbore trajectories that minimizes the cost function.

10. The system of claim 8, wherein the performance objective is to minimize a distance between a target in the geologic formation and the wellbore.

11. The system of claim 10, wherein the cost function receives as an input a plurality of states along a given wellbore trajectory and respective control input for the plurality of states and provides an indication of the distance.

12. The system of claim 8, wherein the constraint limits a trajectory of the wellbore trajectory and the control inputs to predetermined values.

13. The system of claim 8, wherein the device to adjust the wellbore length comprises program code to increase the wellbore length by a predetermined depth.

14. The system of claim 13, further comprising the device to repeatably adjust the wellbore length by different amounts until the one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length.

15. One or more non-transitory machine-readable media comprising program code executable by a processor to perform the functions of:

receiving a performance objective for drilling a wellbore in a geologic formation, a wellbore trajectory model, an indication of wellbore length, and a constraint associated with drilling the wellbore;

determining whether one or more first wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the wellbore length;

if the one or more first wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the wellbore length, then identifying which wellbore trajectory and respective control input of the one or more first wellbore trajectories and respective control inputs minimizes a cost function associated with the performance objective;

if the one or more first wellbore trajectories and respective control inputs does not meet the wellbore trajectory model, the constraint, and the wellbore length, then adjusting the wellbore length;

determining whether one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length;

if the one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length, then identifying which wellbore trajectory and respective control input of the one or more second wellbore trajectories and respective control inputs minimizes the cost function associated with the performance objective; and

outputting the control inputs associated with the wellbore trajectory of the one or more first wellbore trajectories or the one or more second wellbore trajectories that minimizes the cost function.

16. The one or more non-transitory machine-readable media of claim 15, further comprising program code to:

adjust the constraint, if one or more second wellbore trajectories and respective control inputs does not meet the wellbore trajectory model, the constraint, and the adjusted wellbore length;

determine whether one or more third wellbore trajectories and respective control inputs meets the wellbore trajectory model, the adjusted constraint, and the adjusted wellbore length; and

if the one or more third wellbore trajectories and respective control inputs meets the wellbore trajectory model, the adjusted constraint, and the adjusted wellbore length, then identifying which wellbore trajectory and respective control input of the one or more third wellbore trajectories and respective control inputs minimizes the cost function associated with the performance objective; and

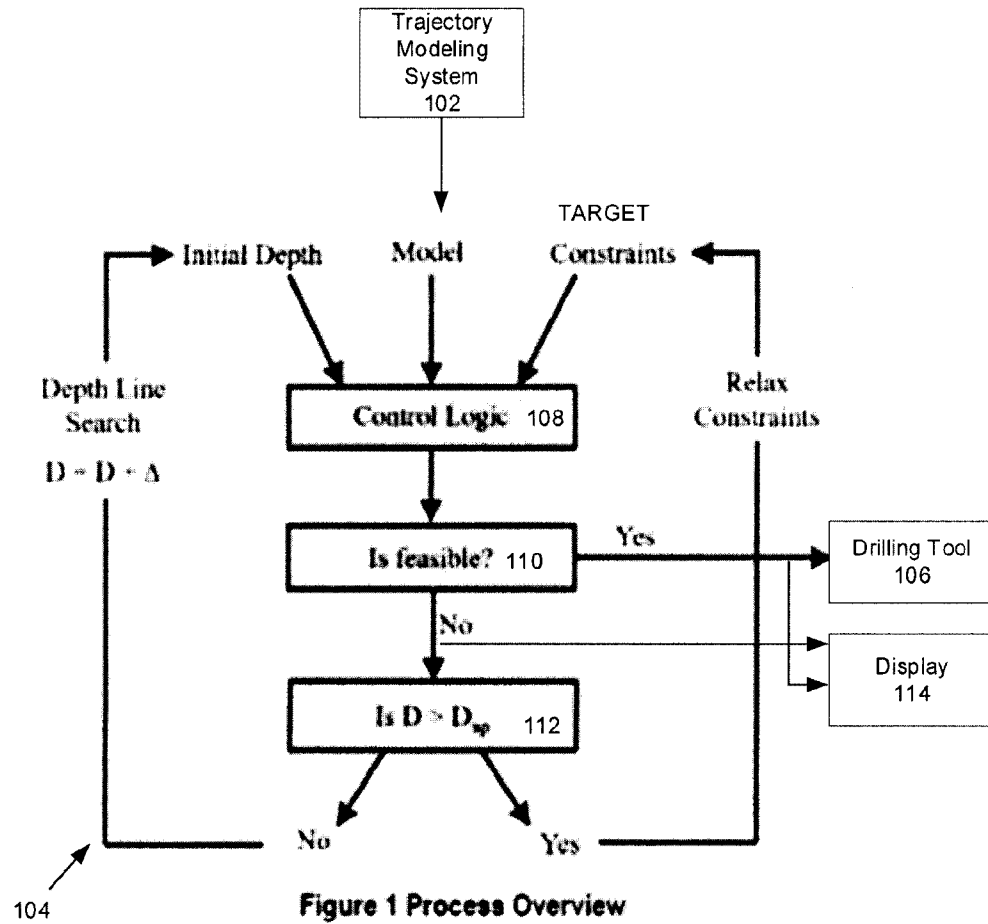
output the control input associated with the wellbore trajectory of the one or more third wellbore trajectories that minimizes the cost function.

17. The one or more non-transitory machine-readable media of claim 15, wherein the performance objective is to minimize a distance between a target in the geologic formation and the wellbore.

18. The one or more non-transitory machine-readable media of claim 17, wherein the cost function receives as an input a plurality of states along a given wellbore trajectory and respective control inputs for the plurality of states and provides an indication of the distance.

19. The one or more non-transitory machine-readable media of claim 15, wherein adjusting the wellbore length comprises increasing the wellbore length by a predetermined depth.

20. The one or more non-transitory machine-readable media of claim 19, further comprising repeatably adjusting the wellbore length by different amounts until the one or more second wellbore trajectories and respective control inputs meets the wellbore trajectory model, the constraint, and the adjusted wellbore length.



Example Performance Objective and Constraints

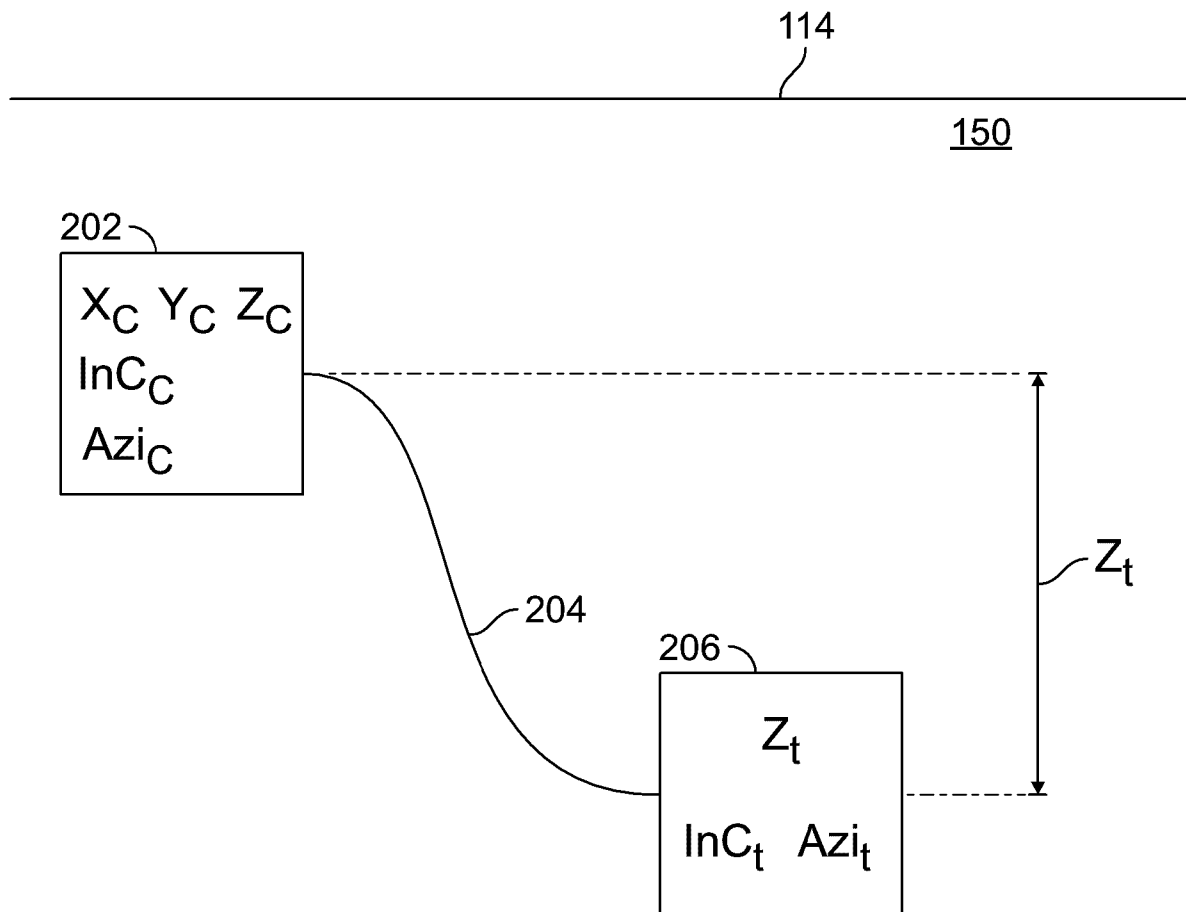


FIG. 2

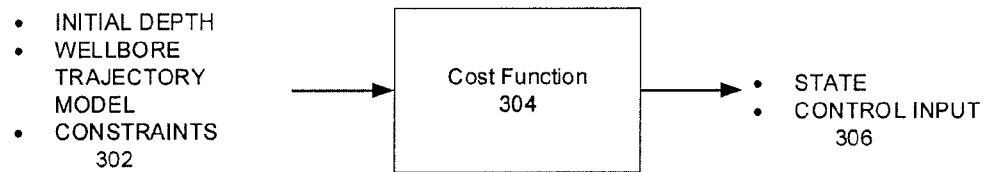


FIG. 3

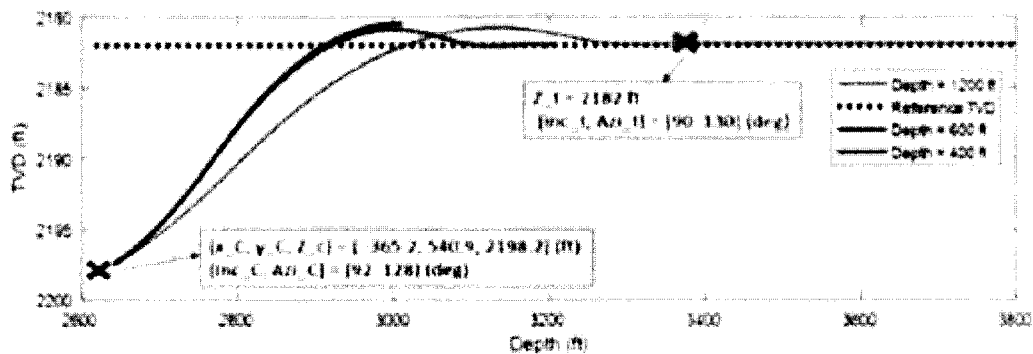
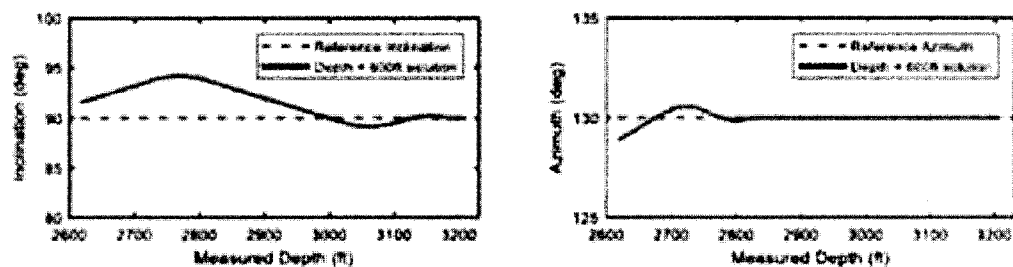


FIG. 4A



Inclination and Azimuth along the trajectory for the optimal solution (Depth = 600ft)

FIG. 4B

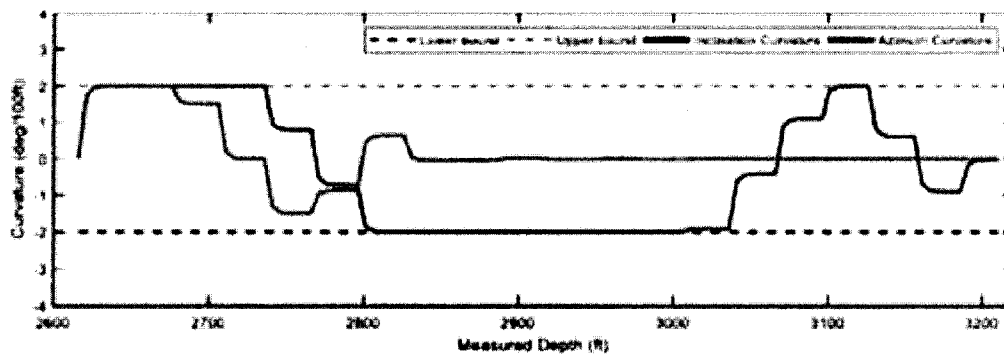


FIG. 4C

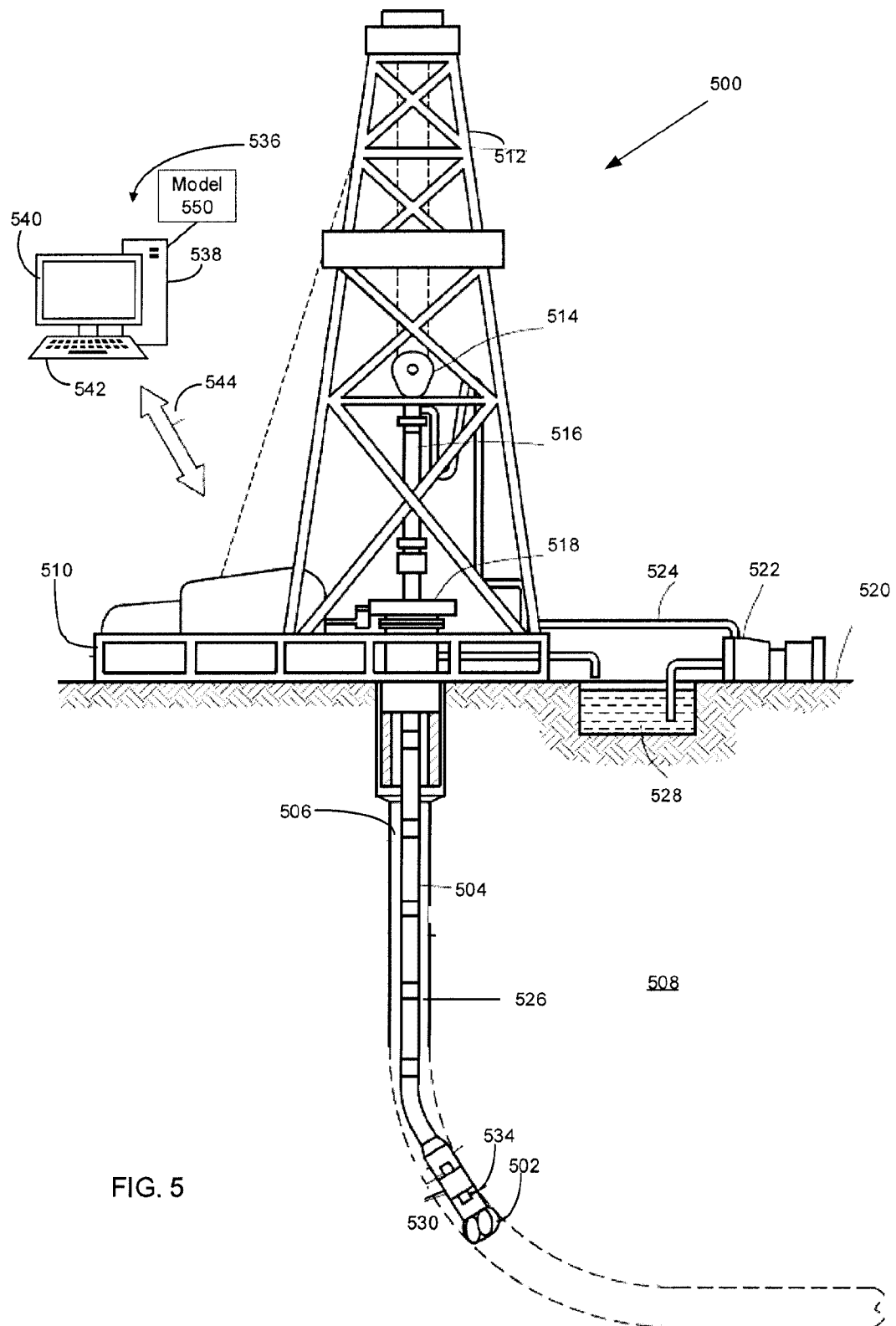


FIG. 5

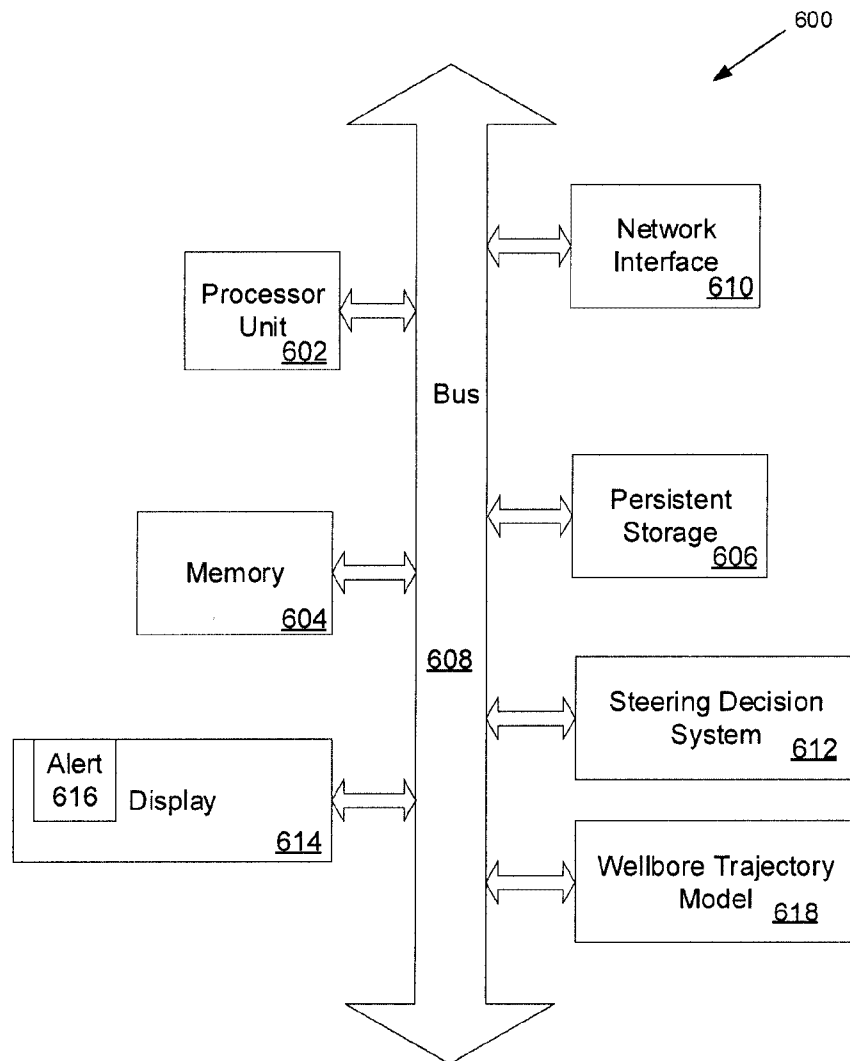


FIG. 6

Trajectory
Modeling
System
102

TARGET

Initial Depth

Model

Constraints

Depth Line
Search

$$D = D + \Delta$$

Control Logic 108

Relax
Constraints

Is feasible? 110

Yes

Drilling Tool
106

No

Is $D > D_w$ 112

Display
114

No

Yes

Process Overview

104

104