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Optimization of Rotary Steerable Drilling

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Abstract- Directional Drilling (DD) is the process of directing the wellbore along a desired trajectory to a predetermined target, using different technologies, including Directional Steering Systems (DSS). DD achieves high well production and improves accessibility of oil reservoirs in complex locations. This paper addresses the problem of real time optimization of drilling parameters in directional drilling to minimize the drilling time, and the deviation from the planned trajectory. This research considered a typical Rotary Steerable System (RSS) for directional drilling with other drilling parameters such as rpm, torque, and weight-on-bit. We assumed no prior knowledge of the formation properties. However, rock specific energy is considered as an unknown disturbance in the model. The cost function parameters can be selected for the best compromise between trajectory tracking, energy consumption, and rate of penetration.

***Keywords*:** Directional drilling, Directional Steering, horizontal drilling, RSS, drilling optimization, ROP optimization, real-time drilling.

1. Introduction

Directional Drilling is the process of directing the wellbore along some trajectory to a predetermined target, Bourgoyne et al (1986). Directional Steering Systems (DSS) facilitate the accessibility of the oil reservoirs if the reservoir is having large surface area and distributed over thin horizontal layer. Wells could also be drilled directionally for several purposes like drilling the underside of an environmental obstacle, or where multiple wells are drilled from one central surface location, such as an offshore platform, Joshi (1991), Baker (2001), and Eustes (2007).

In 1999 a Rotary Steerable System (RSS) was introduced to directional drilling market, (Eustes, 2007). RSS allows three dimensional control of a bit without stopping the drill string rotation, and increases the efficiency of directional drilling operations by reducing drilling time. It also provides better borehole cleaning with fewer wiper trips, optimizes drilling parameters, and provides a higher rate of penetration while drilling (Byliss and Matheus, 2008).

Unlike conventional drilling systems, the directional drilling requires sensors to provide estimations of the azimuth ψ (deviation from the north direction in the horizontal plane), the inclination θ (deviation from the vertical direction, or pitch angle), and the tool face angle ϕ (roll angle) of the drill bit, hence it is called Measurement While Drilling (MWD). MWD systems includes a three-axis magnetometers and three-axis accelerometers to determine the azimuth, the inclination and tool face angles, Thonhauser (2004), and Dunlop (2011).

Modelling of the drilling operation for control and optimization is a challenging problem due to the diversity of the factors affecting drilling as well as uncertainty in their determination. Among these factors are the Bottom Hole Assembly (BHA) dynamics, torques and drags, formation properties, bit-formation interaction and drilling fluid properties and its hydraulics, Bourgoyne and Young (1974).

At the while-drilling mode, the directional drilling system should try to coordinate various control actions (RPM, WOB, mud properties, rate and hydraulic pressure, inclination actuators, azimuth actuators, etc) to keep the down hole path close to the preplanned path trajectory. The control system should be able to accommodate the large uncertainties in the formation properties, and stay within the operational constraints. The main task in directional drilling is to properly orientate the down hole tool to steer the well bore in a desired direction, and minimize the drilling time.

Bourgoyne and Young method is the most important drilling optimization method since it is based on statistical analysis of the past drilling parameters. The model proposed by Bourgoyne and Young (1974) derived equations to perform the ROP estimation using the available input data. This model is considered as one of the complete mathematical drilling models in use of the industry.

William and Jeff (2005) showed how Mechanical Specific Energy (MSE) was implemented in a drilling information system in real time on the rig and at remote monitoring locations. The study showed that the use of MSE in real time is a useful tool for both drillers and drilling engineers. Conducting MSE tests in real time is an effective way to develop an understanding of MSE behavior and contributes to acceptance by rig personnel. The general practice of adjusting drilling parameters to minimize the value of MSE is a good rule of thumb.

Alum and Egbon (2011) developed semi-analytical model for Rate of Penetration (ROP) based on the original Bourgoyne and Young Model using real time bit records, obtained from wells drilled in Niger Delta reservoirs. Simple regression analysis was applied on the equation on the parameters that contain differential pressure to obtain regression constants, which were then used to generate mathematical relationship between ROP and drilling fluid properties.

Rashidi et al. (2008) presented a new method to combine Mechanical Specific Energy (MSE) and Rate of penetration (ROP) models to calculate real time bit wear which takes into consideration the fundamental differences between MSE and ROP models and that the latter only takes into account the effect of bit wear. Encouraging results have been obtained which shows a linear relationship between MSE (Rock Energy) and rock drillability (Drilling Strength).

Rashidi et al. (2010) described the real-time application of a developed model for bit wear analysis.

The model was developed based on the difference between rock energy model, Mechanical Specific Energy (MSE), and rock drillability from rate of penetration model. It has been modified and implemented as an engineering module in the newly developed software, Intelligent Drilling Advisory system (IDA's), and used to estimate real-time bit wear for both rollercone and PDC bits.

Tuna and Evren (2010) developed a model to optimize drilling parameters during drilling operations such as weight on bit, bit rotation speed in order to obtain maximum drilling rate and hence minimize the cost per foot and the overall drilling cost. The model developed used actual field data collected through modern well monitoring and data recording systems, which will be used in predicting the rate of drilling penetration as a function of available parameters. The study demonstrated that drilling rate of penetration could be predicted at relatively accurate levels, based on past drilling trend. The optimum weight on bit and bit rotation speed could be determined in order to achieve minimum cost drilling.

Koederitz and Johnson (2011) described the development and field testing of an autonomous drilling system. This system software uses a test process to evaluate and quantify the drilling performance for a given set of target setpoints. The research method is used to identify these setpoints; its development was based on early work in the application of real-time Mechanical Specific Energy (MSE) display. Overall, the field testing results were favorable, displaying that the potential for autonomous drilling optimization without drilling knowledge is practical, flexible, and economical, exhibiting promise in a range of cost-effective applications.

In this paper we present a unified approach for optimization of the drilling parameters and directional steering. In section 2, we present a simplified model for DSS. In Section 3 we provide the optimization function and procedure. The simulation results are presented in Section 4.

2. Directional Steering System

In order to track the motion of the Bottom Hole Assembly BHA, we are considering two frames: Inertial earth frame (observer from control room) $\{X_E, Y_E, Z_E\}$ and body fixed frame $\{U_b, V_b, W_b\}$. The position of the BHA in the inertial frame is given by the vector $\eta = \{x_E, y_E, z_E\}$. The orientation of the BHA is given by the three Euler angles, namely yaw angle ψ, (azimuth), Pitch angle θ (inclination), and the roll angle ϕ. These three angles form the vector $\Omega = \{\theta, \psi, \phi\}$.

The origin of the Earth reference axis is taken to be the point at which the drilling starts. X_E is taken to be the direction of the North, the Z_E is pointing down towards to the earth centre, and Y_E is pointing towards the East, as shown in Fig. 1.

The azimuth angle, (Az or ψ), is the angle of the well bore direction as projected to a horizontal plane and relative to the North. By industry convention, 0 degree azimuth coincides with North, 90 degree azimuth with East, 180 degree azimuth with South, and 270 degree azimuth with West. The inclination angle is the angle defined by a tangent line to the well bore and a vertical line. The vertical line is always in the direction of earth's gravity. By industry standard, 0 degree inclination is vertical (downward pointing) and 90 degrees inclination is horizontal. An inclination (angle) greater than 90 degrees implies "drilling up".

In the following analysis we assume that that the body axes were aligned with the earth axes at the start of drilling.

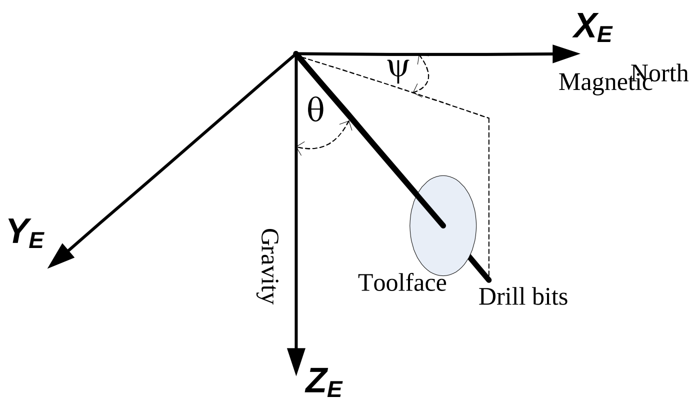

Fig. 1. Illustration of the azimuth angle and the inclination angle.

The orientation of the BHA with respect to the inertia axis is described by the rotational matrix *R*, which is given by equation 1.

$$R = \begin{bmatrix} c\psi s\theta & c\psi c\theta s\phi - s\psi c\phi & c\psi s\theta c\phi + s\psi s\phi \\ s\psi c\theta & s\psi s\theta s\phi + c\psi c\phi & s\psi s\theta c\phi - c\psi s\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \tag{1}$$

where $c\theta$ denotes $\cos\theta$ and $s\theta$ denotes $\sin\theta$.

The rotational matrix *R* defines the transformation of a point *P* from the body axis to the inertia axes as shown in equations 2 and 3.

$$P_{XYZ} = \begin{bmatrix} x_E \\ y_E \\ z_E \end{bmatrix} = RP_{UVW} \quad (2)$$

Where [x_E, y_E, z_E]' is the position of BHA with respect to the inertia frame, and P_{uvw} is the position of the point *P* with respect to the body frame $\{U_b,V_b,W_b\}$.

If we are interested only in the direction of the well bore, we may then ignore the roll rotation of the BHA. In this case R is given by equation 3.

$$R = \begin{bmatrix} c\psi s\theta & -s\psi & c\psi s\theta \\ s\psi c\theta & c\psi & s\psi s\theta \\ -s\theta & 0 & c\theta \end{bmatrix} \quad (3)$$

2. 1. Well bore trajectory.

Although there are several methods for describing a desired well bore trajectory, we assume without loss of generality the target trajectory is given by table of points indexed by the measured distance $w_b(k)$ along the bore hole. The points need not be uniformly spaced.

The kth target point is given by the vector shown in equation 4.

$$P_T(k) = [w_b^t(k), x_E^t(k), y_E^t, x_E^t(k), \theta^t, \psi^t]' \quad (4)$$

2. 2. RSS equations

The most common method for directional steering is known as Rotary Steerable system (RSS), Downton (2007). The rotary steering system has the ability to provide directional drilling control while allowing continuous rotation of the drill-string. Consider the simple representation of a directional drilling system shown in Fig. 2, where the steering **actuator** eccentrically displaces the centre line of the drilling system away from the centre line of the hole by a controllable amount ***ecc*** in a given plane. The steering actuator is placed at a distance L_1 from the bit. At a distance L_2 from the **actuator**, the collar is permitted to pivot about a touch-point with the borehole called a ***stabilizer.*** The stabilizers, steering actuators, and sensors are placed in non-rotating sleeve.

Let us assume now at the stabilizer point the BHA axis is aligned with the bore hole centreline. If the drill bit is currently at location $w_b(k)$ (measured depth) then the stabilizer position is at $[w_b(k) - L_1 - L_2]$ and the actuator position is at location $[w_b(k) - L_1]$. If the actuator creates an eccentricity between the drill string and the hole (*eccu*, *eccv*), measured with respect the BHA axes, then using the small angles approximation, the deviation angles of the drill bit from the stabilizer is given by

$$\delta\theta \cong \frac{eccu}{L_2} \qquad \delta\psi \cong \frac{eccv}{L_2} \quad (5)$$

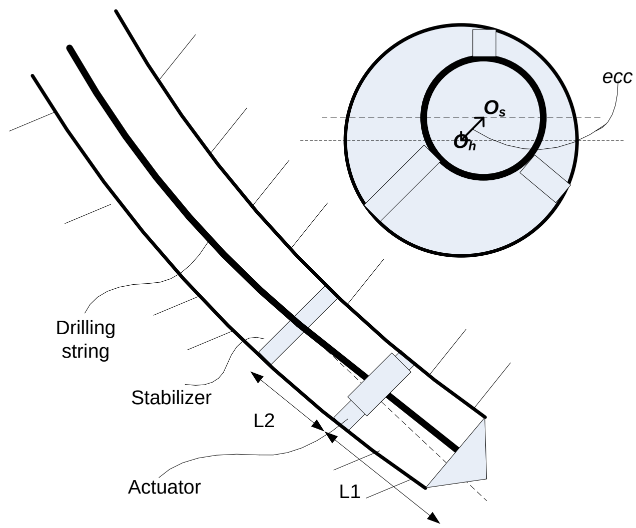

Fig. 2. Rotary Steerable System.

Where *eccu, eccv* are the eccentricity components in the body coordinates U_b, V_b. respectively. The deviation angles are usually about 1.5 degrees, with a maximum of 3-4 degrees. To simplify notations, let us denote $\alpha = eccu, \beta = eccv$.

At the point *k*+1 along the trajectory, the predicted drill position with respect to the body axis is given by

$$\begin{aligned} \Delta u_b(k+1) &= \delta\theta[L_1 + L_2 + (w_b(k+1) - w_b(k))] \\ \Delta v_b(k+1) &= \delta\psi[L_1 + L_2 + (w_b(k+1) - w_b(k))] \\ \Delta w_b(k+1) &= w_b(k+1) - w_b(k) \end{aligned} \tag{6}$$

The predicted location with respect to the inertia axes will be given by

$$\hat{P}_E(k+1) = P_E(k) + R\begin{bmatrix} \Delta u_b(k+1) \\ \Delta v_b(k+1) \\ \Delta w_b(k+1) \end{bmatrix} \tag{7}$$

2. 3. Drilling power balance equation

Real-time Mechanical Specific Energy (MSE) is defined to be ratio between input energy and ROP. On the other hand, the Rock Specific Energy (RSE) is the energy required to destroy a unit volume of rock, and is determined by the rock compressive strength. Efficient drilling should have a value of MSE close to the RSE.

The input power is given by the mechanical motor power, and the hydraulic power for the drilling fluid flow, in addition to the power delivered by the W_{ob}.

$$T\omega + W_{ob}\dot{w}_b + P_{in}Q_F = P_o Q_m + \dot{w}_b A_h E_{rs} \tag{8}$$

Where $\dot{w}_b$ is the ROP in m/sec, T is the drilling torque, ω is the angular velocity of the rotating string, Wob is the weight on bit, Q_F the inlet drilling fluid flow rate, Q_m, is the mud outlet flow rate, P_{in}, P_o are the surface inlet and outlet pressures respectively, A_h is the area of hole bore, and E_{rs} is the rock specific energy.

$$Q_m = Q_F + \dot{w}_b A_h \tag{9}$$

The $\dot{w}_b A_h$ is the volume rate of the crushed rocks. This volume is usually less than 5% of Q_F. Hence we will take $Q_m = Q_F$. Then equation (9) can be simplified as

$$T\omega + W_{ob}\dot{w}_b + P_{in}Q_F = P_o Q_F + \dot{w}_b A_h E_{rs} \tag{10}$$

Since all the parameters, except E_{rs}, are directly measurable online, E_{rs} can be estimated. The estimated value of E_{rs} is then used during optimization to predict $\dot{w}_b$ during the next control step of DSS, as follows

$$\hat{\dot{w}}_b(k+1) = f(T, \omega, DP, W_{ob}, Q_F) = \frac{T\omega + Q_F \Delta P}{A_h \hat{E}_{rs} + P_0 A_h - W_{ob}} \tag{11}$$

3. Drilling Optimization

At each point k, we assume that we have a state vector X, and a target position W_{bt}(k+1), and it is required to find the optimal control parameters

The state vector includes

$$X(k) = [t_{total}, w_b, x_E, y_E, z_E, \theta, \psi, \dot{w}_b, \hat{E}_{rs}] \tag{12}$$

$$U = [T, \omega, W_{ob}, t_k, \alpha, \beta, Q_F, DP] \tag{13}$$

The drilling fluid flow rate is given by

$$Q_F(k+1) = Q_{F0} + \alpha_q A_h \dot{w}_b(k) \tag{14}$$

$$\Delta P(k+1) = 2\mu_p \rho_m g w_b(k) \tag{15}$$

3. 1. Optimization cost function

Clearly the objective is to reach the target position $P_E^t(k+1)$ at the end of this adjustment step.

The value of $w_b(k+1)$ is obtained as follows

$$\dot{\hat{w}}_b(k+1) = f(T,\omega,DP,W_{ob},Q_F) = \frac{T\omega + Q_F\Delta P}{A_h\hat{E}_{rs} + P_0 A_h - W_{ob}} \tag{16}$$

$$\hat{w}_b(k+1) = w_b(k) + t_k f(T,\omega,DP,W_{ob},Q_F) \tag{17}$$

The optimal values of $[T,\omega,W_{ob},t_k,\alpha,\beta]$ are obtained by minimizing the cost function

$$J = (\hat{P}_E(k+1) - P_E^d(k+1))^T \Gamma_1 (\hat{P}_E(k+1) - P_E^d(k+1)) + U^T \Gamma_2 U \tag{18}$$

Where Γ_1 and Γ_2 are positive semi-definite matrices.

4. Simulation

The proposed optimization method is applied to follow the drilling trajectory shown in Figure 3.

This section of a well has a total measured length of 1318 m, and true vertical depth TVD= 254 meters. The section starts by a 30 degree inclination, and proceeds approximately in two continuous build zones to reach almost horizontal drilling (87.9 degrees inclination). The simulated RSE is shown in Fig.3. RSE is assumed to be unknown, but estimated based on the achieved ROP during the previous control step.

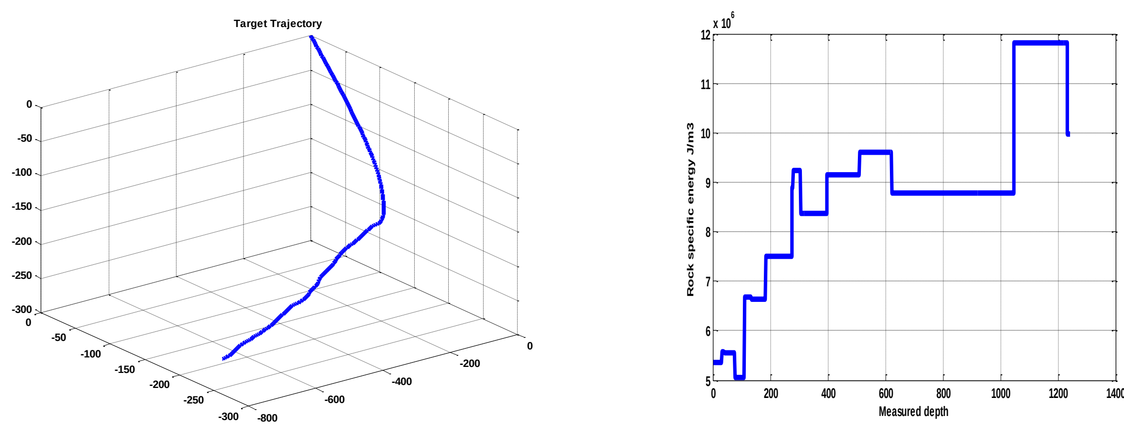

Fig. 3. (Left) the target well bore trajectory. (Right) the RSE.

During simulation Γ_1 is taken to be unit matrix. Two control strategies were simulated. In the first case, Γ_2 was taken to be zero, i.e., no cost for the drilling effort. The drilling time came to 11.3 hours. In the second case the cost of drilling time considered. The Drilling time is reduced to 10.697 hours with minor compromise in the tracking error. It was observed that increasing the cost of time beyond this value did not appreciably reduce the drilling time, but compromises the tracking accuracy.

The minimization of the cost function in Eq. (18) is performed using Matlab constraint minimization function “fmincon”, by the interior-point algorithm. The lower and upper bounds on the control values are given in Table 1.

Table 1. Upper and lower bounds for the control parameters

Parameter	Min	Max
T	50 Nm	1500 NM
Rpm	5 revolutions/min	240
Wob	200 kg	5000 kg

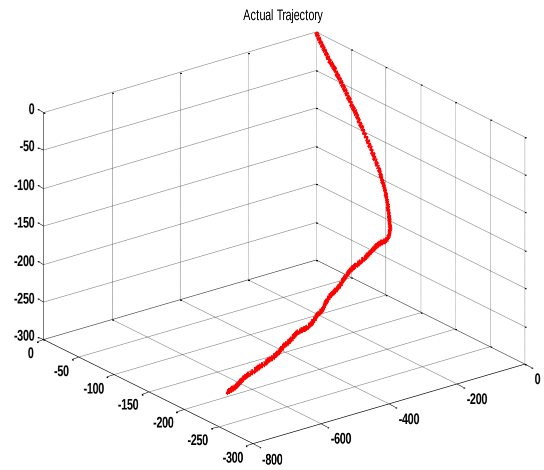

Fig. 4. Optimized well bore trajectory.

Table 2. Nomenclature

ROP	Rate of penetration
$w_b(k)$	Measured depth = hole length up to the kth point.
$\hat{w}_b(k+1)$	Predicted hole length at the end of the kth+1 interval.
$\dot{w}_b(k)$	Rate of penetration (in m/sec) during the kth interval
MSE	Mechanical Specific Energy
RSE	Rock Specific Energy
DD	Directional Drilling
DSS	Directional Steering System
RSS	Rotary Steerable System
Wob	Weight on bit
Pt(k+1)	Target position at the end of the kth+ interval
PE(k)	Vector of the current position of the BHA
BHA	Bottom Hole Assembly
MD	Measured depth, the length of the well bore

5. Conclusion

The paper presents an approach for real-time drilling optimization, which combines the conventional drilling parameters as well as the directional steering control. The objective function compromises between trajectory tracking accuracy, drilling effort, and drilling time. The optimization problem can be solved subject to operations limits and constraints using constraint optimization techniques.

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