Head-target tracking control of well drilling

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Abstract. The method of directional drilling trajectory control for oil and gas wells using predictive models is considered in the paper. The developed method does not apply optimization and therefore there is no need for the high-performance computing. Nevertheless, it allows following the well-plan with high precision taking into account process input saturation. Controller output is calculated both from the present target reference point of the well-plan and from well trajectory prediction with using the analytical model. This method allows following a well-plan not only on angular, but also on the Cartesian coordinates. Simulation of the control system has confirmed the high precision and operation performance with a wide range of random disturbance action.

1. Introduction
Achievements in petroleum geology development depend on the elaboration of up-to-date ideas and methods. Zapivalov N.P. [1] proposes focusing present efforts on two main development directions: the efficient well-targeted development of the active oilfields in order to provide for the production of the residual (hard-to-extract) oil in a soft, sparing and non-damaging way, as well as on discovering new hydrocarbon accumulations, including secondary ones, throughout the whole stratigraphic section in regions where a well-developed diversified infrastructure is already available.

The case of an unexpected deviation of the actual well trajectory from the well-plan is most often considered when estimating the various methods quality of the well trajectory control. Geometric methods [2] are often applied to control the well trajectory, actually re-designing the well-plan (i.e. a new program trajectory calculating) while leaving some points and sections of the previous well-plan unchanged. The disadvantage of such methods is the ignoring of random disturbances, leading to deviation from the program trajectory.

Halliburton employees, Liu Z. et al. [3], consider the "smoothness" of the well trajectory as important. They developed the new minimum-energy criterion to quantify better the complexity of well trajectories and named it the well-profile energy, depending on both the 3-D curvature of the well trajectory and its torsion, since both complicate the construction and operation of wells, and also worsen the technical condition of the pumping equipment. Liu Z. et al. demonstrate the advantages of the minimum-energy method vs. Proportional-Integral-Derivative (PID) control, which typically has some control fluctuation - and this, of course, worsens the tortuosity of the well trajectory [4]. Approaches to the parametric design of PID-controller according to required fluctuation ratio are presented in [5]. Unfortunately, permanently acting random disturbances are ignored during simulation of the control according to this minimum-energy criterion, which can lead to the control advantage loss and to decrease its quality.
Following the well-plan profile without re-designing the program trajectory is another often used method for the well trajectory control, which is especially important for rotary steerable system RSS. This system has a lot of advantages. For example, Novoseltsev D.I. et al. [6] have analyzed the experience of using the RSS and concluded that the average mechanical penetration rate is about 16 m./s. using the RSS, which is twice as large as the traditional technology using screw downhole motor (PDM). Nevertheless, the efficiency of using the RSS is less significant in the total well construction cycle, including round-trip operations RTO, cementing operations, etc., especially since the author himself notes the cases in which the using the PDM is preferable to RSS. In addition, the drilling system with PDM are also able to follow the well-plan in the combined drilling mode without changing the BHA, in which the straight profile section drilling in the "rotary" mode exchanges the curved section drilling in the "sliding" and "rotary" modes.

2. Relevance
The efficiency, high precision and performance with large random disturbances affect, etc. are required from the well trajectory control system. Geometric methods of control search use the BHA motion model with a constant curvature along the 3-D arc in reality and allow one to draw a well trajectory on a paper sheet or on a computer screen visually. Such control is calculated only from angular variables often (i.e. Cartesian coordinates are ignored), control search is entrusted to the operator, so the control system does not offer any options for control programs. Unfortunately, the control program is not corrected with large disturbances affects, therefore control precision is worsened while drilling. The classical model predictive control MPC of well trajectory uses the parameter identification for the dynamic model of the drilling tool movement, as well as precision consideration of several hundred, or even thousands of possible well trajectories simulated during the optimization [7, 8]. Therefore, such a full MPC implementation requires a large amount of mathematical calculations and a high-performance computer. The Model predictive control loses its main advantages under large random disturbance conditions, and its efficiency decreases to the level of simple linear controllers. At the same time, the program control system uses information about the well-plan (the program for setting-point value changing), and this makes it possible to use this information for the control calculation directly, which increases control precision, certainly. Summarizing the above mentioned facts, it can be concluded that studies aimed at the development of a simplified (not requiring a large amount of calculations) well trajectory control under large disturbance conditions with high precision are very relevant.

3. Development of well trajectory control system
Under these circumstances, it is necessary to develop a simple follow-up control system for directional drilling, using trajectory models and linear MPC-controllers, but without multi-iteration optimization, so one can determine the actual control values even on a calculator. The directed drilling control system developed earlier [8] did not use the directional survey receiving delay in simulation. This delay of steel drill pipe length ($\Delta l = 12.5$ m.) affects on the bottom-hole prediction precision (the dependence increases under large disturbances), and, therefore, must influence the actual control calculation. The application of a nonlinear fuzzy-logic controller improves the control quality slightly if a control with the actual deviation of the angular and Cartesian coordinates feedback is used [7]. There is known attempt to develop the fuzzy-logic control system of the well trajectory with the joint-control variables calculation by use of the trend angle, deviation vector, and deviation-vector-change rate [9]. Unfortunately, this attempt ignores random disturbances and the nonlinearity of the control action. Cockburn C B et al. [10] and Matheus J et al. [11] have developed Automatic Trajectory-Control Algorithm for Rotary Steerable Systems that shows high precision, accuracy and robustness. The developed control strategy implemented in two control loops; one that controls the inclination, and a second that controls the azimuth. Pirovolou D et al.[12] rightly state that angular control does not guarantee that the well will be tracking the plan. They developed an automatic trajectory control system using angular and Cartesian coordinates. Field tests demonstrated good results of the tracking
control system as a real-time application. Unfortunately, the system uses target inclination and azimuth only, not target Cartesian coordinates.

The simulation approach for the control system quality estimation has been developed earlier [7, 13]: the trajectory section for the simulation has initial values of the azimuth and zenith angles equal to 0 and 90 deg. respectively. This approach allows one to adjust the controller parameters correctly without additional 3-D calculations using.

The simulation characteristics for estimating the control system quality are as follows:
- the control purpose is to return to the well-plan and then to follow it while determine (up to 0.05 deg./m.) and random (up to 0.1 deg./m.) curvature disturbance action;
- the bottom-hole telemetric system measures the azimuth and zenith every $\Delta l = 12.5$ m. sample, but at a distance of 12.5 m. from the bit (BHA non-measure length).
- bottom hole assembly (BHA) with a $\gamma = 2$ deg. bit-tilt angle of the downhole positive-displacement motor (PDM) adjusting unit forms a well trajectory. This bit-tilt angle value provides a maximum average curvature of 0.15 deg./m. (and cannot exceed it) on section $\Delta l$ with the maximum 75/25 ratio of sliding/rotary intervals. Therefore, the average 3-D curvature on section $\Delta l$ is increasing in the range from 0 to 0.15 deg./m. while the sliding/rotary intervals ratio is increasing in the range from 0/100 to 75/25 values and cannot go beyond these limits. This determines the essentially nonlinear feature of the drilling process input, which is especially important in case of the large disturbance affects. Let us note that the drilling process input nonlinearity is the "saturation" kind.
- each step $\Delta l$ begins with the calculation of control values represented by control operator, $G(l) = \{\phi; (S/R)\}$ (for example, $G(450) = \{15\text{deg.}; (30\% / 70\%)\}$ is the control operator for the well depth of 450 m., which requires the $S = 30\%$ part of step length $\Delta l$ to be drilled in the "sliding" mode with the BHA toolface stabilization of $\phi = 15$ deg., and then the $P = 70\%$ part to be drilled in the rotary mode: in this instance, there is no need for toolface stabilization).
- errors of BHA tool-face orientation in the "sliding" mode and its effect to the average curvature decrease at step $\Delta l$ are not considered separately, and are included in random disturbances composition.

4. Control system simulation
The model of the MIMO (Many Inputs – Many Outputs) control system, developed in the Matlab Simulink and presented in figure 1, includes main subsystems:
- MIMO Control Object drilling process;
- dual-channel Control_X and Control_Y controllers;
- dual-channel Project well-plan with previos, actual and ahead-target coordinates;
- dual-channel Predict_X and Predict_Y bottom-hole predictions;
- MIMO Gamma Saturation control restriction;
and additional units:
- ToolFace calculation unit (BHA orientation);
- Gamma_Delay_X and Gamma_Delay_Y delay units;
- Discrete_X and Discrete_Y $\Delta l$-step sampling units;
- FI, Dimention, Dimention_Error trend displays of ToolFace, state variables and control error, etc.

2-D and 3-D well trajectories with a length of 200-2000 m were simulated to adjust controller parameters. Control of well drilling for standard initial deviations in the direction of $\pm 2$ deg. range and in Cartesian coordinates of $\pm 2$ m. range, as well as nonstandard initial deviations in the direction of $\pm 10$ deg. range and in Cartesian coordinates of $\pm 10$ m. range, was analyzed. The control length of wellbore (length of return to well-plan) and the total control error of the following well-plan in Cartesian coordinates was estimated, as well as the control error dependence on the constant (up to 0.05 deg./m.) and random (up to 0.1 deg./m.) curvature disturbances was estimated too.

The control 3-D simulation of the zenith increasing section with the 0.1 deg./m. constant curvature corresponds to the often performed task of real drilling.

The drilling of this well-plan section was simulated to estimate the MIMO control system
efficiency for the following situation: BHA was oriented in the 90 deg. azimuth direction incorrectly (instead of the 0 deg. well-plan azimuth direction) on the kickoff section from 0 deg. to 2.5 deg. zenith (this required 25 m section drilling at 0.1 deg./m well-plan curvature) due to fault of directed drilling engineer. As a result, the well trajectory has shifted by 0.55 m. in the 90 deg. azimuth direction. At the next stage, the control system corrected the well trajectory while drilling, and the control quality was estimated.

Figure 1. The model of the directed drilling control system.

The well drilling has been simulated to estimate the control quality with the action of constant (0.5 deg/m) and random (up to 0.1 deg/m) curvature disturbances. Plots of simulated control actions and the total dynamic control error are shown in figure 2. The drilling simulation has proved the high quality of the developed control system: it has provided the error of following the well-plan less than 0.3 m.

Figure 2. Control quality charts: A - total control error in Cartesian coordinates, (m.); B - average curvature in steps $\Delta l = 12.5$ m., (deg./10m.); C – BHA ToolFace angle $\varphi$, (rad.).
The plot shows that the control system has returned the well trajectory to the well-plan with 15 deg. zenith after approximately 125 m drilling section after the kickoff error. The drilling simulation has proved the efficiency of the MIMO control system, close to the optimal, because the zenith will increase to the 15 deg. value only after more than 100 m. of the drilling section, even if there will be the maximum possible average curvature of 0.15 deg./m., and there is still a need to correct the 2.5 deg. kickoff error on 90 deg. azimuth and this requires an additional almost 25 m. drilling section with the well-plan curvature. In any case, the control system provides drilling of the real well trajectory inside a curvilinear cylinder of the 0.3 m radius, placed around the well-plan.

5. Conclusion

Application of the developed method and algorithm will allow one to drill directional oil&gas wells precisely and to follow the well-plan with minimal deviations in conditions of a wide range of random disturbances. Even an Android-smart-phone computing performance allows one to provide the algorithm.

References

[1] Zapivalov N P 2016 J. Power industry of Tatarstan 2 54-61
[2] Mamedtagizade A M, Shmoncheva E E, Samedov V N and Dzhabbarova G V 2011 Improvement of mathematical model for horizontal well control during drilling Proc. of NIP J NEFTYANOE 4 32-35
[3] Liu Z and Samuel R 2016 Wellbore-Trajectory Control by Use of Minimum Well-Profile-Energy Criterion for Drilling Automation SPE Journal 21 02 449-458
[4] Samuel R and Liu X 2009 Wellbore tortuosity, torsion, drilling indices, and energy: What do they have to do with well path design? Proc. of SPE Annual Technical Conference and Exhibition 5 (Society of Petroleum Engineers) pp 2831-44
[5] Ayazyant 0, Novozhent 0 and Tausheve 0 2014 Proc. of XII Russian meeting of control issues VSPU-2014 (Moscow) pp 147-159
[6] Novoseltsev O I and Epikhin A V 2015 Proc. of Int. Conf. Modern problems of hydrogeology, geology engineering and hydrogeoecology in Eurasia (Tomsk) pp 628-632
[7] Vasilyev O I, Nugaev O F and Agzamov Z V 1995 Automatic control with prediction for autonomous robot-drill Proc. of 4th Int. Conf. on Intelligent Autonomous System (Karlsruhe) pp 461-464
[8] Alimbekov O I, Vasiliev O I, Nugaev O F, Agzamov Z V and Shulakov A S 2000 Computerized technologies for controlling inclined-directional drilling J. NEFTYANOE KHOZYAISTVO 12 120-122
[9] Xue Q, Wang R, Song W and Huang L 2012 Simulation Study on Fuzzy Control of Rotary Steering Drilling Trajectory Res. J. Appl. Sci. Eng. Tech. 4 13 1862-67
[10] Cockburn C B, Matheus J and Dang K L P 2011 Automatic Trajectory Control in Extended Reach Wells Proc. of SPE Middle East Oil and Gas Show and Conf. (Society of Petroleum Engineers) 3 pp 2084-96
[11] Matheus J and Naganathan S 2010 Drilling automation: Novel trajectory control algorithms for RSS Proc. of SPE-IADC Drilling Conf. 1 (Society of Petroleum Engineers) pp 136-145
[12] Pirovolou D, Chapman C D, Chau M T, Arismendi H, Ahorukomeye M and Penaranda J 2011 Drilling automation: An automatic trajectory control system J. of Petroleum Technology 63(12) 84-87
[13] Nugaev O F 2006 J. Automation, telemechanization and communication in oil industry 5 14-18