Dynamic Control of 3D Directional Drilling Systems with State Estimation

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Summary. Directional drilling systems are used to drill boreholes with complex three-dimensional (3D) geometries into the earth's crust in order to access difficult-to-reach reservoirs. Current state-of-practice techniques can potentially generate undesired oscillations of the borehole, due to the nonlinear dynamics involving spatial delays. Based on a recently developed nonlinear model for directional drilling, we present a stabilizing observer-based control strategy that guarantees the avoidance of borehole oscillations, by only using orientation measurements available in practice. The effectiveness of this control strategy is evidenced via a simulation study for a realistic drilling scenario.

Introduction

Complex trajectories for deep boreholes can now be achieved using down-hole robotic actuators called Rotary Steerable Systems (RSS). However, oscillations of the borehole trajectory, known as borehole spiraling, often develops whether an RSS is used or not, see e.g. [1]. This spiraling effect is detrimental to the quality of the borehole. The oscillations reflect an instability of the directional drilling system. It is a result of a feedback from the stabilizers — short elements that center the BHA in the borehole — to the bit. Indeed, the direction of propagation of the borehole depends on the applied force and moment at the bit; they are affected not only by the action of the RSS but also by the deformed configuration of the BHA, which is constrained by the stabilizers to espouse the existing borehole. Figure 1 shows a schematic drawing of a directional drilling system. In this work, we develop a control strategy for 3D directional drilling systems, which 1) avoids the occurrence of borehole oscillations 2) relies only on available sensor measurements of the orientation of the down-hole steel pipe-section known as bottom-hole-assembly (BHA) and 3) guarantees robustness against key parameter uncertainty. These goals are difficult to achieve, since the underlying dynamics of the 3D model are highly complex due to the presence of nonlinearities, delays and the multivariable nature of the process. The main contribution of this research is the development of a control strategy which fulfills the previous goals, based on the model developed in [2], that captures the key dynamics that influence the borehole evolution.

Directional drilling model

The model used as a basis for control is presented as a set of nonlinear delay differential equations in terms of the (dimensionless) total length of the borehole from surface to the bit, ξ, which is considered as the independent variable. The delay nature of the system comes from the fact that the BHA has to fit in a borehole that has already been drilled. The variables to be controlled are the borehole inclination (Θ) and the borehole azimuth (Φ) at the bit. We derive a state-space representation of the system defining $x_\Theta = [\Theta, \langle\Theta\rangle_1, \langle\Theta\rangle_2]^T$ and $x_\Phi = [\Phi, \langle\Phi\rangle_1, \langle\Phi\rangle_2]^T$ as states, where $\langle i\rangle_j$, for $i = \Theta, \Phi$ and $j = 1, 2$, are the average inclination and azimuth of the system at the stabilizers. We use what is called a neutral bit walk model (see [3]) for which the delay differential equations are given as follows:

$$\begin{aligned}\begin{bmatrix} x'_\Theta \\ x'_\Phi \end{bmatrix} &= \begin{bmatrix} A_0 & 0 \\ 0 & A_0 \end{bmatrix}\begin{bmatrix} x_\Theta(\xi) \\ x_\Phi(\xi) \end{bmatrix} + \begin{bmatrix} A_1 & 0 \\ 0 & A_1 \end{bmatrix}\begin{bmatrix} x_\Theta(\xi_1) \\ x_\Phi(\xi_1) \end{bmatrix} + \begin{bmatrix} A_2 & 0 \\ 0 & A_2 \end{bmatrix}\begin{bmatrix} x_\Theta(\xi_2) \\ x_\Phi(\xi_2) \end{bmatrix} \\ &+ \begin{bmatrix} B_{0\Theta} & 0 \\ 0 & B_{0\Phi}(\Theta,\Theta') \end{bmatrix}\begin{bmatrix} \Gamma_\Theta \\ \Gamma_\Phi \end{bmatrix} + \begin{bmatrix} B_{1\Theta} & 0 \\ 0 & B_{1\Phi}(\Theta) \end{bmatrix}\begin{bmatrix} \Gamma'_\Theta \\ \Gamma'_\Phi \end{bmatrix} + \begin{bmatrix} BW \\ 0 \end{bmatrix},\end{aligned} \tag{1}$$

with output equations

$$y_\Theta = C_\Theta x_\Theta + D_\Theta \Gamma_\Theta + W_y, \tag{2a}$$

$$y_\Phi = C_\Phi x_\Phi + D_\Phi \frac{\Gamma_\Phi}{\sin\Theta}, \tag{2b}$$

and where ξ_1 and ξ_2 represent the spatial delay coordinates corresponding to the location of the stabilizers and $(\cdot)'$ is the derivative with respect to ξ. Matrices and vectors A_0, A_1, A_2, B_{0i} and B_{1i}, for $i = \Theta, \Phi$, are dependent on the configuration of the BHA and (except for $B_{0\Phi}$ and $B_{1\Phi}$) are constant. The terms W_y and W represent the influence of gravity. The control inputs of the system are represented by Γ_Θ and Γ_Φ, which are the RSS actuator forces affecting the inclination and azimuth, respectively. The structure of these equations may suggest decoupling of the inclination and azimuth states, nevertheless, vectors $B_{0\Phi}$ and $B_{1\Phi}$ depend on Θ, this dependency induces a unilateral nonlinear coupling.

Controller design

The main control objectives of the system are 1) to track a desired reference borehole trajectory ($\Theta_r(\xi)$ and $\Phi_r(\xi)$, defining the tracking error dynamics as $e_i = x_{ri} - x_i$, for $i = \Theta, \Phi$) and 2) having a favorable transient response (avoid

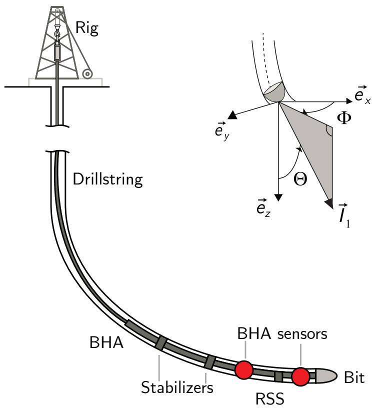

Figure 1: Schematic of a directional drilling system and inclination (Θ) and azimuth (Φ) angles of the bit measured from vector $\vec{I}_1$ tangent to the borehole axis with respect to the earth's fixed frame.

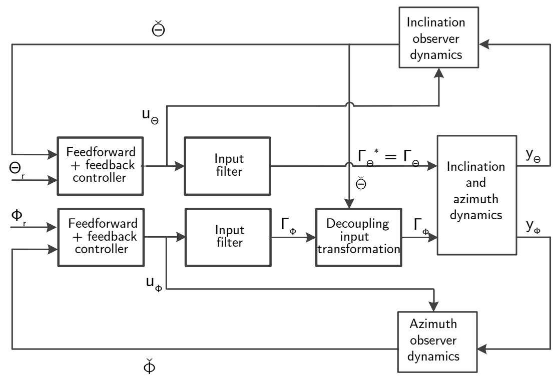

Figure 2: Closed-loop control strategy implemented to the directional drilling system.

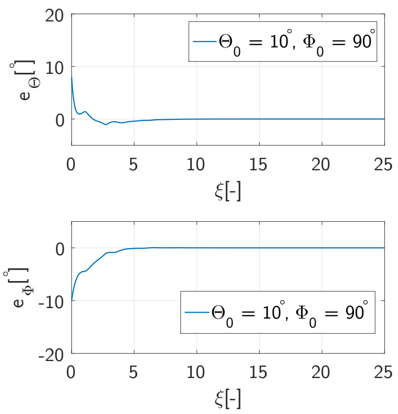

Figure 3: Tracking error response.

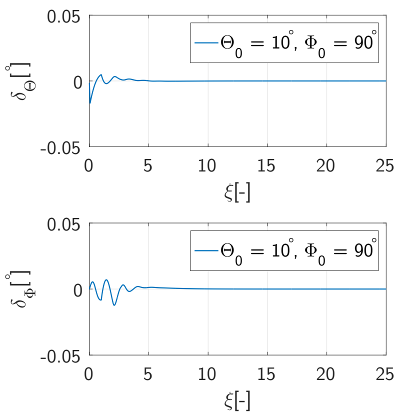

Figure 4: Observer error response.

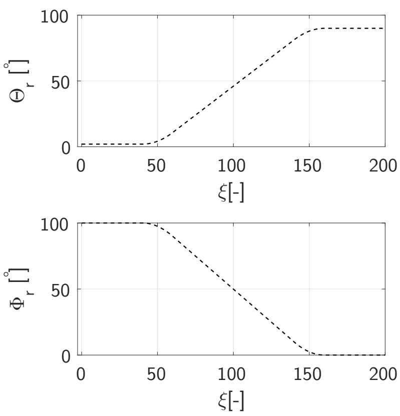

Figure 5: Reference Trajectory.

negative effects such as spiraling). Figure 2 shows a block diagram of the implemented closed-loop control strategy. The feedforward and feedback controller blocks deal with the solution of the reference tracking problem for both Θ and Φ, followed by an input filter which is used to cope with the presence of the derivative of the input in (1). We implement the decoupling input transformation of [3] to deal with the nonlinearities in the RSS-related input terms in (1). Finally, the observer blocks are used to provide the state estimates $\check{\Theta}$ and $\check{\Phi}$ of the system based on the measured outputs given by (2). The synthesis of the controller and observer gains was performed using an optimization-based pole placement technique for delay differential equations, applied to a linearization of the nonlinear tracking and observer error dynamics (defined as $\delta_i = x_i - \check{x}_i$, for $i = \Theta, \Phi$) around a steady-state solution associated to zero tracking and observer errors. This design guarantees the local asymptotic stability of the desired 3D borehole trajectory, while avoiding borehole spiraling. The tracking error response is shown in Figure 3, which shows that indeed a desired trajectory (Figure 5) is stabilized and that a fast transient response is achieved without borehole spiraling. Furthermore, Figure 4 shows that the observer error response has a rather small level of oscillations and converges to zero rapidly.

Conclusions

A dynamic output-feedback control approach for a three-dimensional drilling system has been proposed that enables the tracking of complex 3D borehole geometries while avoiding undesired borehole spiraling behavior. Furthermore, the controller relies only on available measurements of the BHA orientation sensors.

References

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