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Dynamic state-feedback control of nonlinear three-dimensional directional drilling systems

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Abstract: Directional drilling systems generate complex curved boreholes in the earth's crust for the exploration and harvesting of oil, gas and geothermal energy. In practice, boreholes drilled with such systems often show instability-induced borehole spiraling, which negatively affects the borehole quality and increases drag losses while drilling. This paper presents a dynamic state-feedback controller design approach for the stable generation of complex, three-dimensional borehole geometries, while avoiding undesired borehole spiraling. The design is based on a model for three-dimensional borehole propagation in terms of nonlinear delay differential equations. After casting the problem of borehole propagation into a tracking problem, it is shown that complex, three-dimensional borehole geometries can be asymptotically stabilized with the proposed controller. The effectiveness of the proposed approach is evidenced in an illustrative benchmark study.

Keywords: Directional drilling, tracking control, nonlinear systems, delay differential equations.

1. INTRODUCTION

The exploration and harvesting of hard-to-reach underground energy resources (such as oil, gas and geothermal energy) requires drilling complex curved boreholes. Directional drilling systems, including down-hole robotic systems known as rotary steerable systems (RSS), are used for this purpose. This work aims at the development of novel strategies for the control enabling three-dimensional borehole generation using such an RSS actuation mechanism.

Experimental evidence has shown that state-of-practice directional drilling (control) techniques can induce borehole oscillations, see e.g Marck et al. (2014). These oscillations in the borehole geometry are undesirable as they 1) compromise borehole stability, 2) reduce drilling efficiency), 3) reduce target accuracy, 4) make it more difficult to insert the borehole casing to prepare for production, and 5) reduce the rate-of-penetration (i.e. the speed of the drilling process). In this work, we aim to develop a model-based controller synthesis approach, which enables the drilling of complex three-dimensional (3D) borehole geometries while preventing borehole spiraling.

Several works exist on the topic of the control of directional drilling processes. In Panchal et al. (2012), controllers are developed based on empirical models of the borehole propagation process, in which a direct link between the force applied by the RSS and the curvature of the borehole is assumed. This approach ignores (physically relevant) transient behavior of the borehole propagation, which is essential in preventing borehole spiraling. In Bayliss and Matheus (2009), a state-space model for borehole propagation is derived and on the basis of this model, a controller is designed. However, the essential delay nature of the borehole propagation dynamics (see Neubert and Heisig (1996); Downton (2007); Perneder (2013)) is not captured in this model. In Sun et al. (2011), an $\mathcal{L}_1$ adaptive controller is designed, based on the directional drilling model of Downton (2007). In Kremers et al. (2015), a robust output-feedback approach for inclination control is proposed based on the model in Perneder (2013); Detournay and Perneder (2011).

All of the above control approaches focus on *two-dimensional* directional models, in which only the inclination dynamics is investigated. However, in practice complex *three-dimensional* borehole geometries need to be generated. Hence, control strategies applicable to three-dimensional directional drilling models are required that avoid undesired borehole spiraling effects. Compared to the two-dimensional case studied in the literature above, this is challenging due to the fact that existing three-dimensional models for directional drilling are described in terms of rather complex, multi-variable, nonlinear delay differential equations (DDEs).

The main contribution of this work is the development of a design strategy for controllers for three-dimensional direc-

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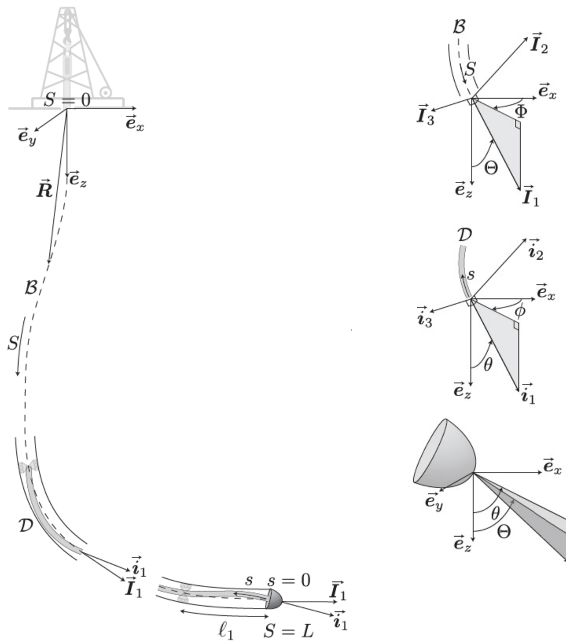

Fig. 1. Geometric description of the directional drilling system (left), borehole (top right), Bottom-Hole-Assembly (right middle) and bit (bottom right) (Perneder (2013)).

tional drilling systems. More detailed contributions are as follows. Firstly, the proposed method is based on a closed-form model description for three-dimensional borehole propagation, as proposed in Perneder (2013); Perneder and Detournay (2013b,a), which captures the essential, physically relevant, behavior of a three-dimensional directional drilling system. Secondly, unlike existing control methods, with Kremers et al. (2015) as an exception, the goal of the controller synthesis method is to design a controller which reduces borehole spiraling and prevents oscillations in the transient closed-loop response (both of which are detrimental to borehole quality). Thirdly, the proposed controller effectively deals with the nonlinear coupling between the inclination and azimuth dynamics characteristic to the dynamics of three-dimensional borehole propagation. Fourthly, a control strategy is proposed in which two identical and decoupled controllers for the inclination and azimuth dynamics are used, which simplifies the design and alleviates the burden of practical implementation.

2. 3D DIRECTIONAL DRILLING MODEL

As a basis for controller synthesis, we employ a three-dimensional, nonlinear model for directional drilling as developed in Perneder (2013); Perneder and Detournay (2013b,a). The schematic in Figure 1 (left figure) reflects that the directional borehole propagation process is primarily determined by the Bottom-Hole-Assembly (BHA), being the lowest part of the drill-string, which is laterally stabilized in the borehole by so-called stabilizers, and by the bit and rock properties. Figure 2 illustrates that the model comprises three main components. Firstly, the forces and moments acting on the bit are obtained by modeling the deformation of the BHA inside the borehole. Since the BHA is constrained in the borehole by the stabilizers in contact with the borehole wall, see Figure 1, the existing borehole geometry affects the forces and moments on the bit in a spatially delayed manner. Secondly, the bit-rock interface law determines how these forces and moments on the bit are related to the penetration of the bit into the rock. Finally, the bit motion is related to the propagation of the borehole geometry through kinematic relationships.

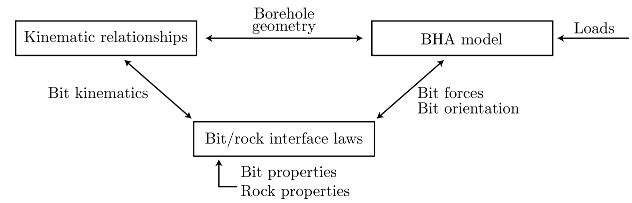

Fig. 2. Three components of the model and their interaction (Perneder and Detournay (2013b)).

2.1 Borehole evolution equations

This nonlinear model involves evolution equations for two angles fully describing the 3D borehole geometry: the borehole inclination Θ and the borehole azimuth Φ, as defined in Figure 1:

$$\eta\Pi\Big((\theta-\Theta)\cos\varpi+\sin\Theta\sin\varpi\,(\phi-\Phi)\Big)=\mathcal{F}_b\left(\theta-\langle\Theta\rangle_1\right)$$

$$+\mathcal{F}_w\Upsilon\sin\langle\Theta\rangle_1+\mathcal{F}_r\Gamma_\Theta+\sum_{i=1}^{n-1}\mathcal{F}_i\left(\langle\Theta\rangle_i-\langle\Theta\rangle_{i+1}\right), \quad (1a)$$

$$-\chi\Pi\theta'=\mathcal{M}_b\left(\theta-\langle\Theta\rangle_1\right)+\mathcal{M}_w\Upsilon\sin\langle\Theta\rangle_1+\mathcal{M}_r\Gamma_\Theta$$

$$+\sum_{i=1}^{n-1}\mathcal{M}_i\left(\langle\Theta\rangle_i-\langle\Theta\rangle_{i+1}\right), \quad (1b)$$

$$\eta\Pi\left(-\frac{(\theta-\Theta)\sin\varpi}{\sin\Theta}+\cos\varpi\,(\phi-\Phi)\right)=\mathcal{F}_b\left(\phi-\langle\Phi\rangle_1\right)$$

$$+\mathcal{F}_r\frac{\Gamma_\Phi}{\sin\Theta}+\sum_{i=1}^{n-1}\mathcal{F}_i\left(\langle\Phi\rangle_i-\langle\Phi\rangle_{i+1}\right), \quad (1c)$$

$$-\chi\Pi\phi'=\mathcal{M}_b\left(\phi-\langle\Phi\rangle_1\right)+\mathcal{M}_r\frac{\Gamma_\Phi}{\sin\Theta}$$

$$+\sum_{i=1}^{n-1}\mathcal{M}_i\left(\langle\Phi\rangle_i-\langle\Phi\rangle_{i+1}\right). \quad (1d)$$

In (1), $(\cdot)'$ indicates a derivative with respect to the (dimensionless) length of the borehole $\xi := L/l_1$ with L the length of the borehole and l_1 the distance between the bit and the first stabilizer, see Figure 1. Note that the independent variable in the model in (1) is the dimensionless spatial variable ξ. The variables θ and ϕ indicate the inclination and azimuth of the BHA, which differ from that of the borehole due to deformation of the BHA, see Figure 1. All angle variables in (1) are evaluated at the bit (in Figure 1 such variables are indicated with the ˆ symbol, which is omitted here for the sake of transparency). In (1), the average inclination and azimuth of the borehole in the i-th BHA segment (the segment between the $i-1$-th and i-th stabilizer, with $i = 0$ indicating the bit) are given respectively as:

$$\langle\Theta\rangle_i := \frac{1}{\lambda_i}\int_{\xi_i}^{\xi_{i-1}}\Theta(\sigma)d\sigma,\ \langle\Phi\rangle_i := \frac{1}{\lambda_i}\int_{\xi_i}^{\xi_{i-1}}\Phi(\sigma)d\sigma, \quad (2)$$