# Multivariate Nonlinear Model Predictive Controller for Managed Drilling Processes



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### Introduction

Why drilling automation and control?

- Extracting oil is more challenging with tighter formations and harsher environments
- Drilling is a very costly process, reduced drilling time means significantly less cost
- Improve the safety, automatically attenuate abnormal conditions with a preventative versus reactive approach
- Improved sensors and data transfer rate, e.g. wired pipe drilling





# Managed Pressure Drilling





Known variables:

- Surface measurements
- Downhole RPM, WOB
- Annulus pressure (mud pulse / wired pipe)

Unknown variables in annulus:

- Density (annulus)
- Friction Factor (annulus)
- Gas influx flow rate
- Drilling fluid flow rate (downhole)





#### **Previous Research**



- Pressure and ROP control and optimization as two separate applications
- Estimation of downhole pressure instead of direct measurements

#### Innovation



- Interaction between drillstring and hydraulics
- Quantify benefit of direct downhole pressure measurements (wired drillpipe)

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# Model Components

- Pressure Hydraulics: Lower order model (Stames et al.)
  - 4 state equations:
    - Mud pump pressure (pp)
    - Choke valve pressure (pc)
    - Drill bit flow rate (qbit)
    - Drilling height (h)

$$\dot{p_p} = f_1(q_{pump}, q_{bit})$$

 $\dot{p_c} = f_2(q_{bit}, q_{choke}, q_{influx}, ROP, q_{back})$ 

$$q_{bit} = f_3(p_p, p_{bit}, q_{bit}, h)$$

$$\begin{split} \dot{h} &= ROP \\ p_{bit} &= p_c + \rho_a F_a |q_{bit} + q_{res}| (q_{bit} + q_{res})h + \rho_a gh_{bit} \\ p_i - p_{i+1} &= \rho_{a,i} F_{a,i} |q_{bit} + q_{res}| (q_{bit} + q_{res})(h_i - h_{i-1}) + \rho_{a,i} g(h_{v,i} - h_{v,i-1}) \end{split}$$

- ROP: Bourgoyne & Young model
  - 8 functions:
    - Formation strength
    - Pressure differential of bottom hole
    - Formation compaction
    - Bit diameter and weight
    - Rotary speed
    - Tooth wear
    - Hydraulics

$$ROP = exp\left(a_1 + \sum_{i=2}^8 a_i x_i\right)$$



**Drill String Dynamics** 

series

**BYU** 

- First order plus dead time model
  - Surface WOB -> Downhole WOB

Johannessen, M.K. and T. Myrvold

Multiple mass-spring-damper pendulums in

- Rotation Speed (RPM) effect on Friction Factor
  - Fluid and cuttings rotational movement
  - Affect hydrostatic head downhole •
  - Ozbayoglu et al. model •

$$Re_{a} = \frac{757 \rho v_{a} (D_{o} - D_{i})}{\mu_{a}}$$
Velocity in Axial Direction

$$f_a = a \, Re^b_{axial} + c \, Re_{angular}$$

 $\frac{2.025 \,\rho \, RPM \,(D_o - D_i) \,D_i}{2.025 \,\rho \, RPM \,(D_o - D_i) \,D_i}$  $Re_{\omega} =$  $\mu_{\omega}$ Rotation Speed of Drill String







# **Kick Attenuation Mode**





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# **Control and Estimation**



#### Nonlinear Model predictive controller and Moving Horizon Estimator

- Objective function:  $\ell$ 1-norm

$$\begin{split} \min_{x,y_m,u} \Phi &= w_{hi}^T e_{hi} + w_{ho}^T e_{lo} + y_m^T c_y + u^T c_u + \Delta u^T \\ s.t. \quad 0 &= f(\dot{x}, x, u, d) \\ 0 &= g(y_x, x, u, d) \\ a &\geq h(x, u, d) \geq b \\ \tau_c \frac{\delta y_{t,hi}}{\delta t} + y_{t,hi} &= sp_{hi} \\ \tau_c \frac{\delta y_{t,lo}}{\delta t} + y_{t,lo} &= sp_{lo} \\ e_{hi} &\geq (y_m - y_{t,hi}) \\ e_{lo} \geq (y_{t,lo} - y_m) \end{split}$$

- Orthogonal collocation on finite elements for DAE to NLP conversion
- Active set Method or Interior Point Optimization Method

#### **Moving Horizon Estimator**

- Estimates the values of densities in the annulus

#### **Extended Kalman Filter**

- Estimates the gas influx flow rate



# L1 norm vs. Squared Error



**Squared** Error

<u>ℓ1-norm</u>





# **Results - Normal Drilling**





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# **Results – Kick Attenuation**





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### Conclusion



### **Multivariate Nonlinear Controller**

- Estimation (MHE and EKF) and optimizing control (NMPC)
- Regulating pressure and ROP simultaneously

### **Enhanced Economics**

- Higher ROP
- Less ROP fluctuations

### **Enhanced Safety**

- Improved gas influx attenuation





#### We appreciate the support of National Oilwell Varco



#### SPE/IADC SPE-168953-MS

#### Addressing UBO and MPD Challenges with Wired Drill Pipe Telemetry

David S. Pixton, SPE, NOV IntelliServ; Reza Asgharzadeh Shishavan, Hector D. Perez, and John D. Hedengren, SPE, Brigham Young University; and Andrew Craig, SPE, NOV IntelliServ

#### SPE-170275-MS

#### Combined Rate of Penetration and Pressure Regulation for Drilling Optimization Using High Speed Telemetry

Reza Asgharzadeh Shishavan, SPE, Casey Hubbell, SPE, Hector D. Perez, SPE, John D. Hedengren, SPE, Brigham Young University, David S. Pixton, SPE, NOV IntelliServ

#### SPE 170962

### Multivariate Control for Managed Pressure Drilling Systems Using High Speed Telemetry

Reza Asgharzadeh Shishavan, SPE, Casey Hubbell, SPE, Hector D. Perez, SPE, John D. Hedengren, SPE, Brigham Young University, David S. Pixton, SPE, NOV IntelliServ, Anthony P. Pink, NOV





# **Thank You For Your Attention**

# **Questions ?**

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