Multivariate Nonlinear Model Predictive Controller for Managed Drilling Processes

Reza Asgharzadeh
Hector Perez
John Hedengren

Brigham Young University

18 Nov 2014
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)
Schematic of the MPD Controller

- **WOB MPC**
- **RPM MPC**
- **Main Mud Pump**
- **Choke Valve**
- **Back Pressure Pump**
- **Downhole RPM SP**
- **Downhole WOB SP**
- **Surface Measurements**
  - $\rho_a$, $f_a$
- **Estimator**
- **Gas Influx**
- **Pressure Controller**
- **ROP and RPM set point**
- **Operator Input**
- **ROP Optimizer**
- **Pressure set point**
- **Reservoir**
- **Downhole Pressure, WOB, RPM**

Multivariate nonlinear model predictive controller for managed drilling processes

Nov 18, 2014
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)

\[
p_p = f_1(p_{pump}, q_{bit})
\]
\[
p_c = f_2(q_{bit}, q_{choke}, q_{influx}, ROP, q_{back})
\]
\[
q_{bit} = f_3(p_p, p_{bit}, q_{bit}, h)
\]
\[
h = ROP
\]
\[
p_{bit} = p_c + \rho_a F_a |q_{bit} + q_{res}|(q_{bit} + q_{res})h + \rho_a g h_{bit}
\]
\[
p_i - p_{i+1} = \rho_a F_{a,i} |q_{bit} + q_{res}|(q_{bit} + q_{res})(h_i - h_{i-1}) + \rho_{a,i} g(h_{v,i} - h_{v,i-1})
\]

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

\[
ROP = \exp\left( a_1 + \sum_{i=2}^{8} a_i x_i \right)
\]
Model Components (Cont.)

- Drill String Dynamics
  - Multiple mass-spring-damper pendulums in series
  - Johannessen, M.K. and T. Myrvold

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

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

\[
R_{e_a} = \frac{757 \rho v_a (D_o - D_i)}{\mu_a}
\]

Velocity in Axial Direction

\[
R_{e_\omega} = \frac{2.025 \rho \text{RPM} (D_o - D_i) D_i}{\mu_\omega}
\]

Rotation Speed of Drill String

\[
f_a = a R_{e_{axial}}^b + c R_{e_{angular}}
\]
Kick Attenuation Mode

Normal Drilling Operation

\[ P_{bit} > Safety\ Margin + P_{sp} \text{ and } q_{influx} > 0 \]

Switch the controlled variable from downhole pressure into choke valve pressure and set the set point as

\[ P_{CSP} = P_{C\ before\ kick} + k_pE + k_I \int E + k_d \frac{dE}{dt} \]

\[ E = P_{bottom\ current} - P_{bottom \ sp} \]

Change choke valve opening, surface RPM and pump flow rate

Hold until \( q_{bit} < \) specified limit

Switch the controlled variable from choke valve pressure to downhole pressure

Nov 18, 2014
Nonlinear Model predictive controller and Moving Horizon Estimator

- Objective function: $\ell_1$-norm

$$
\min_{x, y_m, u} \Phi = w_{hi}^T e_{hi} + w_{lo}^T e_{lo} + y_m^T c_y + u^T c_u + \Delta u^T
$$

s.t.  
$$
0 = f(\dot{x}, x, u, d)
$$
$$
0 = g(y_x, x, u, d)
$$
$$
a \geq h(x, u, d) \geq b
$$

$$
\tau_c \frac{\delta y_{t, hi}}{\delta t} + y_{t, hi} = s p_{hi}
$$

$$
\tau_c \frac{\delta y_{t, lo}}{\delta t} + y_{t, lo} = s p_{lo}
$$

$$
e_{hi} \geq (y_m - y_{t, hi})
$$

$$
e_{lo} \geq (y_{t, lo} - y_m)
$$

- 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**

- **Clean Data**
  - Graph showing Annulus Mud Density vs. Time, s
  - The line is smooth with minor fluctuations.
- **Corrupted Data**
  - Graph showing Annulus Mud Density vs. Time, s
  - The line shows significant fluctuations indicating noise and outlier points.

**ε1-norm**

- **Clean Data**
  - Graph showing Annulus Mud Density vs. Time, s
  - The line is smooth with minor fluctuations.
- **Corrupted Data**
  - Graph showing Annulus Mud Density vs. Time, s
  - The line shows significant fluctuations indicating noise and outlier points.

**Deviation**

- **Clean Data**
  - **Noise** 5.93% dev.
  - **Outlier** 0.82% dev.
- **Corrupted Data**
  - **Noise** 1.67% dev.
  - **Outlier** 0.41% dev.
Results - Normal Drilling

- Comprehensive Controller Case
- Single ROP Controller Case

Drill Bit Pressure, bar

Choke Valve Pressure, bar

Density, kg/m³

Multivariate nonlinear model predictive controller for managed drilling processes
Results – Kick Attenuation

Multivariate nonlinear model predictive controller for managed drilling processes

Kick Attenuation

- Single Pressure Controller
- Comprehensive Controller
- Manual Control

Time, s

Gas influx, L/min

- Downhole RPM
- Surface RPM
- RPM Set Point

Time, s

Rotation Speed, RPM

- Downhole WOB
- Downhole WOB
- WOB Set Point

Time, s

Weight on Bit, lb

Time, s

Pump Flow Rate

Time, s

Pump Flow Rate, L/min
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 ?