High-Speed Data and High-Fidelity Models: Opportunities and Challenges in Well Manufacturing

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Why Automate Drilling?

• Benefits of Automated MPD
  • HSE—faster response to problems
  • Economic—operate closer to constraints, shorter drilling time, 
d    especially with challenging market conditions
  • Average of 4 uncontrolled well situations in the Gulf of Mexico each 
d    year (Morris, 2014)

• Benefits of Advanced Control
  • Optimized control resulting in greater accuracy and managing multivariate 
d    relationships than PID control
What are the Opportunities?

• High Fidelity Modeling (Model)
  • Wellbore Hydraulics
  • Drill String Dynamics

• Optimization Algorithms (Solve)
  • Computing hardware and optimization algorithms
    (MILP Benchmarks 1,000,000 times faster in 15 years)

• High Speed Drill String Telemetry (Measure)
  • Wired Drill Pipe
  • Real-time Sensing and Feedback Control
Advances in High Fidelity Models

• High Fidelity Modeling
  • Wellbore Hydraulics
  • Drill String Dynamics

Courtesy eDrilling
Advances in High Fidelity Models

- High Fidelity Modeling
- Wellbore Hydraulics
- Drill String Dynamics

Courtesy MSC Software
Advances in Optimization

- Estimate
  - Kalman Filtering
  - Moving Horizon Estimation
- Control
  - PID
  - Model Predictive Control
- Solvers and Models
  - Large-scale (100,000+ variables)
  - Differential Algebraic Equations
  - Nonlinear Programming

\[
\min_d \Phi = w_m^T(e_U + e_L) + w_p^T(c_U + c_L)
\]

subject to
\[
0 = f\left(\frac{\partial x}{\partial t}, x, u, p, d\right)
\]
\[
0 = g(y, x, u, d)
\]
\[
0 \leq h(x, u, d)
\]
Advances in Telemetry

Downhole Network Electronics Improvements
Surface Network Electronics Improvements
Coupler Reliability Improvements
Cable Reliability Improvements

- Toughened Coupler Assembly, Protected Location
- Enhanced Noise Monitoring and Management
- Elevated Shock and Vibration Robustness
- More Intimate Integration with 3rd Party Tools

Increased Corrosion Resistance
Low Coupler Stress (Externally Biased)
Rules Based Diagnostics and Recommended Actions
Smart Battery Controller

Smart Battery Controller

More Intimate Integration with 3rd Party Tools
Nonlinearity in MPD Process

Increasing mud pump flow

Typical Operation Range

Downhole Pressure (bar)

Choke Valve Opening (%)

Mud Flowrate (m³/min)
- 0.24
- 0.6
- 0.96
- 1.32
- 1.68
- 2.04
- 2.4
- 2.76
- 3.12
### Lower Order Models for Control

#### Control Overview

<table>
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<tr>
<th>Manipulated Variables</th>
<th>Controlled Variables</th>
<th>Estimated Variables</th>
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\[
\dot{p}_p = \frac{\beta_d}{V_d} (q_{pump} - q_{bit}) \\
\dot{p}_c = \frac{\beta_a}{V_a} (q_{bit} + q_{back} - q_{choke} + q_{res} - ROP) \\
p_{bit} = p_c + \left( \sum_{i=1}^{n-1} \rho_{ai} \times F_{ai} \right) |q_{bit} + q_{res}|(q_{bit} + q_{res})h + \rho_{a}g(h_{bit} - (n-1)h) \\
p_{an} = p_c + \sum_{i=1}^{n-1} \left( \rho_{ai} \times F_{ai} \times h |q_{i}| + \rho_{ai}g(h) \right) + \rho_{an} \times F_{an} \times h |q_{n}|(q_{n}) + \rho_{an}g(h) \\
q_{choke} = K_{c}Z_{choke} \sqrt{\rho_{an}(p_c - p_0)} \\
M_a = \rho_a \int_0^{l_w} \frac{1}{A_a(x)} \, dx \\
M_d = \rho_d \int_0^{l_{AN}} \frac{1}{A_d(x)} \, dx \\
M = M_a + M_d \\
\dot{q}_{bit} = \frac{1}{M} \left( p_p - F_d |q_{bit}|q_{bit} + \rho_d g h_{bit} - p_{bit} \right)
\]
Lower Order Model Match with WeMod (MHE)
PID and Model Predictive Control

Conventional (PID)

- **Input** (eg. Flow rate)
- **Output** (eg. Valve)

Advanced (MPC)

- Reference Trajectory
- Predicted Output
- Measured Output
- Predicted Control Input
- Past Control Input

https://en.wikipedia.org/wiki/Model_predictive_control
Simulated Pressure Control with MPC

Conventional (PID)

Advanced (MPC)
Exploit Multivariate Relationships in MPC for MPD

Single-Input-Single-Output

PID or MPC

\[ \text{CV}_1 \rightarrow \text{SP}_1 \rightarrow \text{PID or MPC} \rightarrow \text{MV}_1 \]

\[ \text{CV}_2 \rightarrow \text{SP}_2 \rightarrow \text{PID or MPC} \rightarrow \text{MV}_2 \]

Multi-Input-Multi-Output

Set point or Range

\[ \text{CV}_1 \rightarrow \text{SP}_1 \rightarrow \text{MPC} \rightarrow \text{MV}_1 \]

\[ \text{CV}_2 \rightarrow \text{SP}_2 \rightarrow \text{MPC} \rightarrow \text{MV}_2 \]

\[ \text{CV}_n \rightarrow \text{SP}_n \rightarrow \text{MPC} \rightarrow \text{MV}_n \]
Combine Flow and Drill String Models

Drilling parameters:
- Weight on Bit
- Rotation Speed
- Drill String
- Annulus

Flow diagram:
- Reservoir
- Choke Valve
- Drill String
- Back Pressure Pump
- Main Mud Pump
- Band-Limited White Noise
- Process
- Drilling
- Measured Values
- MHE
- MPC

Web resource:
[http://apmonitor.com/do](http://apmonitor.com/do)
Combine Flow and Drill String Models

**Pressure Hydraulics**
- Lower order model (Stamnes et. al)

**Interaction Between Drill String and Hydraulics**
- ROP depends on the downhole pressure (Bourgoyne and Young)
- Friction factor depends on axial and rotational flow
- Rotation Speed (RPM) effect on Friction Factor

**Drill String Dynamics**
- Drill String Dynamics
  - Multiple mass-spring-damper pendulums (Johannessen and Myrvold)
- WOB Dynamics
  - First order plus dead time model
  - Surface WOB -> Downhole WOB
Pressure Control and Rate Optimization

Choke Valve Opening
Pump Flow Rates
Pressure

Weight on Bit (WOB)
Rev per Minute (RPM)
ROP
Rate of Penetration (ROP)

Combined Controller
Rate of Penetration (ROP)
Downhole Pressure

Pressure Controller
Pressure

Single Pressure Controller
Comprehensive Controller
Manual Control
Pressure Control: Kicks and Connections

Connection Procedure:
• The controller is able to control the drill bit pressure +/- 3 bar

Kick Attenuation:
• Immediate action avoids more intrusive well control efforts
Challenges of Automation

• Automation systems can become unreliable if the control model is not calibrated or is not sufficiently accurate.

• Advanced nonlinear, predictive controllers can fail to converge and result in lost or poor control.

To address these challenges, an ensemble control structure maintains model accuracy and controller stability without interrupting the drilling process.
Enhanced Stability with Ensemble Control

• Consists of a supervisory switch and 3 model predictive controllers with distinct control models: empirical, low-order, and high fidelity

• A simple switching algorithm uses the high fidelity controller when available, the low-order next, and the empirical last
Advantages of Ensemble Control

• Robust and adaptive control
• Controller tuning and troubleshooting without interrupting drilling
• Addresses the issue of failed solver convergence
• Redundant control models have the same reliability benefits associated with redundant hardware

These benefits are demonstrated through an automated drilling simulation
Prove Controller Through Simulation

- Simulates a typical horizontal well at 7,054 ft. TVD
- Uses SINTEF high fidelity flow model
- Realistic noise, outliers, and drift added to well measurements used by the controller
Pressure Control Through Automation

• Normal drilling operations and a pipe connection procedure are simulated.

• Objective is to keep bit pressure within ±1 bar of 400 bar during normal drilling and within ±5 bar of 340 bar during a pipe connection procedure.

• Mud pump flow rate and choke pressure are adjusted to meet the objective.

http://www.rockstone-research.com
Seamless Switching During Normal Drilling

• At 10 and 20 minutes control is switched to the controller indicated.

• Despite model inaccuracies the bit pressure is kept within the target range.

• Switching between controllers is seamless.
Pressure Control During Pipe Connections

• When the mud pump is down, bit pressure measurements cease and *the controller only uses the model predictions for control*

• The unacceptable spikes in bit pressure are caused by the inaccuracy of the low-order model

• This demonstrates the need for *accurate model predictions*
Improved Control with High Fidelity Model

• Pipe connection using only the high fidelity controller

• The high fidelity controller predictions are sufficiently accurate to maintain the bit pressure within $\pm 5$ bar of the 340 bar set point with no bit pressure feedback measurements
Avoiding Formation Damage – US Land

- Operational Changes Managed with R/T Data
  - Pump startup
  - Fluid inconsistencies and uncertainties
  - Displacement of mud with foam
  - ECD and BHP monitored and managed in real-time
Closing the Loop – Offshore SE Asia

• Shallow high-pressure gas-bearing sands
• Required fast kick control response
• Required monitoring and control of BHP with pumps off
• Solution: MPD and control system with Wired Drill Pipe
• BHP Maintained:
  +/-15 psi (drilling), +/-45 psi (connections)
Closing the Loop – Latin America Land

- Risk Mitigation Enables Drilling
- Severely depleted reservoir, formation fluid influx in upper well sections, wellbore stability problems
- Required monitoring and control of BHP at all times, including pumps off
- Solution: MPD with Wired Drill Pipe
- BHP Control Improvements:
  - Data after pump shutdown
  - Multiple AP measurements improve model and refine choke control
  - Multiphase fluid model calibration
Conclusion

• Automation solution create significant value with high-speed, two-way communication

• Ensemble controller maintains model accuracy and controller stability without interrupting the drilling process

• Predictive control provides a robust and adaptive framework for automated drilling

• Next generation automation solutions build upon high-speed, real-time data and predictive models