Multivariate Nonlinear Model Predictive Controller for Managed Drilling Processes

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Introduction

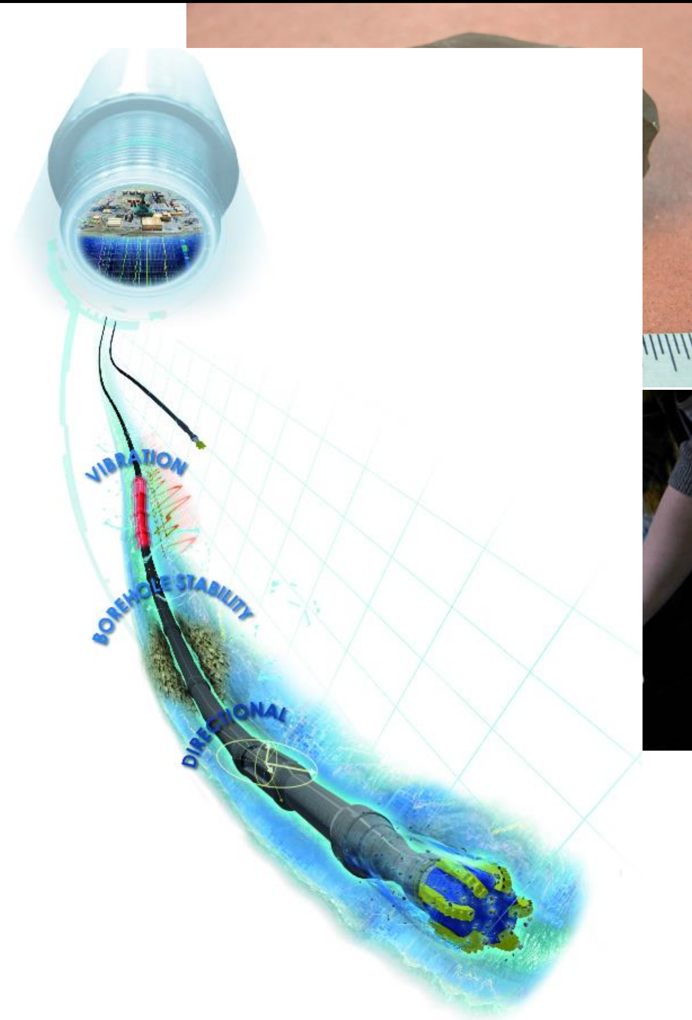
Why drilling automation and control?

- Extracting oil is more challenging with tighter formations and harsher environments

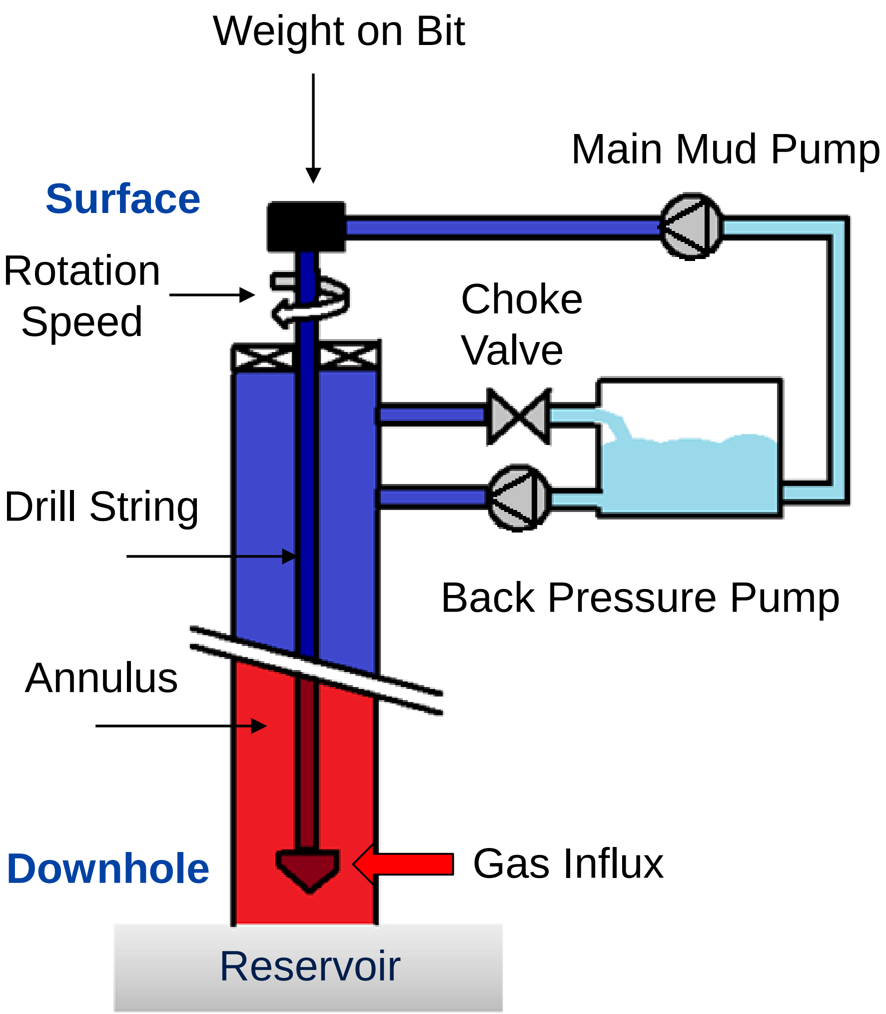
- Drilling is a very costly process, reduced drilling time means significantly less cost

- 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



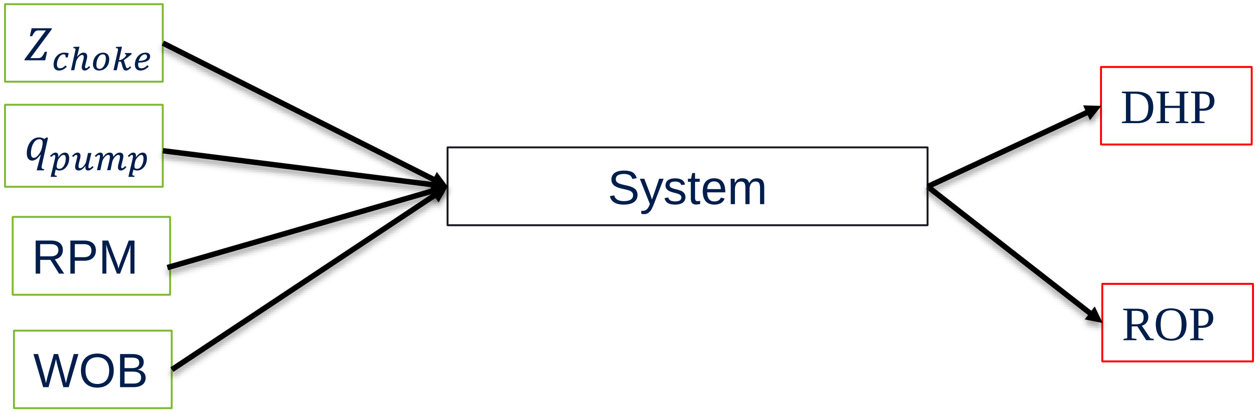
Known variables:
- Surface measurements
- Downhole RPM, WOB
- Annulus pressure (mud pulse / wired pipe)

Unknown variables in annulus:
- Density (annulus)
- Friction Factor (annulus)
- Gas influx flow rate
- Drilling fluid flow rate (downhole)

Previous Research

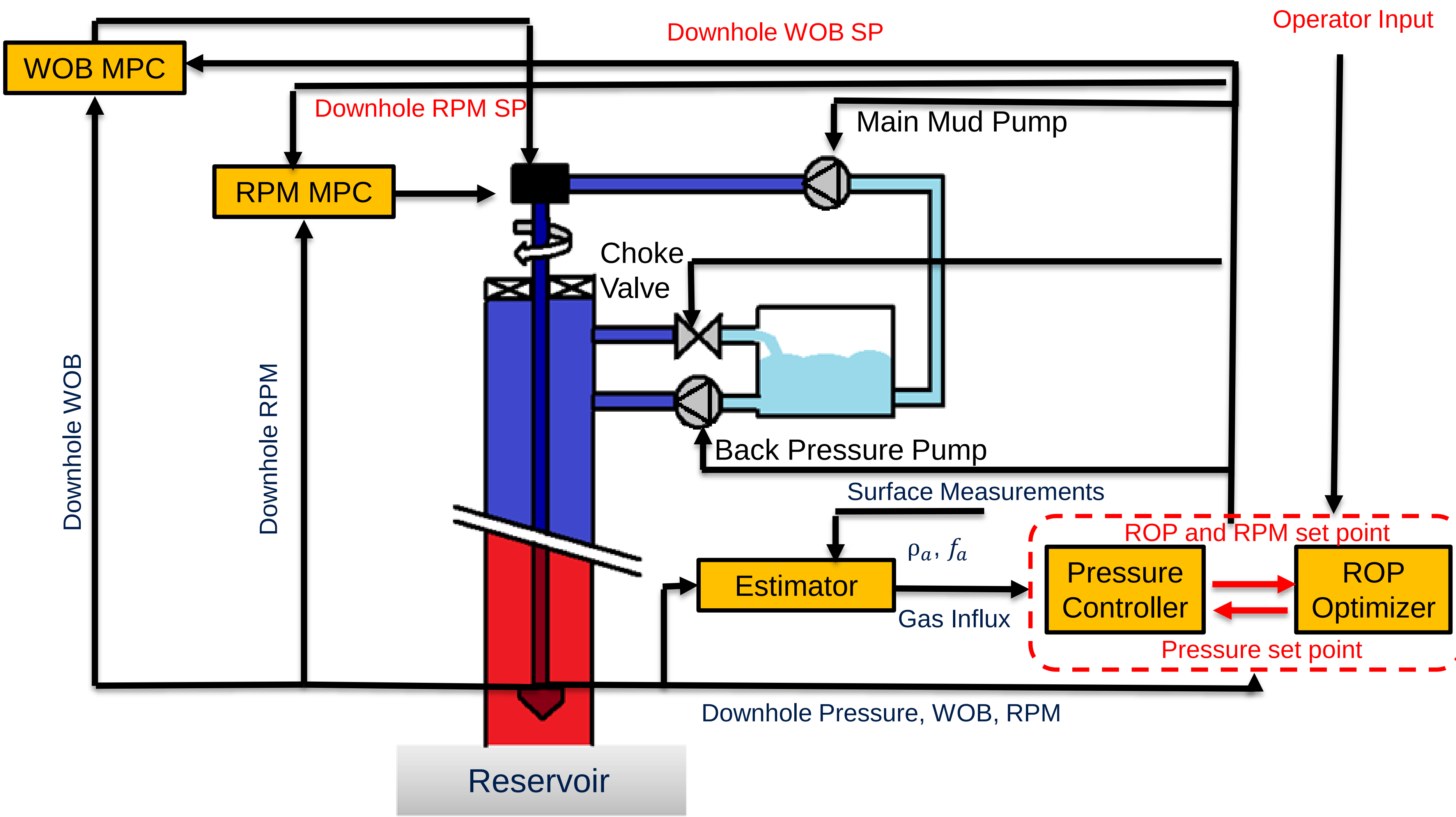
- Pressure and ROP control and optimization as two separate applications
- Estimation of downhole pressure instead of direct measurements

Innovation



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

Schematic of the MPD Controller



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)

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

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

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

$$\dot{h} = ROP$$

$$p_{bit} = p_c + \rho_a F_a |q_{bit} + q_{res}|(q_{bit} + q_{res})h + \rho_a g h_{bit}$$

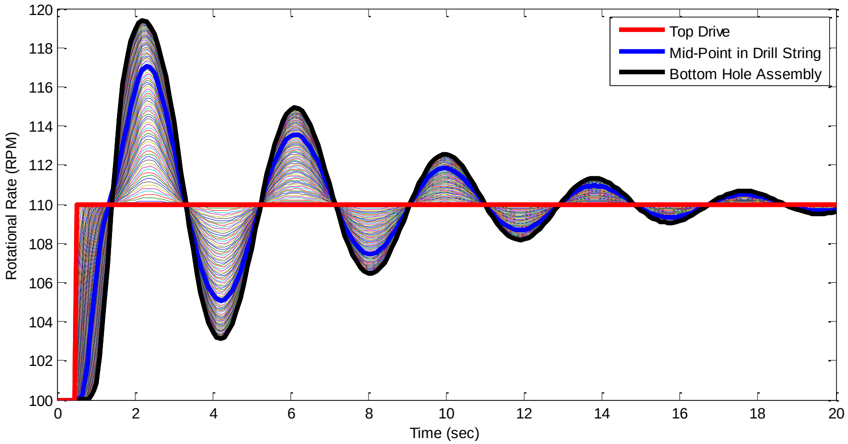
$$p_i - p_{i+1} = \rho_{a,i} F_{a,i} |q_{bit} + q_{res}|(q_{bit} + q_{res})(h_i - h_{i-1}) + \rho_{a,i} g (h_{v,i} - h_{v,i-1})$$

- 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 Facto
  - Fluid and cuttings rotational movement
  - Affect hydrostatic head downhole
  - Ozbayoglu et al. model



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

$$Re_a = \frac{757\, \rho\, v_a\, (D_o - D_i)}{\mu_a}$$

Velocity in Axial Direction

$$Re_\omega = \frac{2.025\, \rho\, RPM\, (D_o - D_i)\, D_i}{\mu_\omega}$$

Rotation Speed of Drill String

Kick Attenuation Mode

Normal Drilling Operation

$P_{bit} > Safety\ Margin + P_{sp}$ and $q_{influx} > 0$

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

$$P_C^{SP} = P_C^{before\ kick} + k_p E + k_I \int E + k_d \frac{dE}{dt}$$

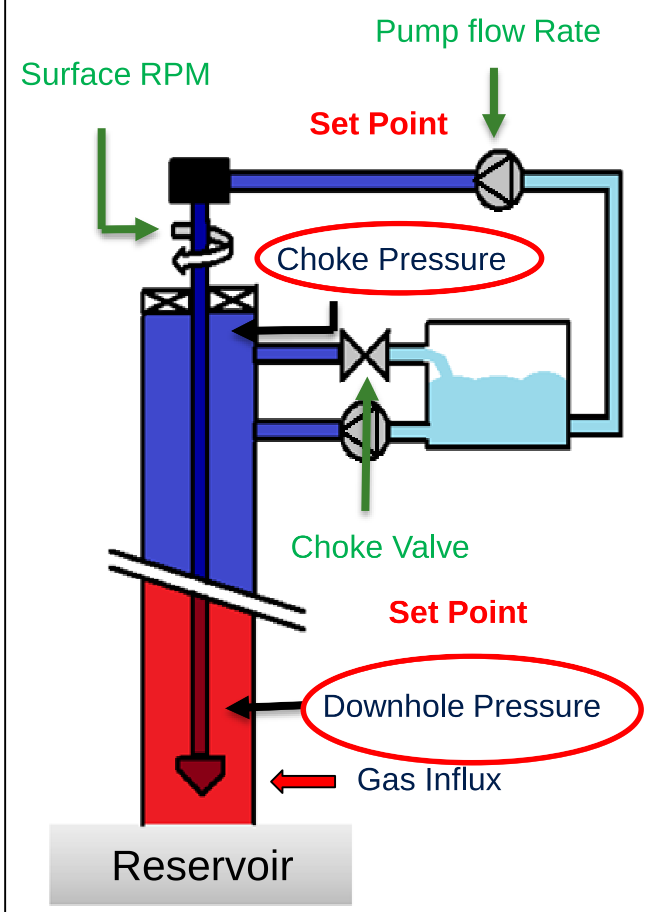
$$E = P_{bottom}^{current} - P_{bottom}^{sp}$$

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

Calculate the new reservoir pore pressure (P_{res})



Nonlinear Model predictive controller and Moving Horizon Estimator

- Objective function: $\ell 1$-norm

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

- 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

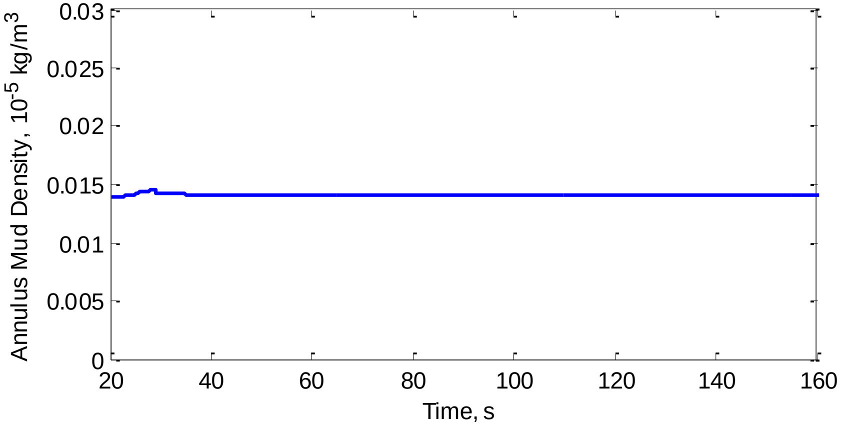
Extended Kalman Filter

- Estimates the gas influx flow rate

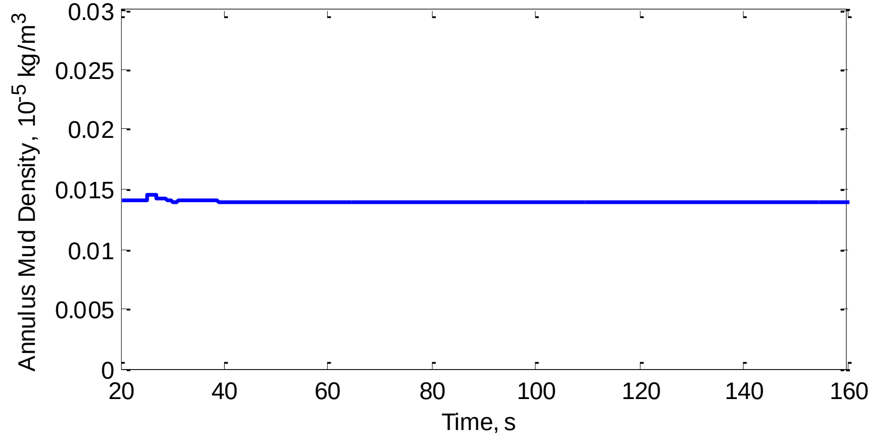
L1 norm vs. Squared Error

Clean Data

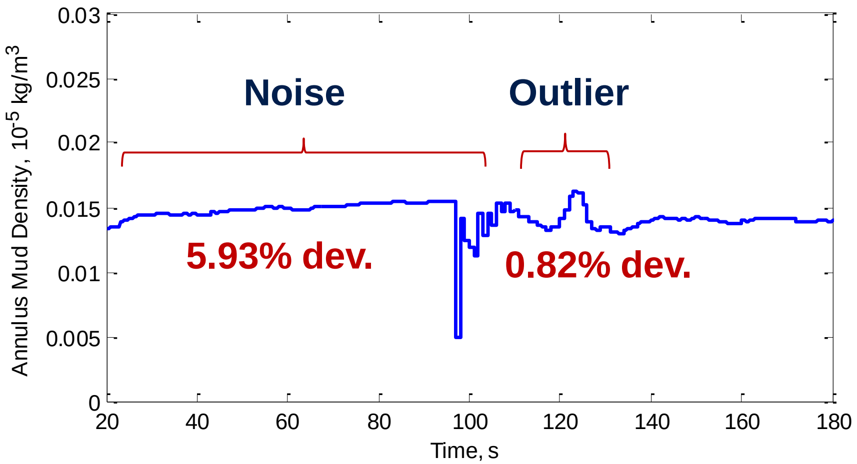
Squared Error

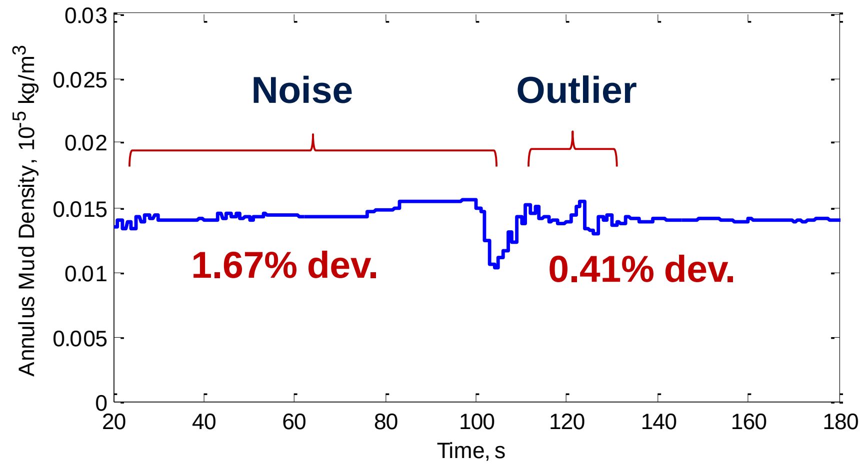


ℓ1-norm

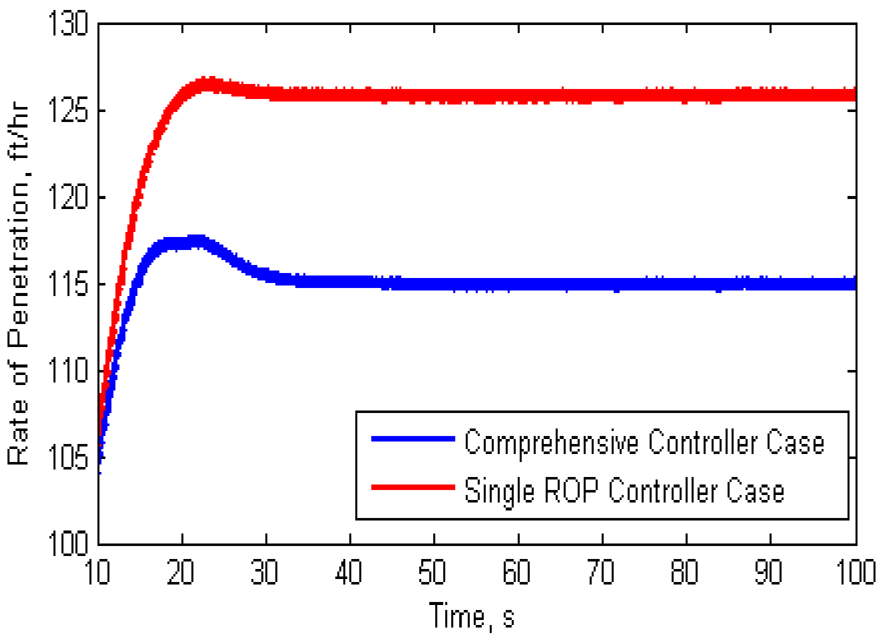


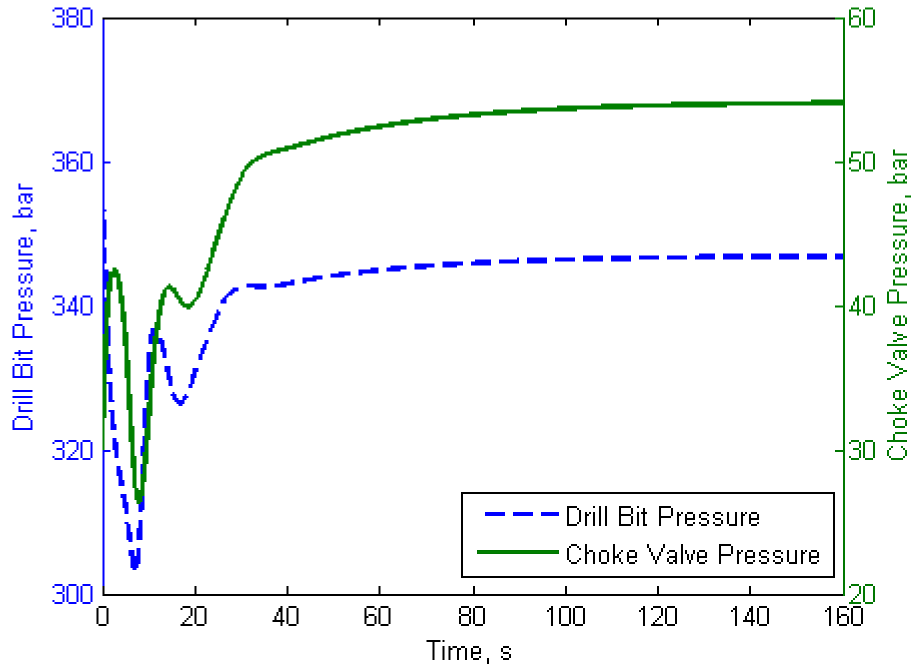
Corrupted Data

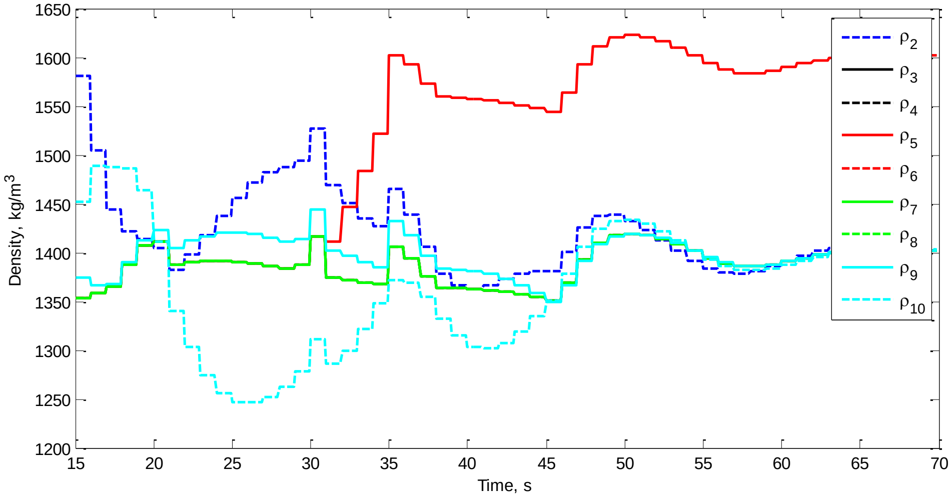




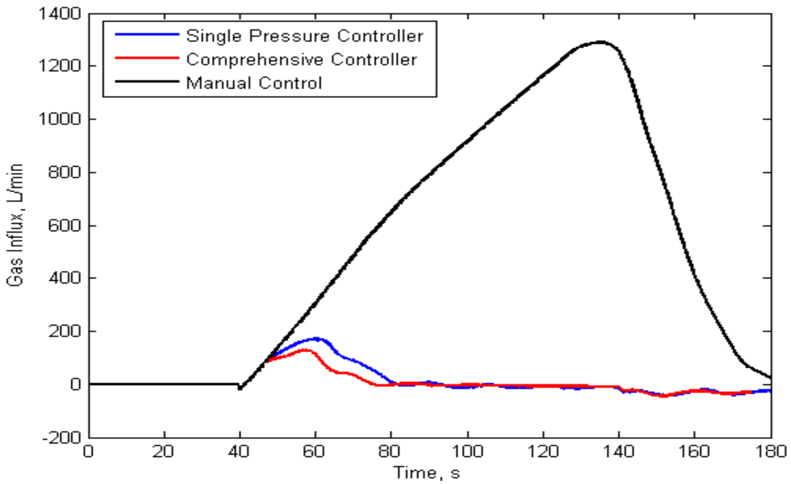
Results - Normal Drilling

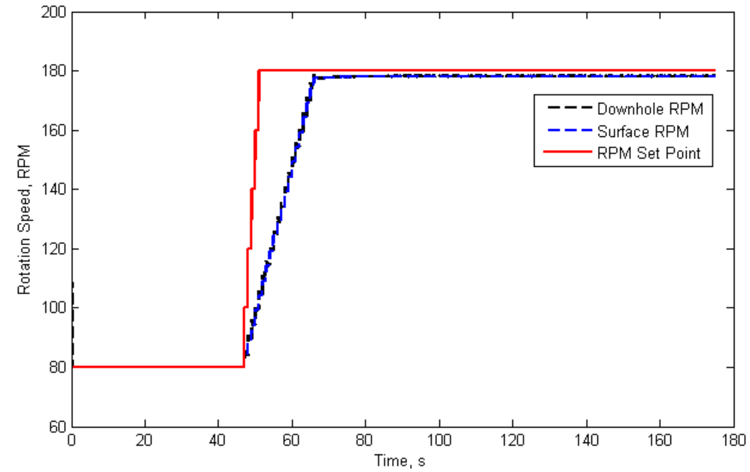


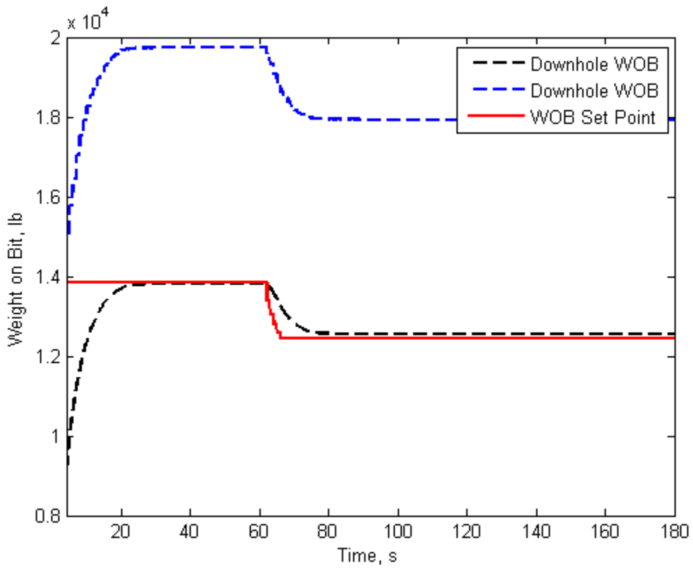


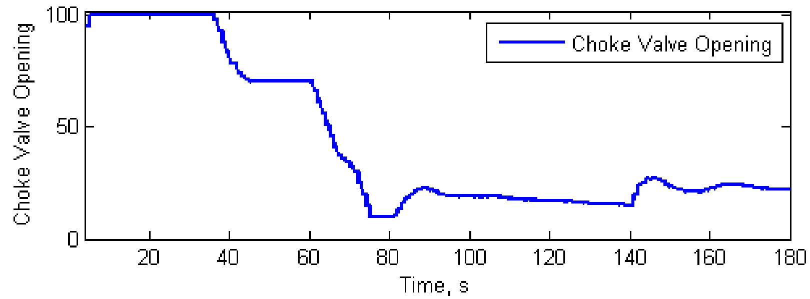


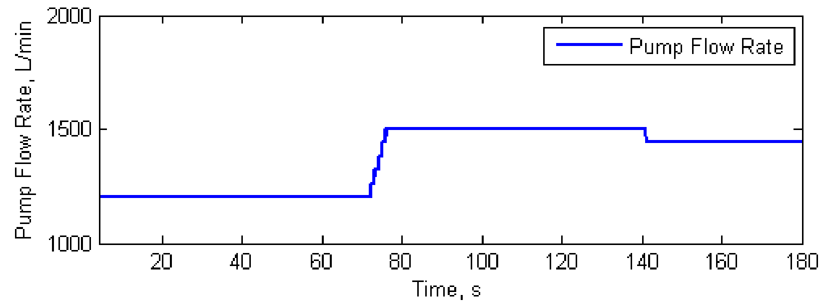
Results – Kick Attenuation











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

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Addressing UBO and MPD Challenges with Wired Drill Pipe Telemetry
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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

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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 ?