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

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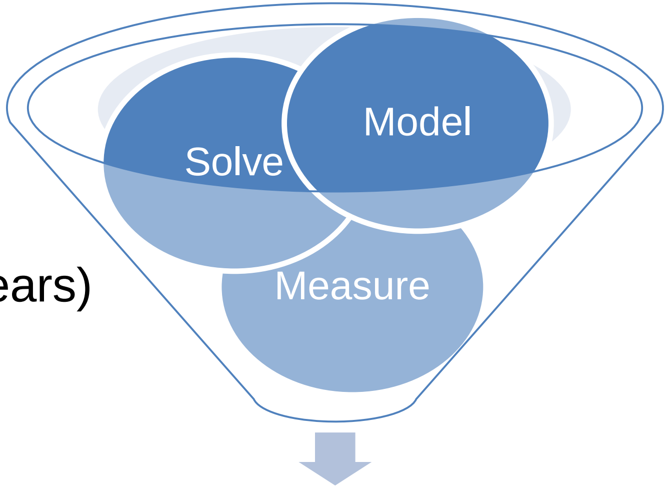
Why Automate Drilling?

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

- Benefits of Advanced Control
  - Optimized control resulting in greater accuracy and managing multivariate 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



Automation

Advances in High Fidelity Models

- High Fidelity Modeling
  - Wellbore Hydraulics
  - Drill String Dynamics

Courtesy eDrilling

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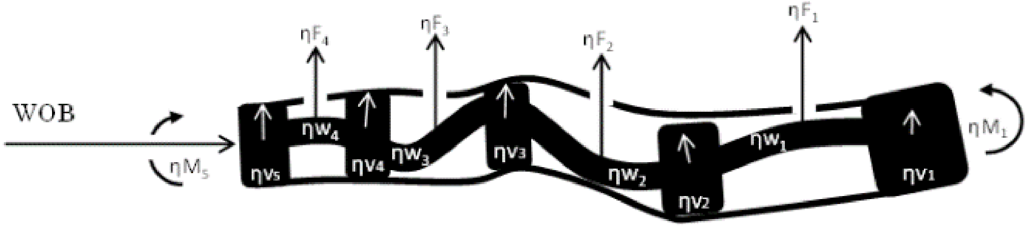
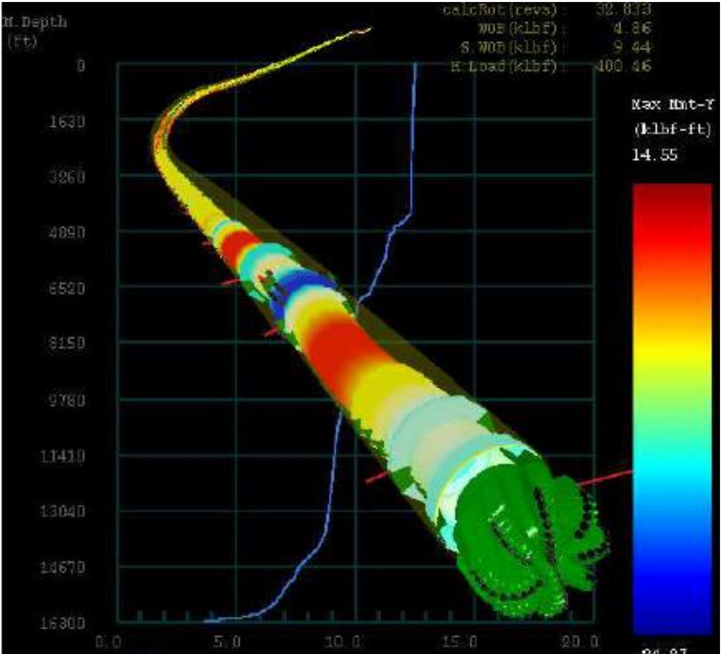
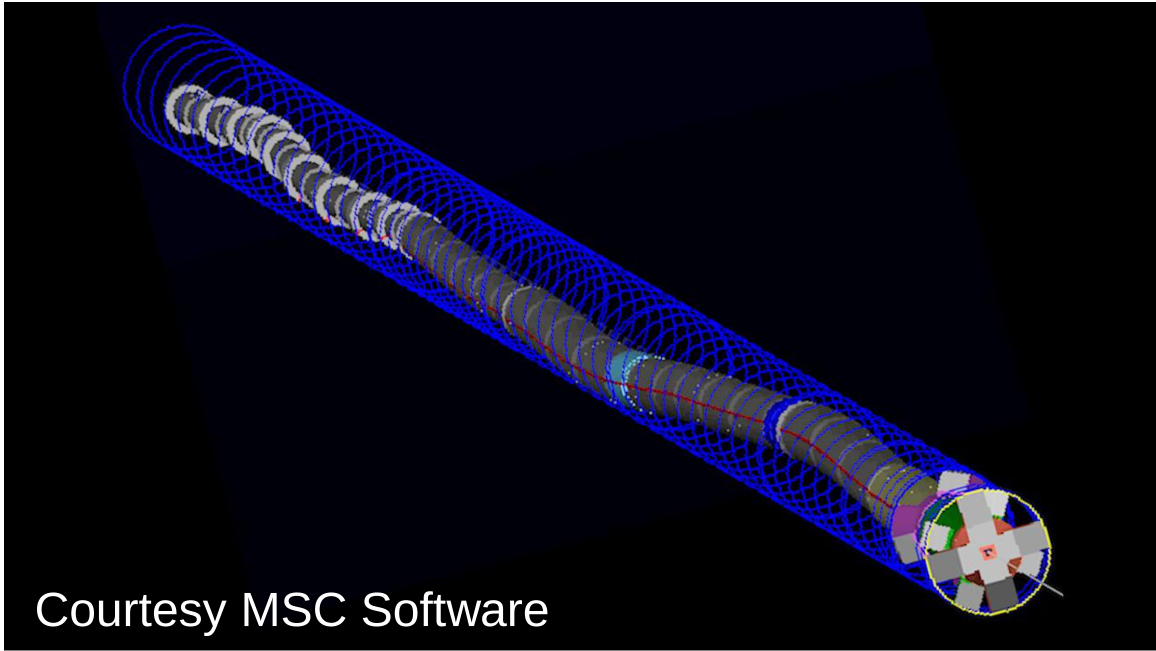






Courtesy MSC Software

Advances in Optimization

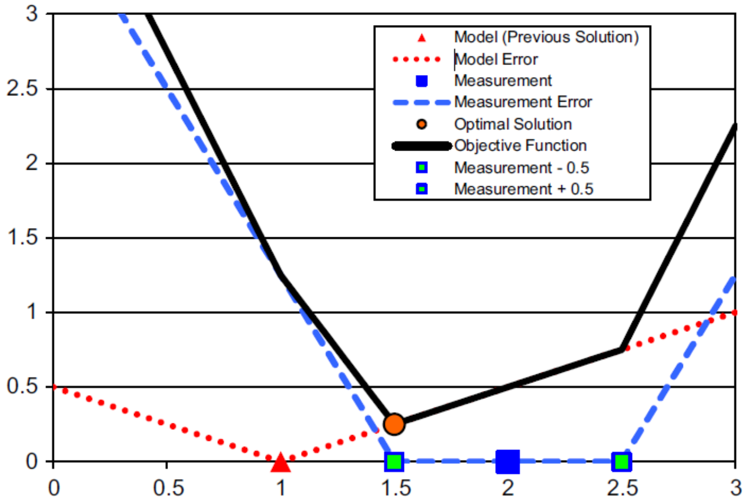
- Estimate
  - Kalman Filtering
  - *Moving Horizon Estimation*
- Control
  - PID
  - *Model Predictive Control*
- Solvers and Models
  - Large-scale (100,000+ variables)
  - Differential Algebraic Equations
  - Nonlinear Programming

$$\min_{d} \Phi = w_m^T (e_U + e_L) + w_p^T (c_U + c_L)$$

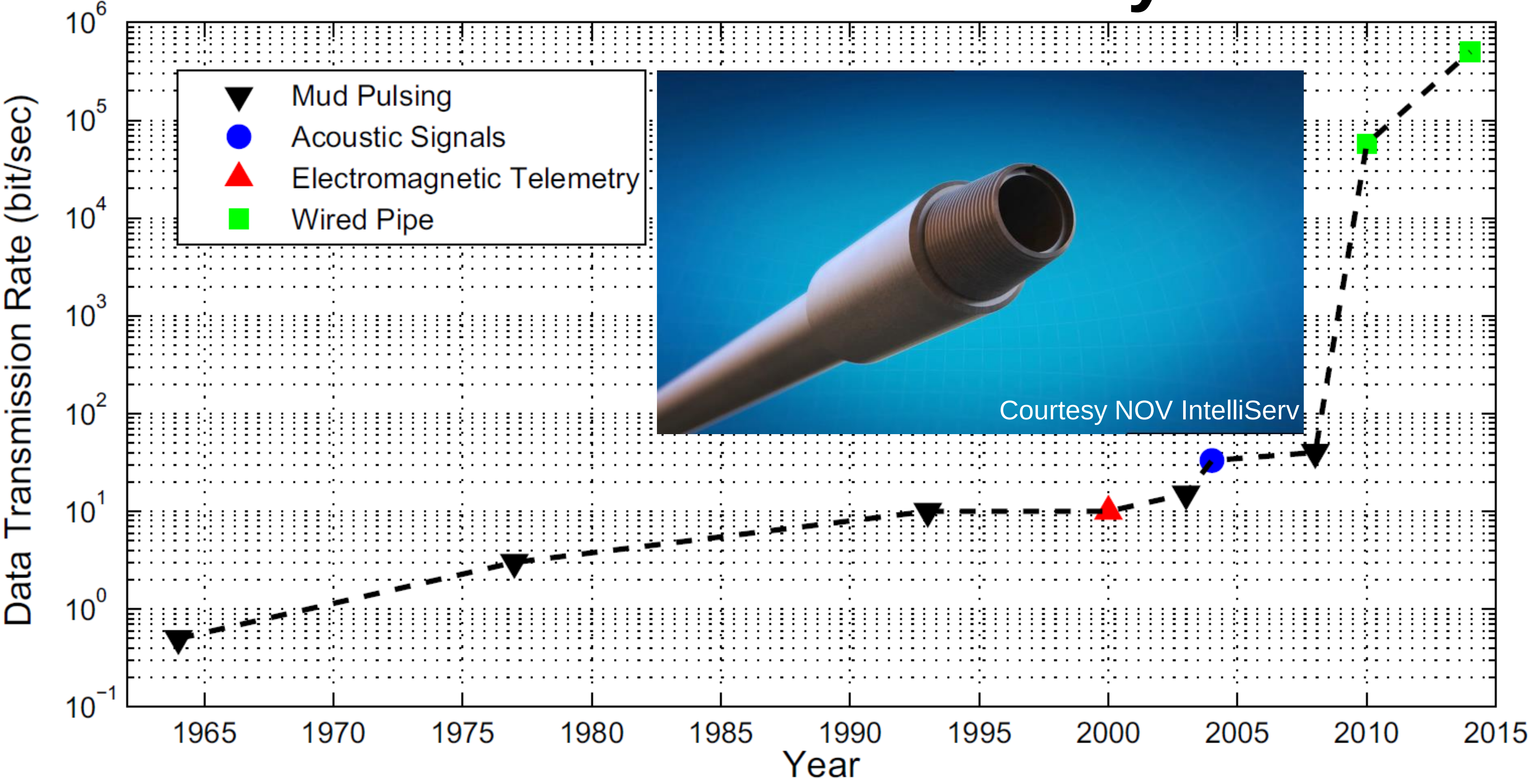
$$\text{s.t.} \quad 0 = f\left(\frac{\partial x}{\partial t}, x, u, p, d\right)$$

$$0 = g(y, x, u, d)$$

$$0 \leq h(x, u, d)$$



Advances in Telemetry



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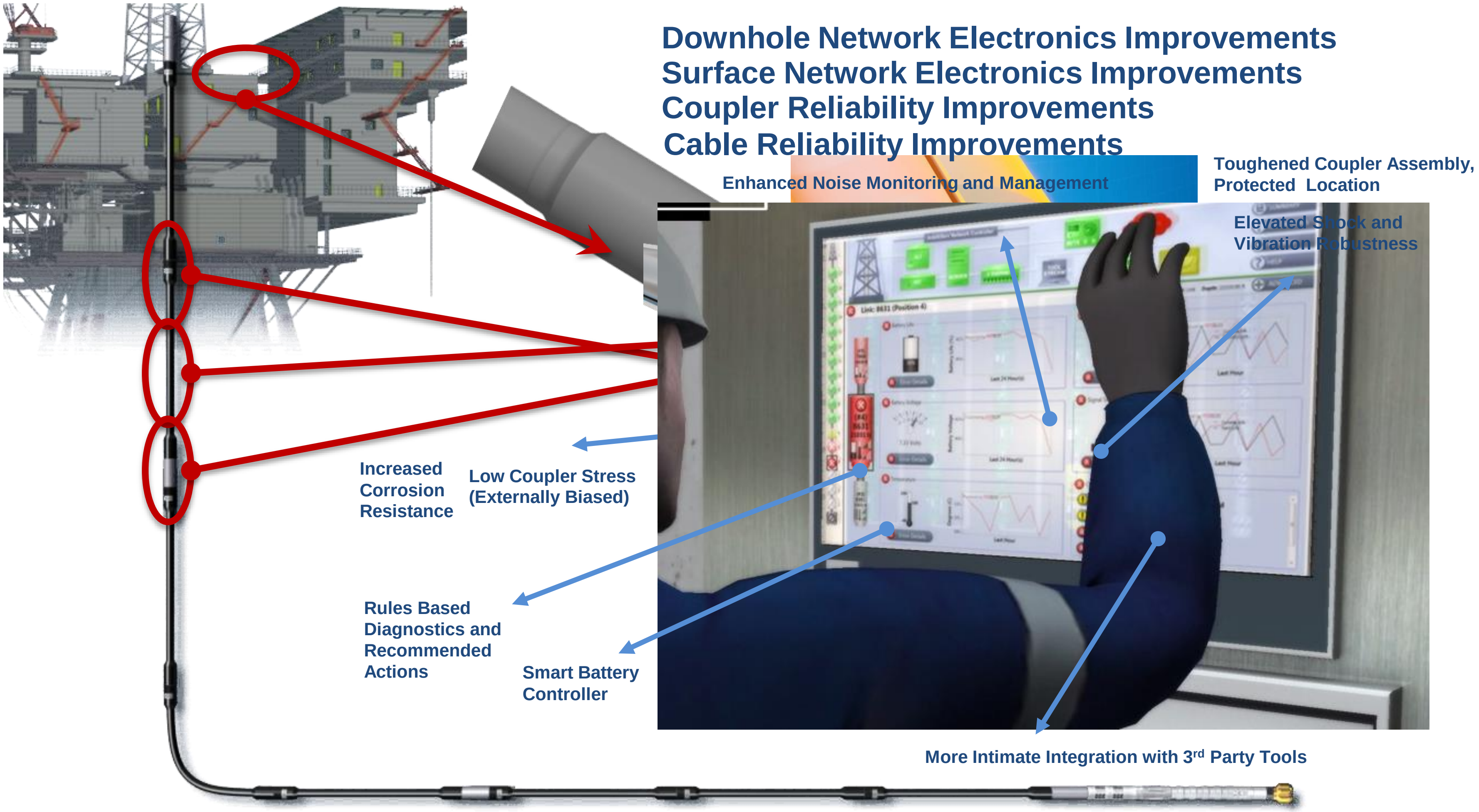
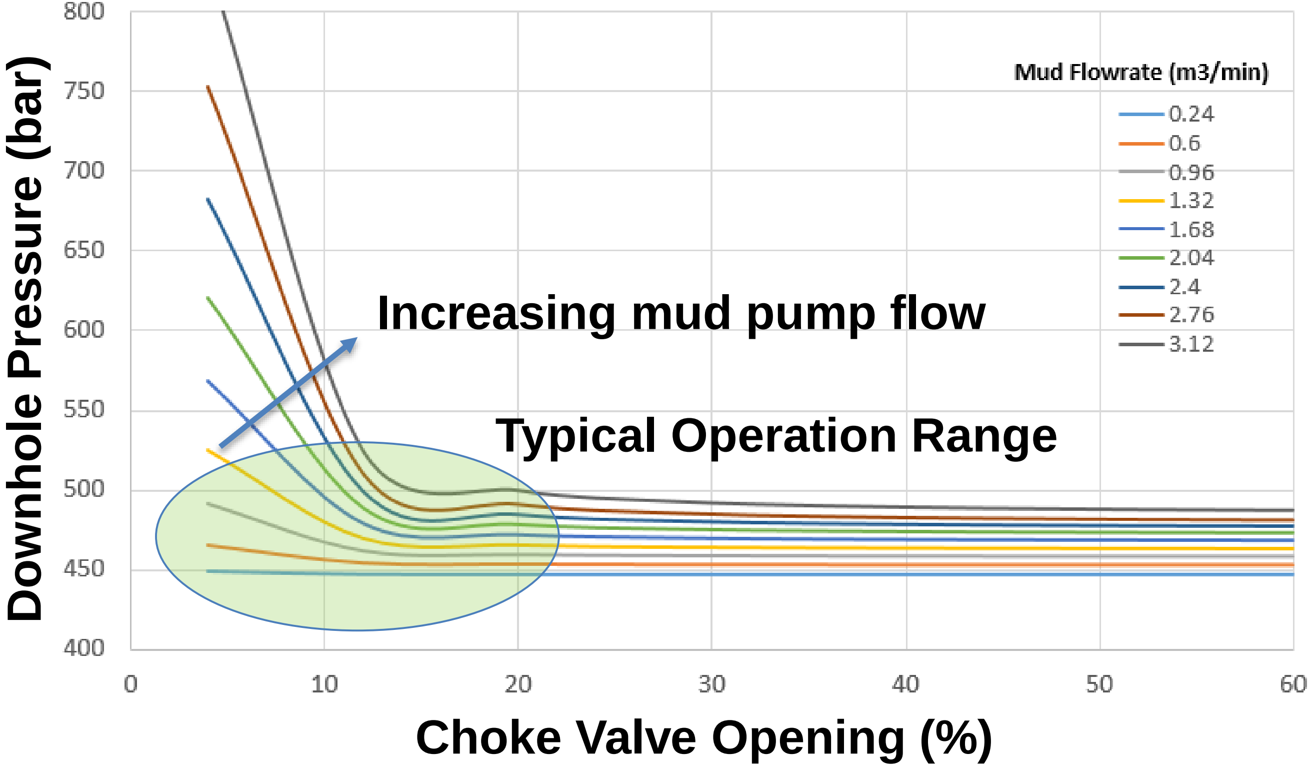
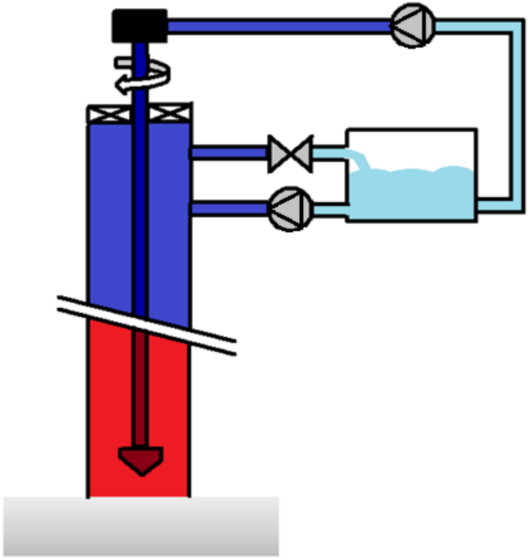


Nonlinearity in MPD Process





Lower Order Models for Control

Control Overview		
Manipulated Variables	Controlled Variables	Estimated Variables
Rig Pump Flow Rate	BHP	Annulus Drill Fluid Density
Choke Valve Opening	Annular Pressures	Annulus Friction Factor
Back Pressure Pump Flow	Choke Valve Pressure	Reservoir Pore Pressure

$$\dot{p}_p = \frac{\beta_d}{V_d}\left(q_{pump} - q_{bit}\right)$$

$$\dot{p}_c = \frac{\beta_a}{V_a}\left(q_{bit} + q_{back} - q_{choke} + q_{res} - ROP\right)$$

$$M_a = \rho_a \int_0^{l_w} \frac{1}{A_a(x)} dx$$

$$M_d = \rho_d \int_0^{L_{dN}} \frac{1}{A_d(x)} dx$$

$$M = M_a + M_d$$

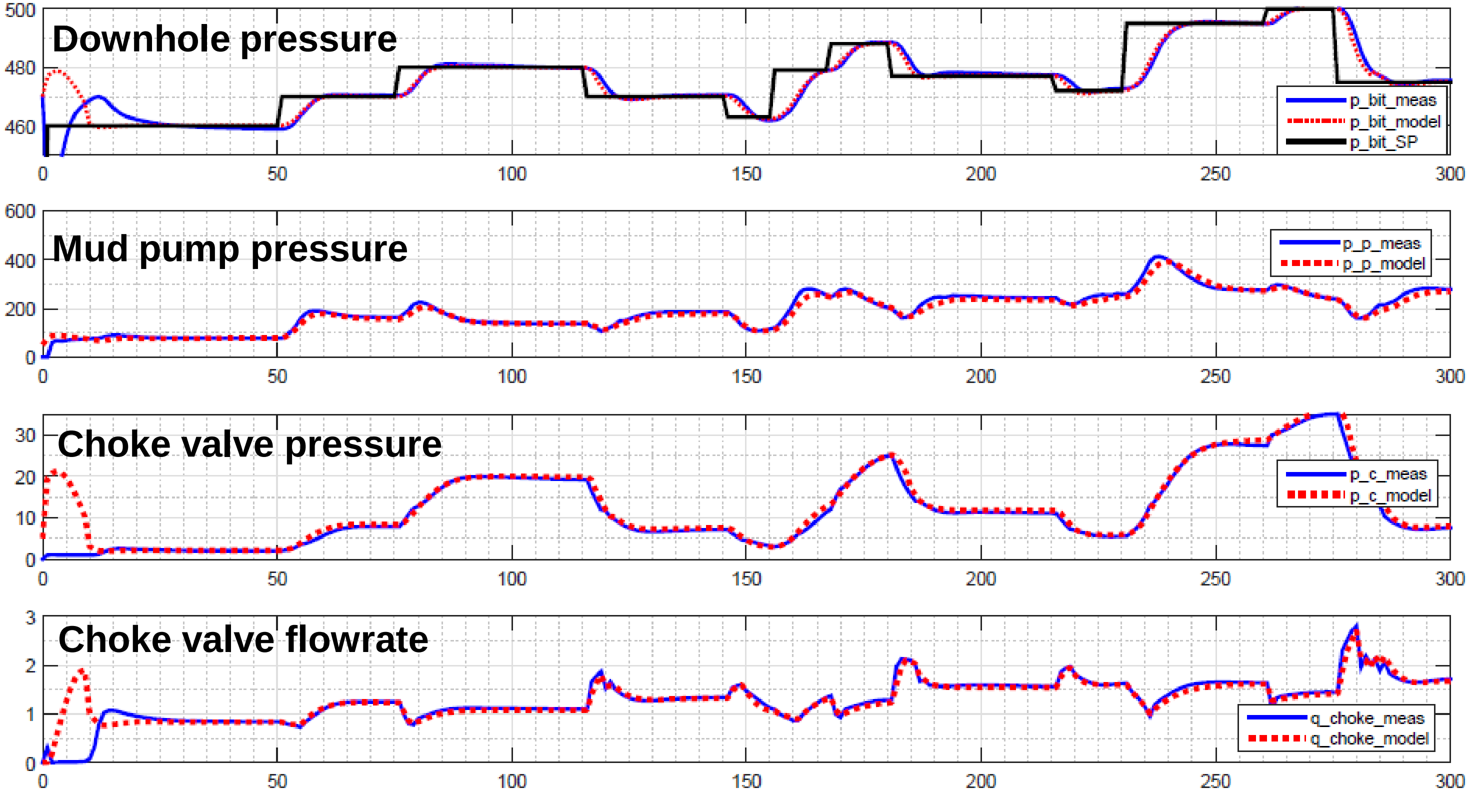
$$p_{bit} = p_c + \left(\sum_{i=1}^{n-1} \rho_{ai} \times F_{ai}\right) |q_{bit} + q_{res}|(q_{bit} + q_{res})h + \rho_a g(h_{bit} - (n-1)h)$$

$$q_{choke} = K_c z_{choke} \sqrt{\rho_{an}(p_c - p_0)}$$

$$p_{a_n} = p_c + \sum_{i=1}^{n-1} (\rho_{ai} \times F_{a_i} \times h|q_i|(q_i) + \rho_{ai} g(h)) + \rho_{an} \times F_{an} \times h|q_n|(q_n) + \rho_{an} g(h)$$

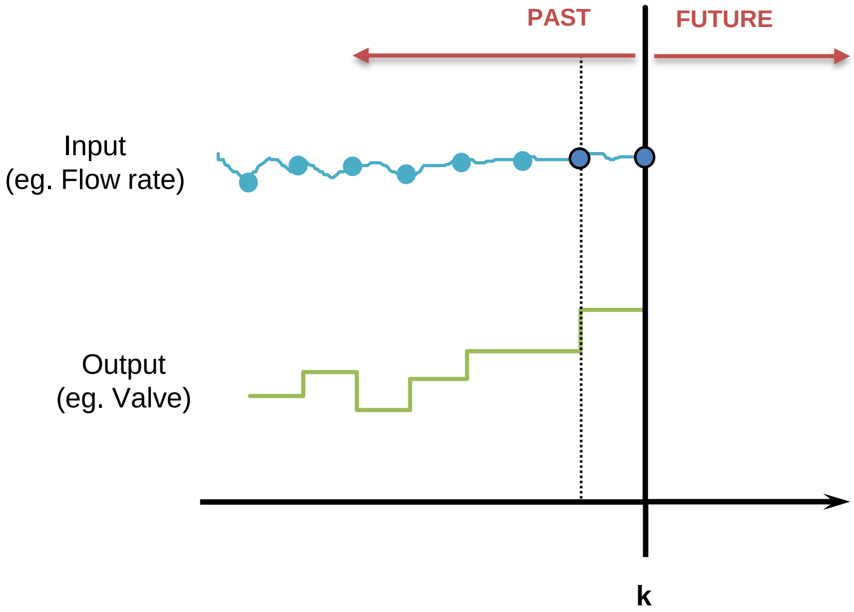
$$\dot{q}_{bit} = \frac{1}{M}\left(p_p - F_d|q_{bit}|q_{bit} + \rho_d g h_{bit} - p_{bit}\right)$$

Lower Order Model Match with WeMod (MHE)

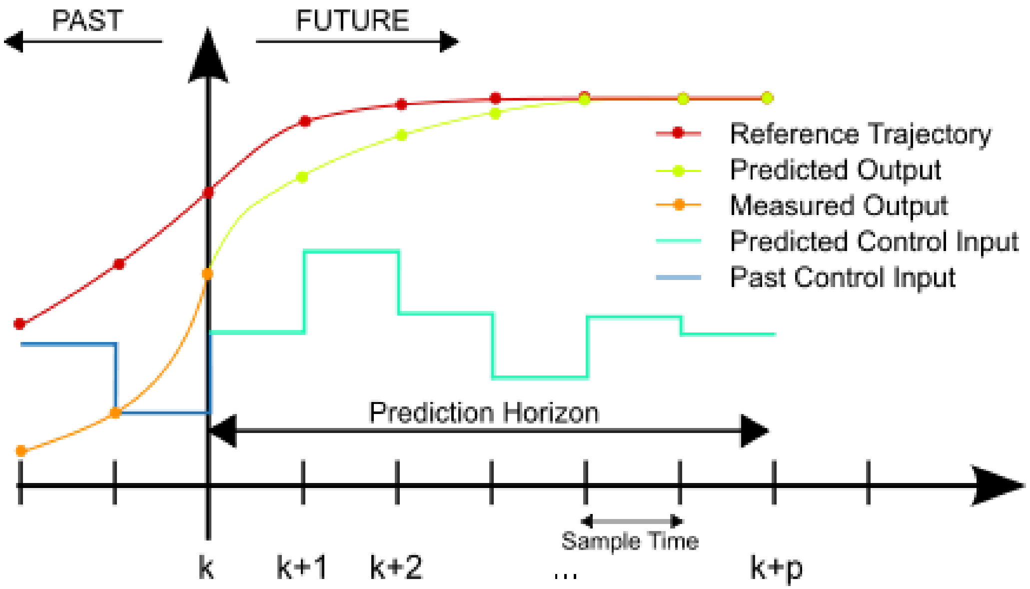


PID and Model Predictive Control

Conventional (PID)



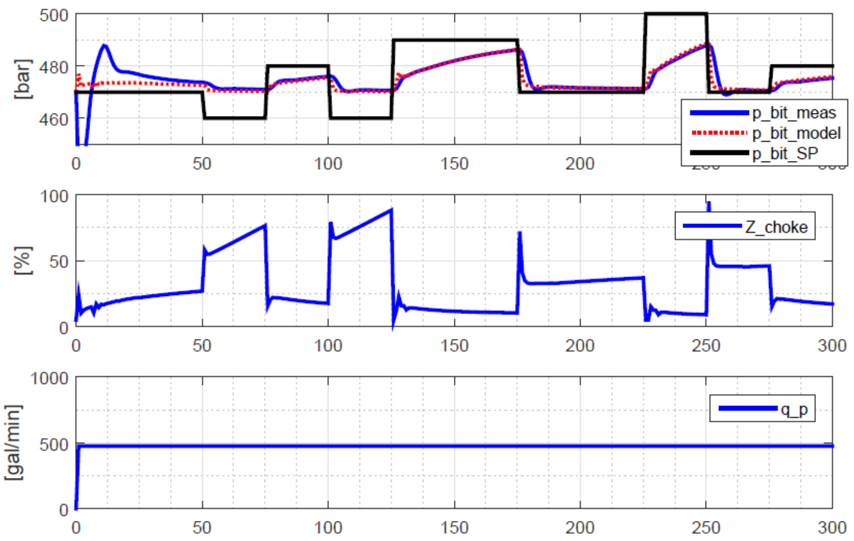
Advanced (MPC)



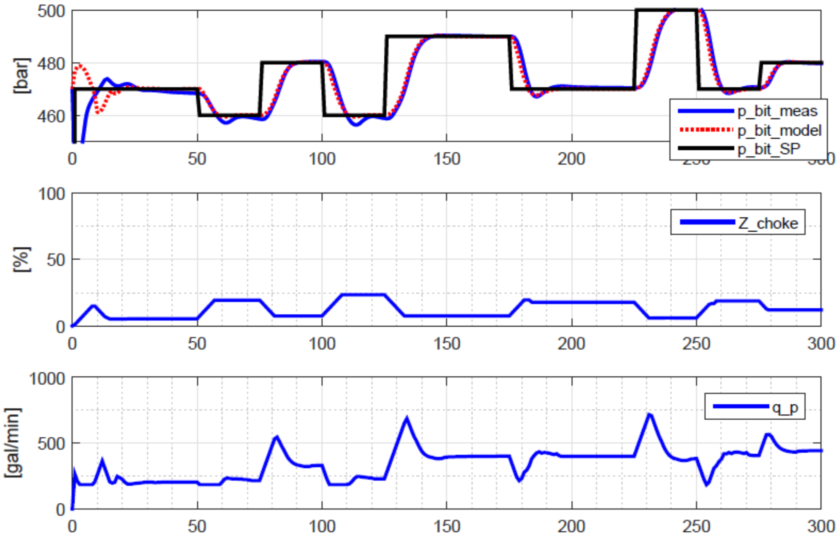
https://en.wikipedia.org/wiki/Model_predictive_control

Simulated Pressure Control with MPC

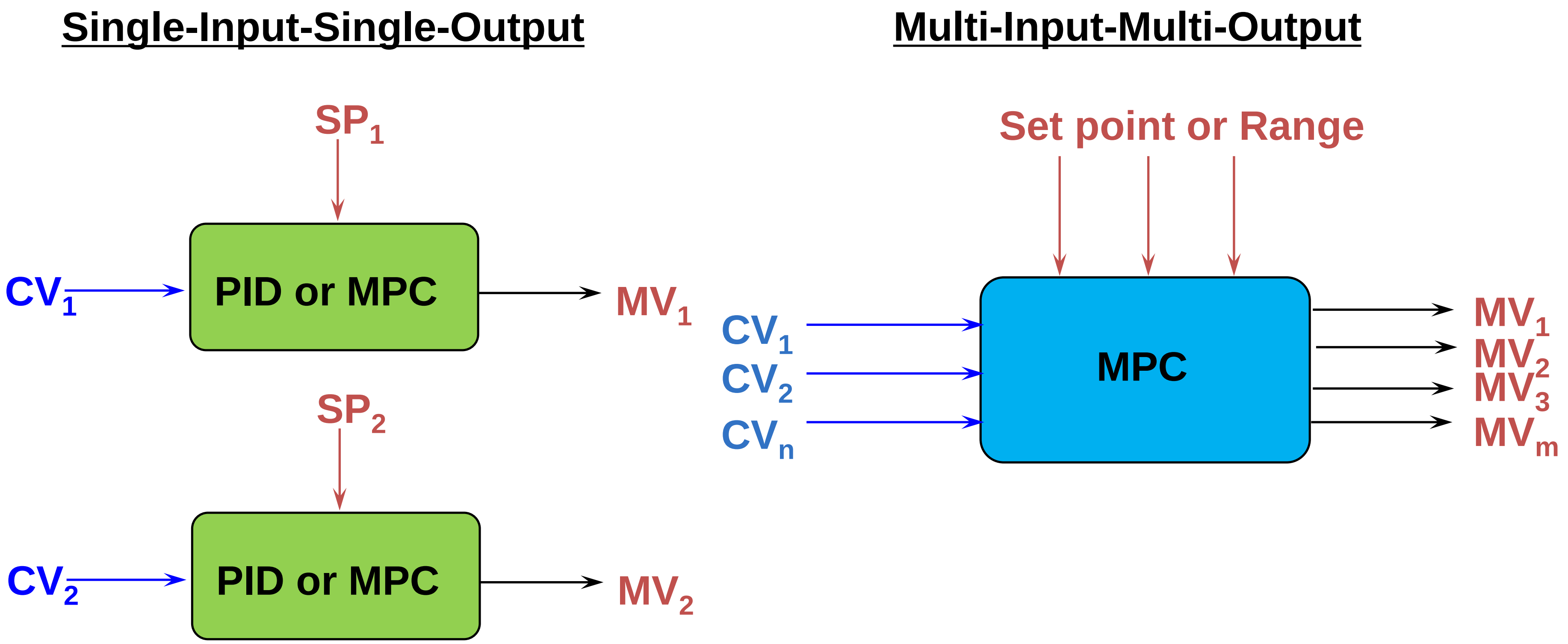
Conventional (PID)



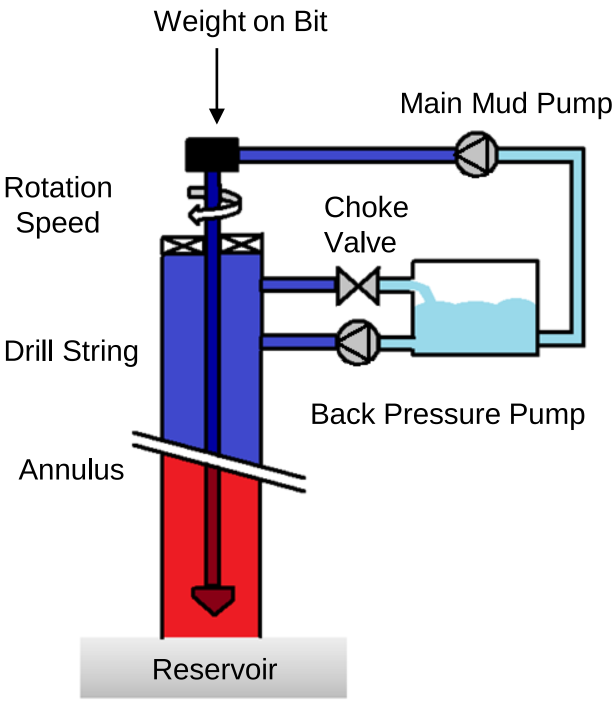
Advanced (MPC)

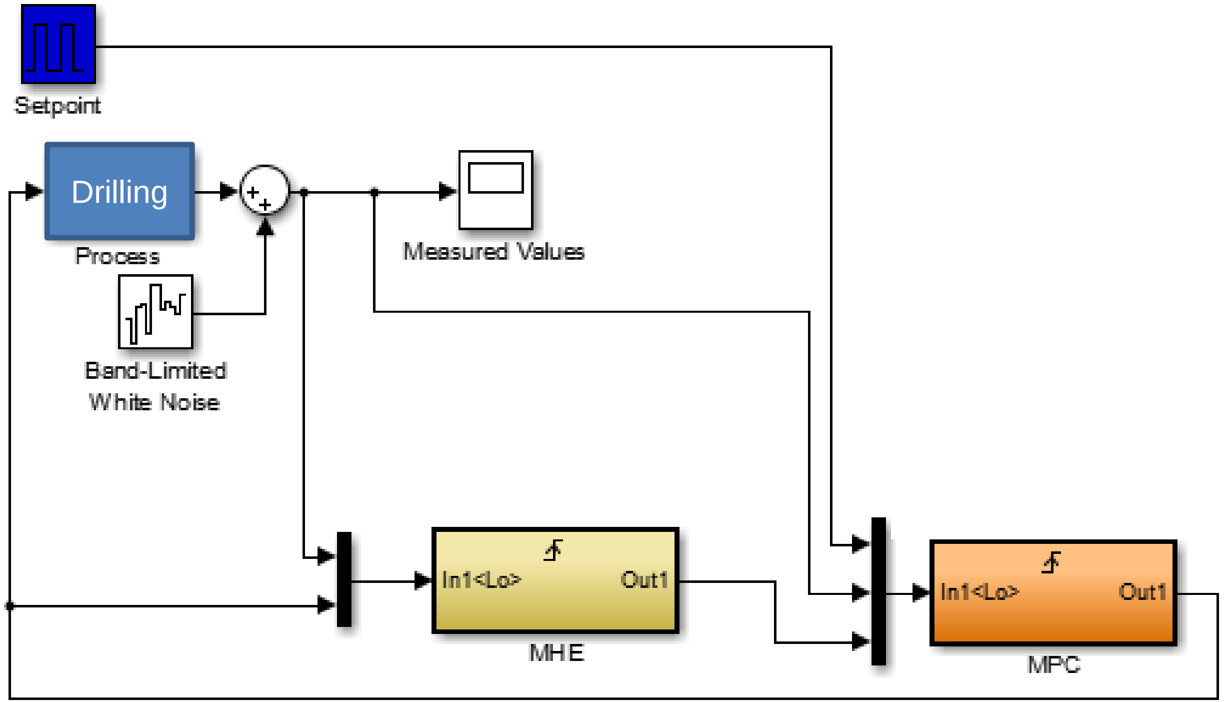


Exploit Multivariate Relationships in MPC for MPD



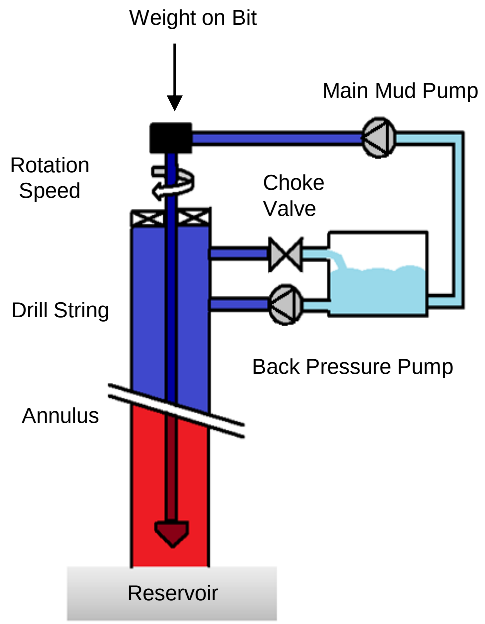
Combine Flow and Drill String Models

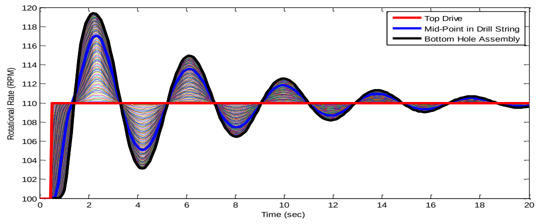




http://apmonitor.com/do

Combine Flow and Drill String Models





<u>Pressure Hydraulics</u>

- Lower order model (Stamnes et. al)

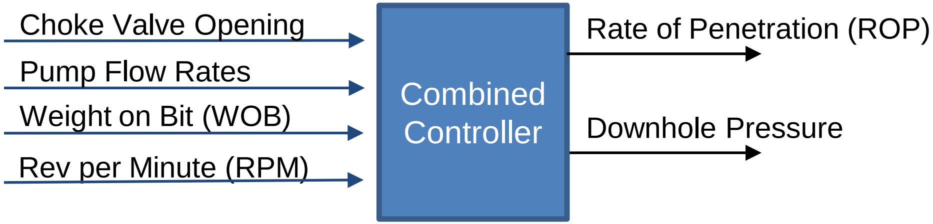
<u>Interaction Between Drill String and Hydraulics</u>

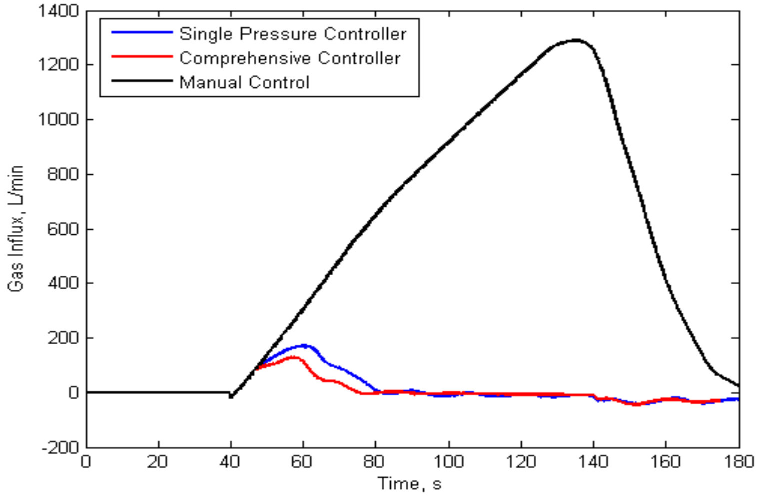
- ROP depends on the downhole pressure (Bourgoyne and Young)
- Friction factor depends on axial and rotational flow
- Rotation Speed (RPM) effect on Friction Factor

<u>Drill String Dynamics</u>

- 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

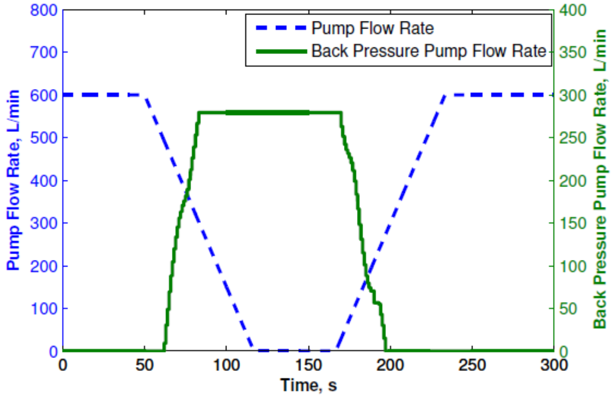


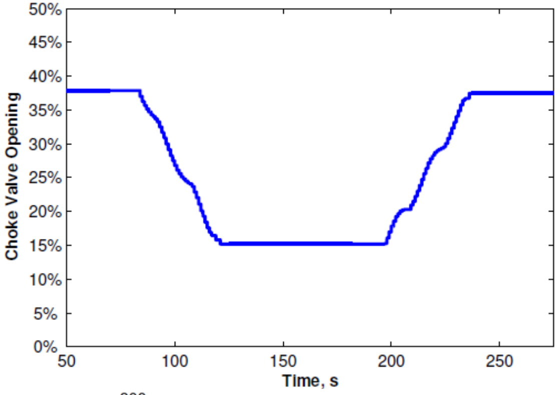


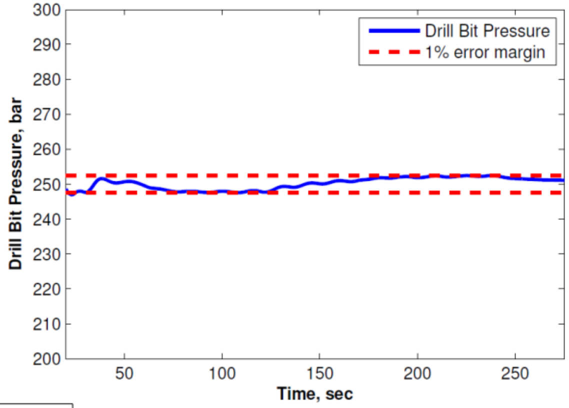
Pressure Control: Kicks and Connections

Connection Procedure:

- The controller is able to control the drill bit pressure +/- 3 bar

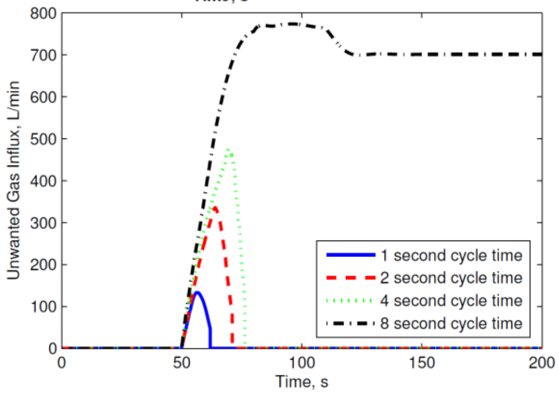






Kick Attenuation:

- Immediate action avoids more intrusive well control efforts



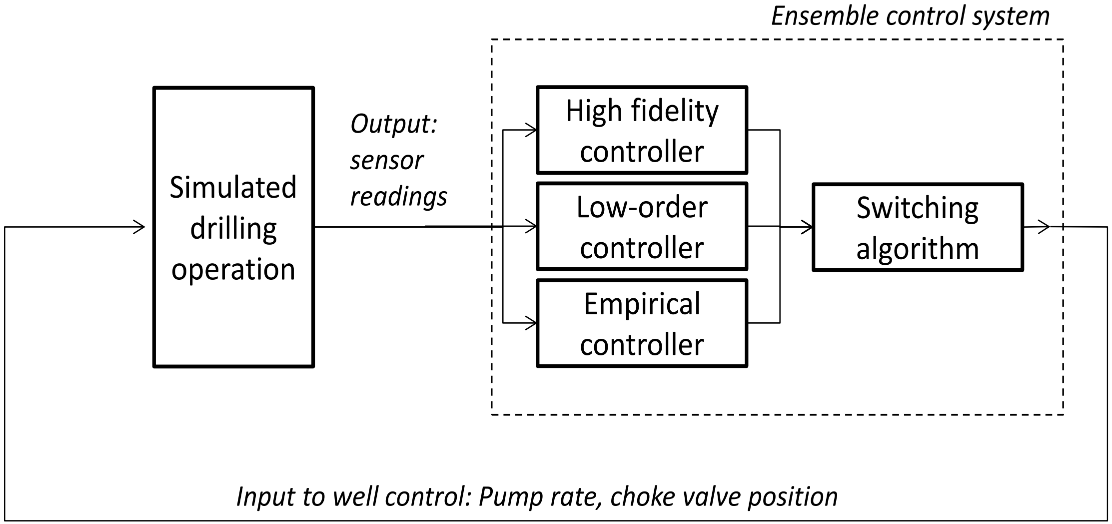
Challenges of Automation

- 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



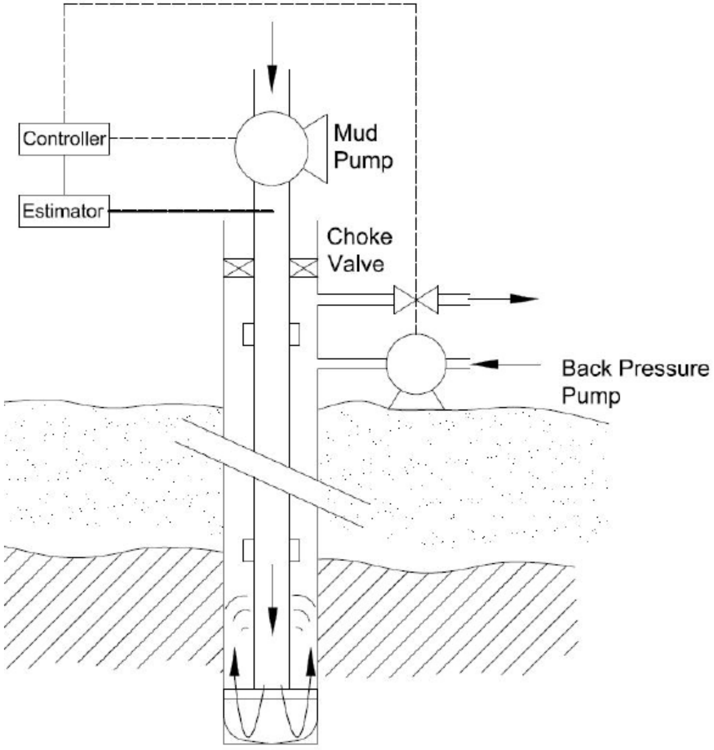
Advantages of Ensemble Control

- 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



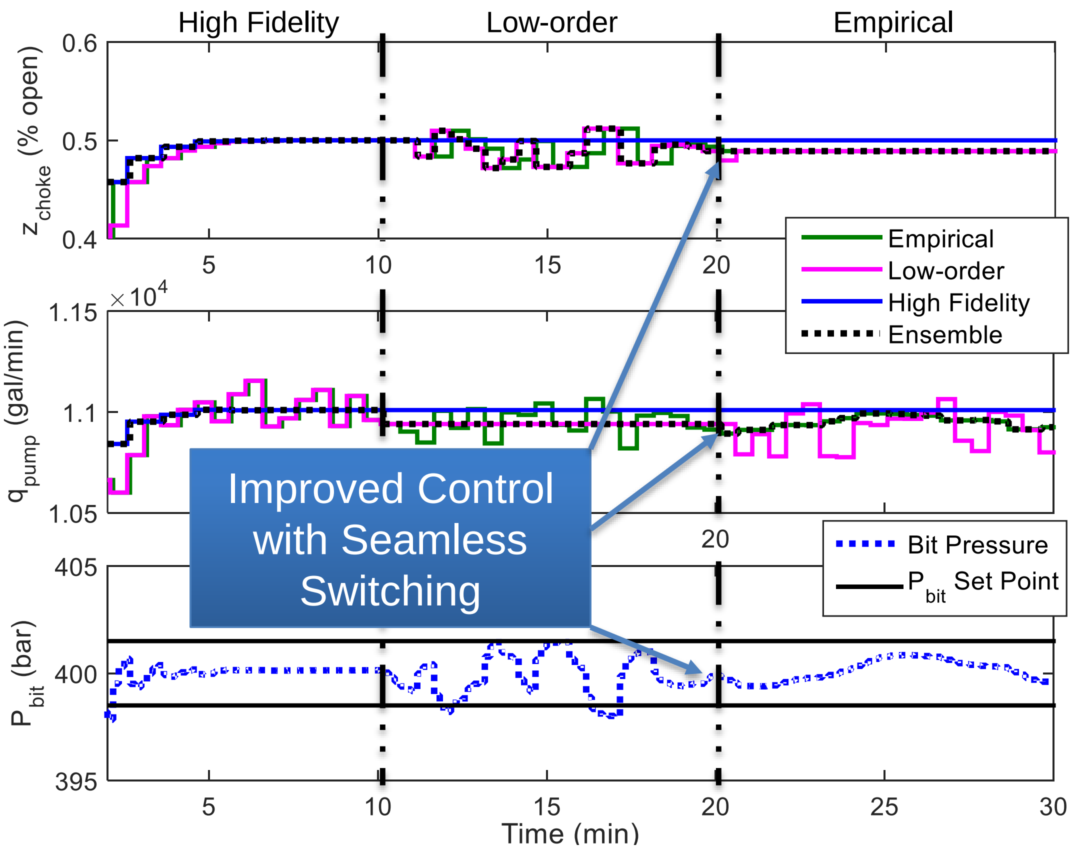
Pressure Control Through Automation

- 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

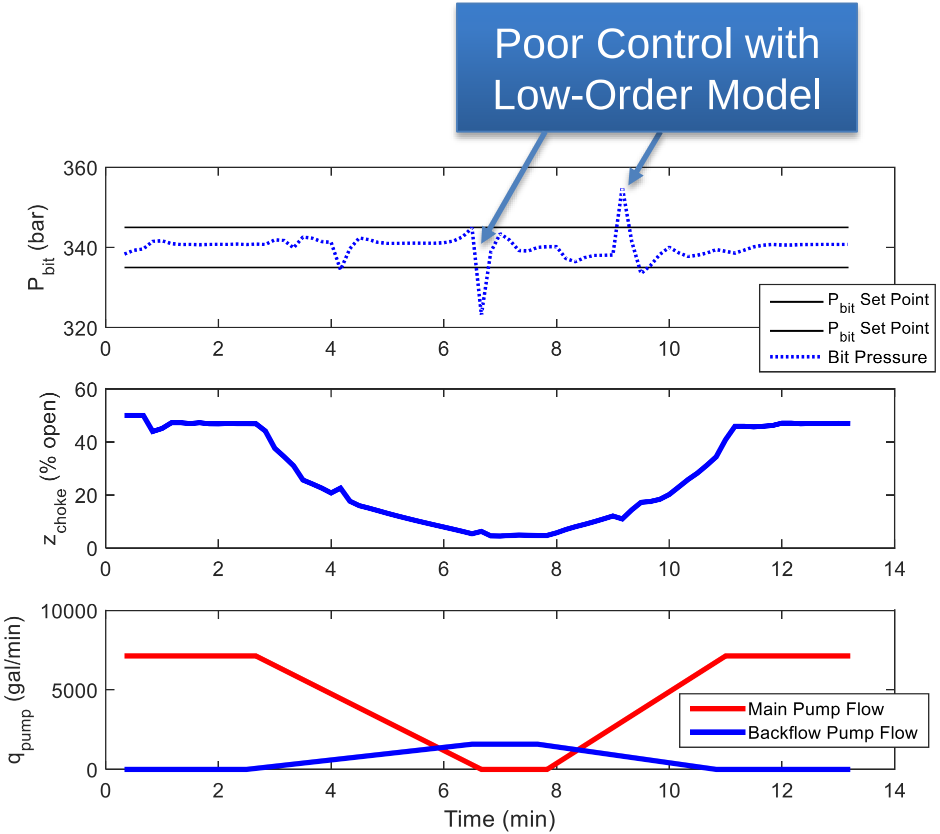
Seamless Switching During Normal Drilling

- At 10 and 20 minutes control is switched to the controller indicated
- Despite model inaccuracies <u>the bit pressure is kept within the target range</u>
- Switching between controllers is *seamless*



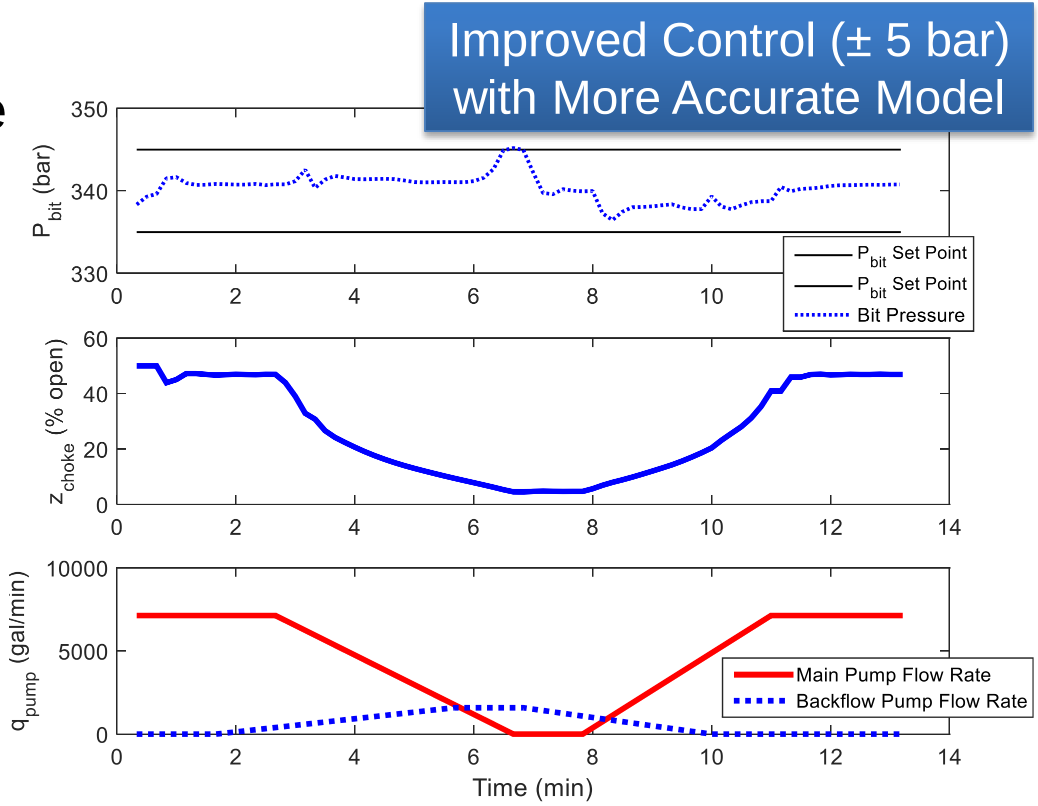
Pressure Control During Pipe Connections

- 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*



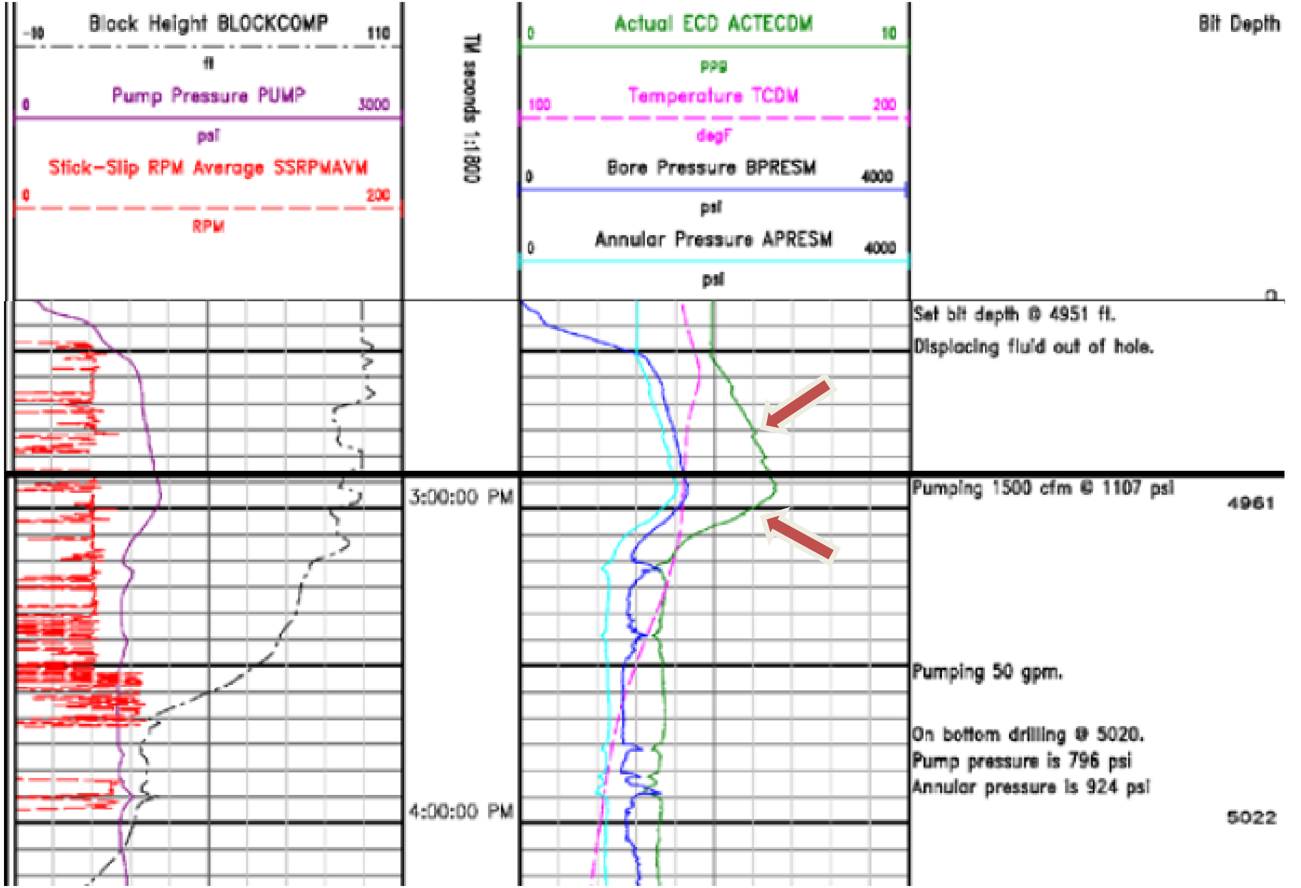
Improved Control with High Fidelity Model

- Pipe connection using only the high fidelity controller
- The high fidelity controller predictions are sufficiently accurate to maintain the bit pressure within ±5 bar of the 340 bar set point with no bit pressure feedback measurements



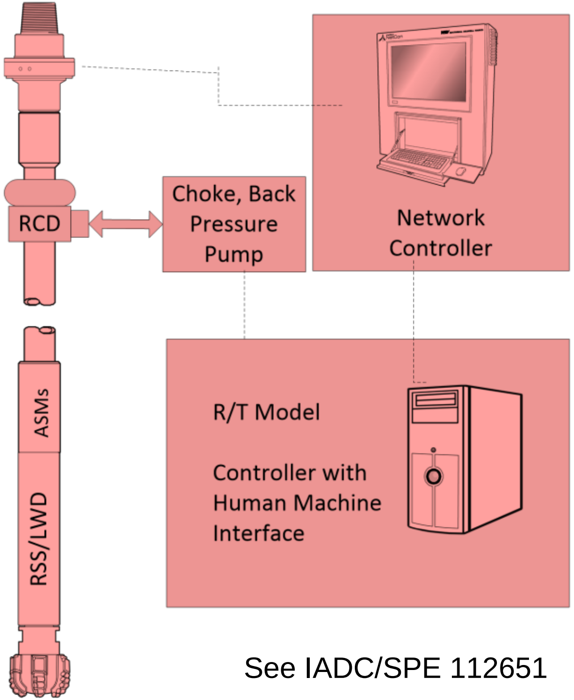
Avoiding Formation Damage – US Land

- 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

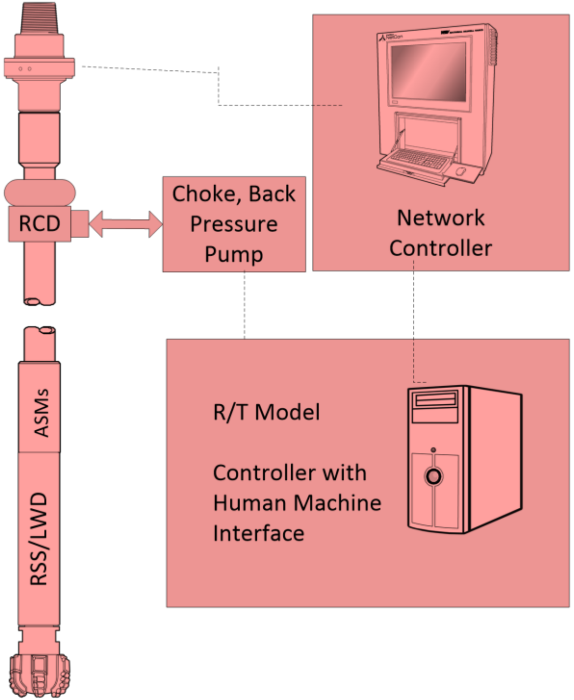
- Shallow high-pressure gas-bearing sands
- Required fast kick control response
- Required monitoring and control of BHP with pumps off
- Solution: MPD and control system with Wired Drill Pipe
- BHP Maintained:
  +/-15 psi (drilling), +/-45 psi (connections)



See IADC/SPE 112651

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