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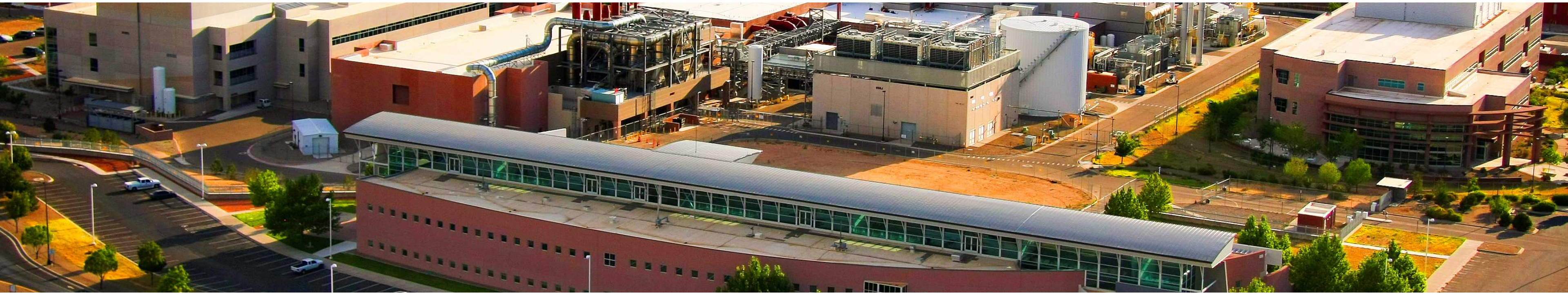

Estimation and Control for Efficient Autonomous Drilling through Layered Materials

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Sandia National Laboratories

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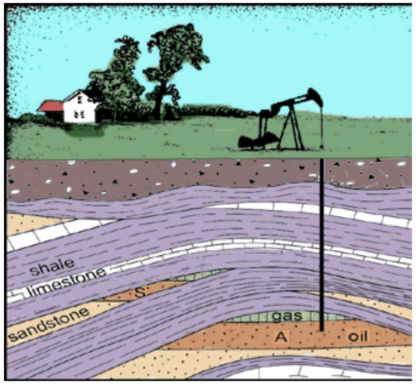
Drilling Automation & Control

- Why automate drilling?
  - Economic impact
    - US drilling products & services industry is ~$60B annually
    - Land rigs cost tens of $k/day; offshore hundreds of $k/day to operate
    - Even marginal operating savings have a huge impact
  - Task characteristics
    - Repetitive, dangerous
    - Limited data at surface makes optimization difficult
  - Most operations are manual – depend on expert operators
- Prior work in drilling automation
  - Online estimation of efficiency (MSE) to prompt operator (ExxonMobile Fastdrill)
  - Rate of penetration maximization based on measured signals
    - Including rock model fitting; over multiple settings (e.g. Bayesian)
    - (Dunlop 2011, Chapman 2012, Sui 2013, Boyadjieff 2003)

Our View of the Problem

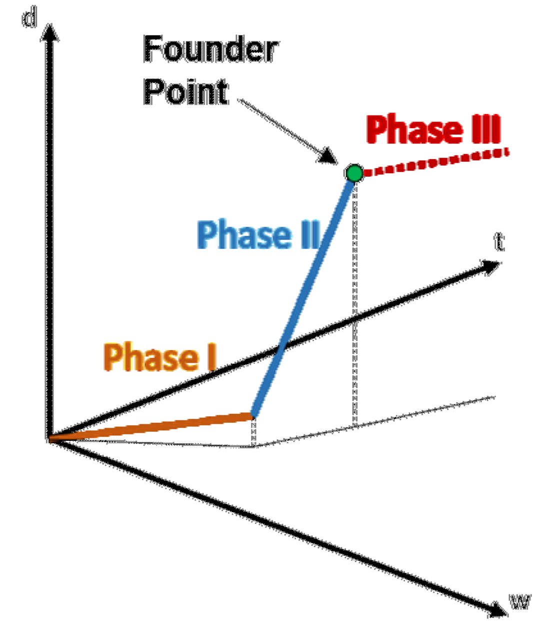


Illinois State Geological Survey

- Control challenges
  - Interested in sharp transitions between different materials
    - Particularly challenging for material removal systems
    - Want to react quickly – avoid pathologies and operator intervention
  - Multiple physical mechanisms: different materials fail differently
- Approach
  - Derive real-time controllers from models of drilling mechanics
    - Detournay model: prevalent for PDC drag bit drilling (Detournay 2008)
  - Want to estimate material with single operating point
    - Use prior drilling database that captures rock/bit interactions
  - Inform settings with history, but optimize locally in real-time
  - Translate drilling requirements into control system requirements
    - Stability: Converge to continuous drilling, even through disturbances (transitions)
    - Performance: Go fast and efficiently

Rotary Drilling Model & Performance Metrics

- Key drilling performance metrics
  - ROP (rate of penetration)
  - MSE (mechanical specific energy)
- Detournay model for PDC drag bit drilling
  - Relates scaled torque (t), scaled WOB (w), depth of cut (d)
  - Piecewise linear within drilling phases 1 & 2; we assume linear for phase 3 also
- Drilling regions / phases (increase with w)
  - Phase 1: Cutter flat contact area increases with w
  - Phase 2: Cutters fully engaged
    - ROP & MSE maximized at top of Phase 2
  - Phase 3: Further w increases do not translate into more pure cutting



$$MSE = \frac{w}{\pi R} + \frac{t}{d}$$

$$ROP = d\ \omega\ N$$

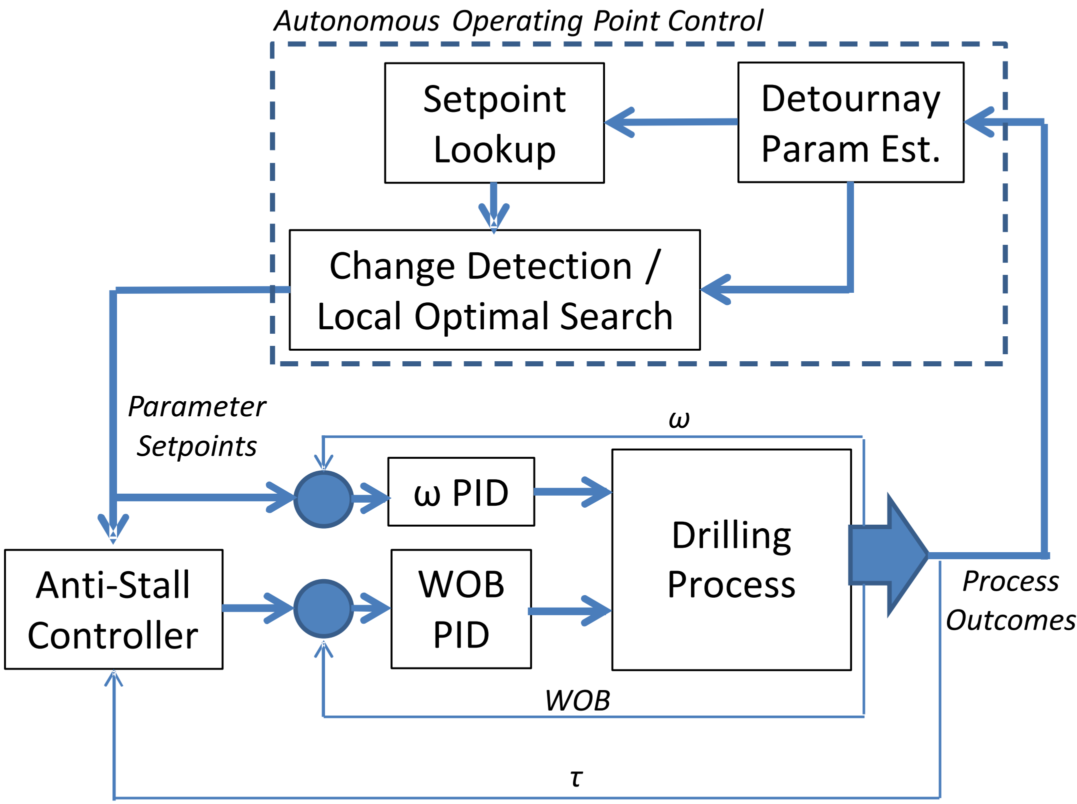
angular velocity

number of blades

WOB = Weight on Bit or Thrust

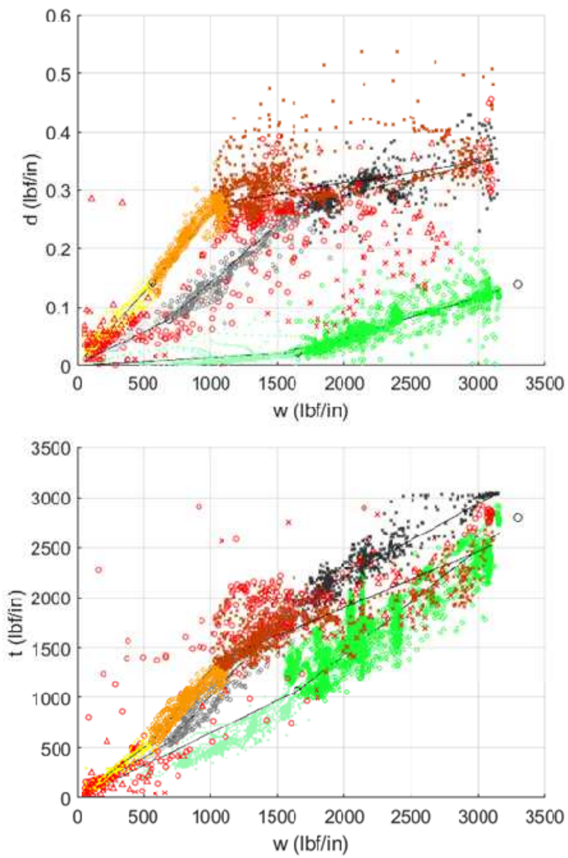
Overall Control Approach

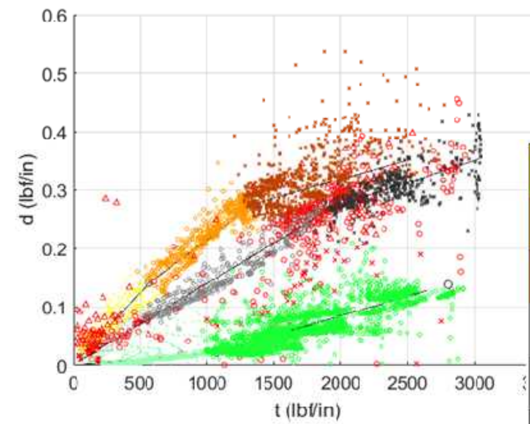
- System controls WOB and ω
- Rock-bit interactions determine outcomes
  - Torque (τ)
  - ROP
  - MSE & other high-level metrics
- Multi-level control
  - Estimate drilling parameters
  - When material change detected, conduct optimum search around setpoint
  - Low-level control achieves target setpoint
  - Fast-acting reactive control avoids stalls (not implemented)

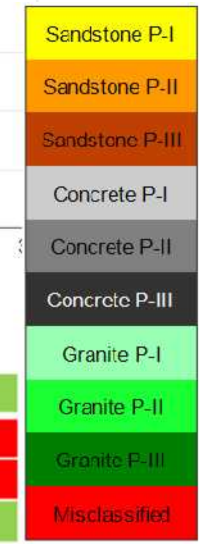


Material Estimation

- Fit Detournay model parameters from training runs for each rock type
  - 17 granite (hard)
  - 10 concrete (soft)
  - 13 sandstone (soft)
  - Generates piecewise linear model
- Real-time fit based on single operating point (averaged over 4 sec)
  - ID drilling region for each material
  - Compare distance to models







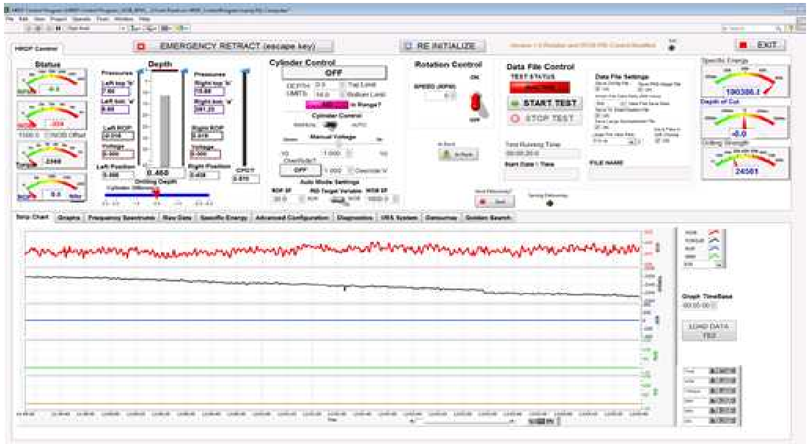
	Rock 1	Rock 2	Rock 3
Sandstone	84.6%	14.9%	0.4%
Concrete	11.1%	86.0%	2.8%
Granite	0.2%	0.6%	99.2%

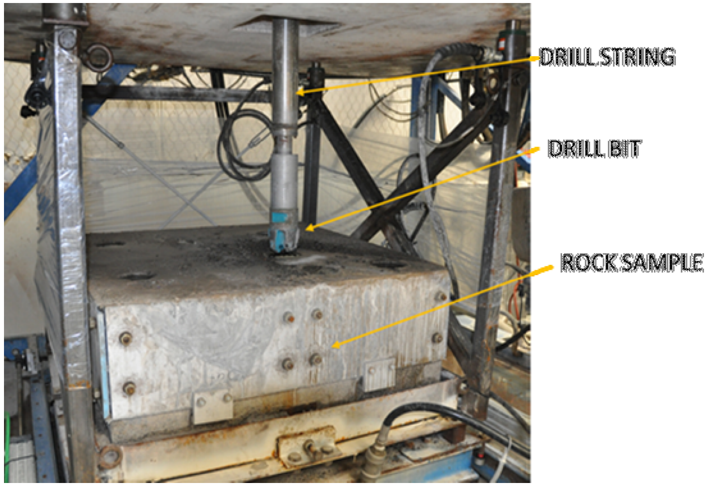
Similarities between concrete & sandstone in some regimes produce ~15% confusion

Experimental Apparatus

Sandia National Laboratories

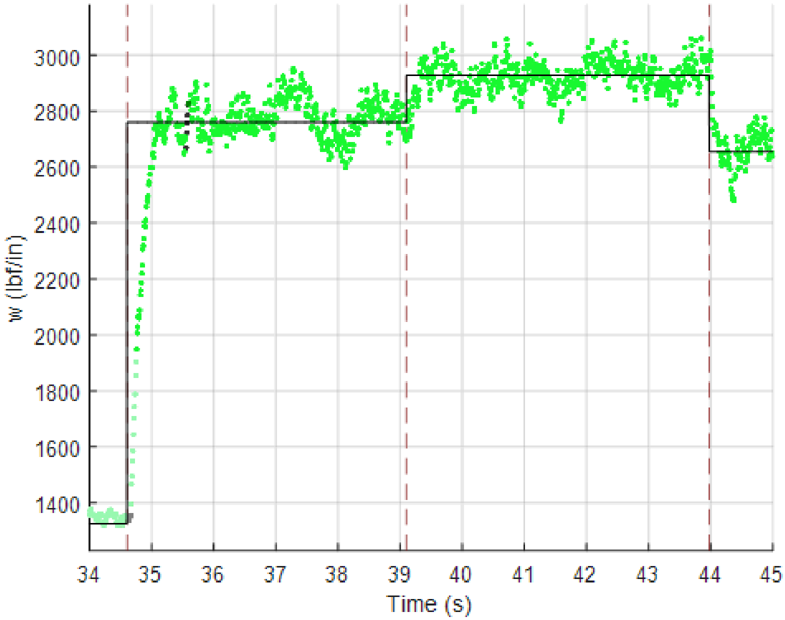
- Sandia Hard Rock Drilling Facility
  - Up to 6k lbf, 560 ft*lbf
- 3.75” Ulterra 5-blade PDC bit
- Classifiers trained on uniform materials
- Autonomous drilling tests done on concrete-granite multilayer samples
- Labview control interface / operator display



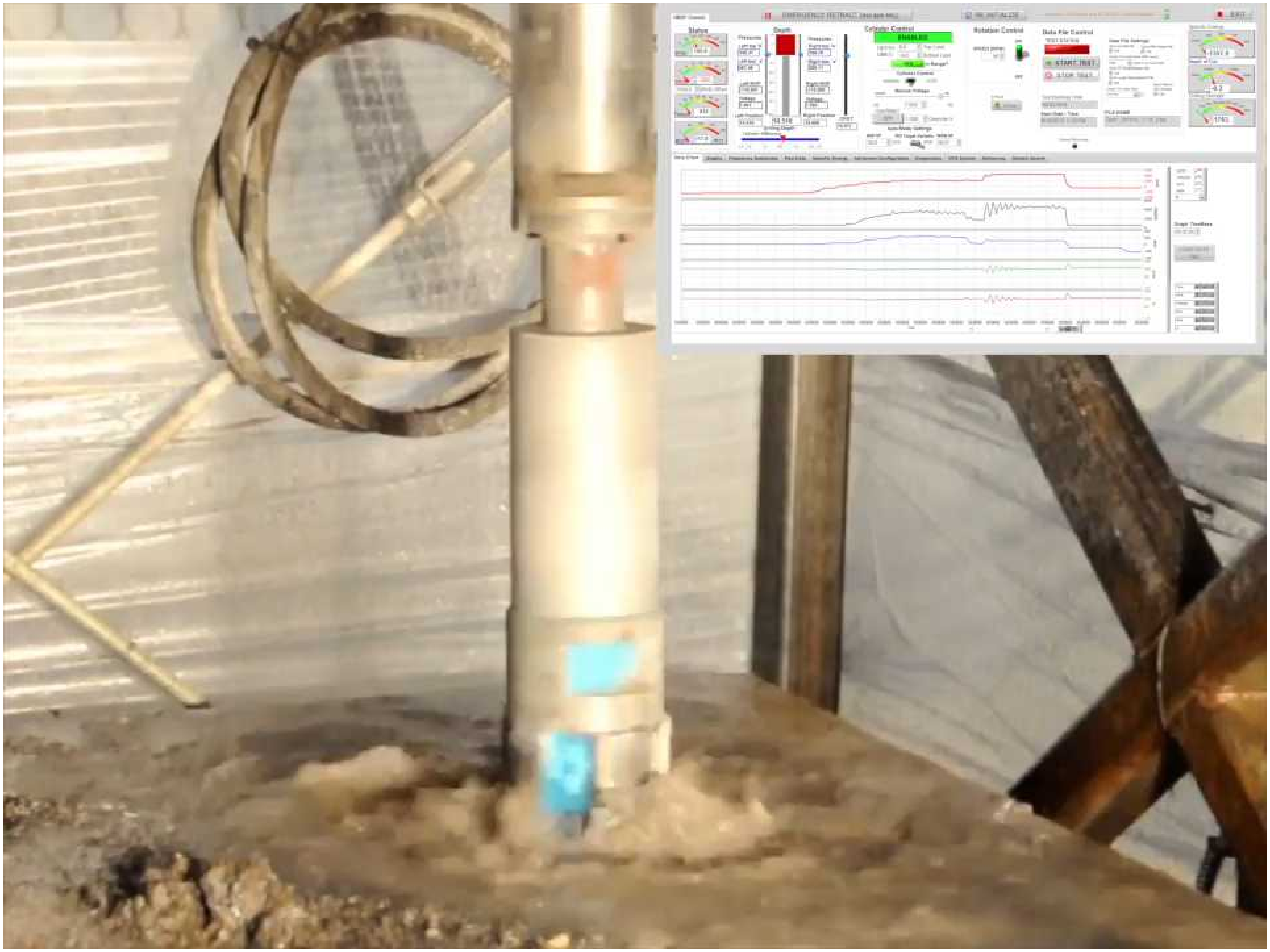


Low-Level Closed-Loop Control

- Angular velocity control
  - Voltage-controlled proportional valves modulate hydraulic flow to motor
  - Pressure relief valve limits torque
  - PI control
- WOB control
  - Voltage-controlled proportional valves modulate cylinder pressure
  - PI control
    - Rise time ~0.1 s for small steps, ~0.5 s for larger steps (nonlinear)

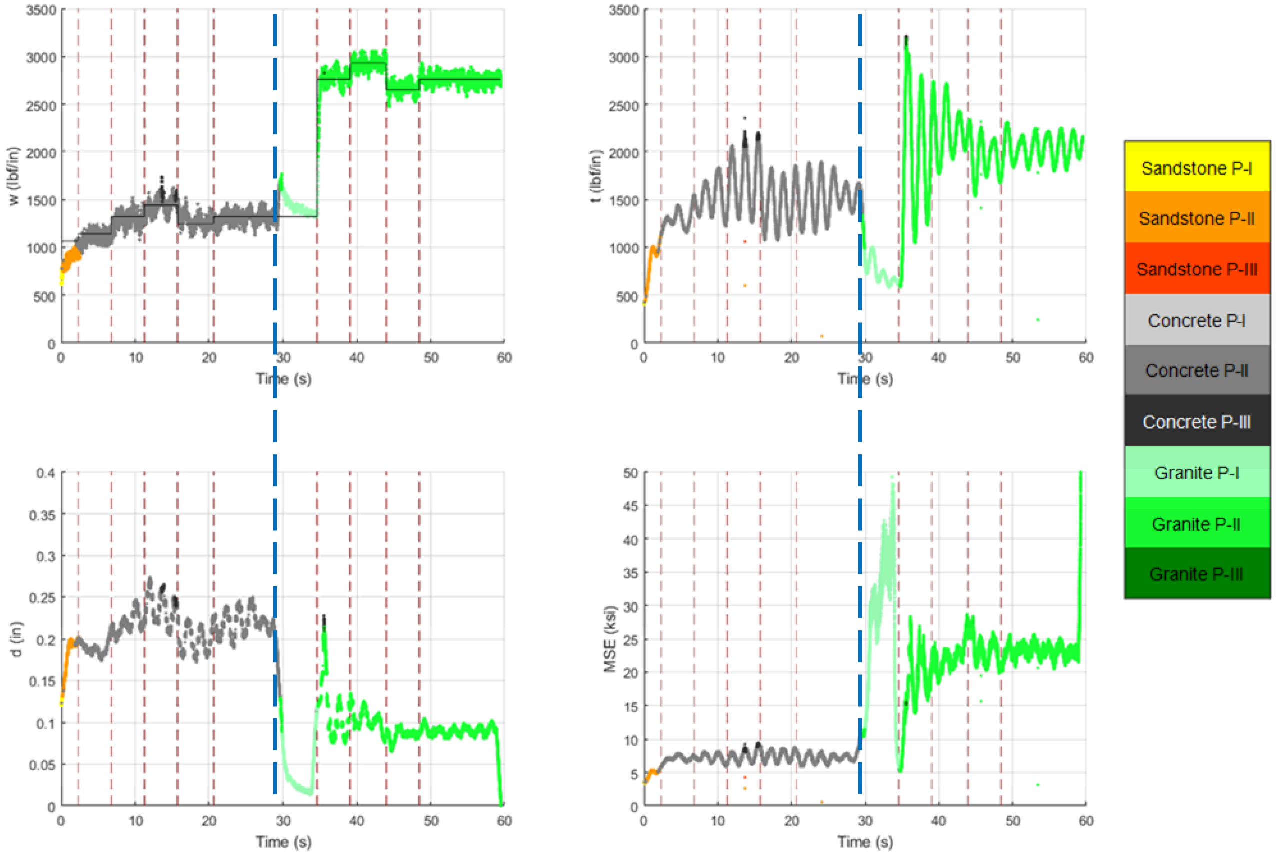


Multi-Material Autonomous Drilling Video



Multi-Material Drilling Results

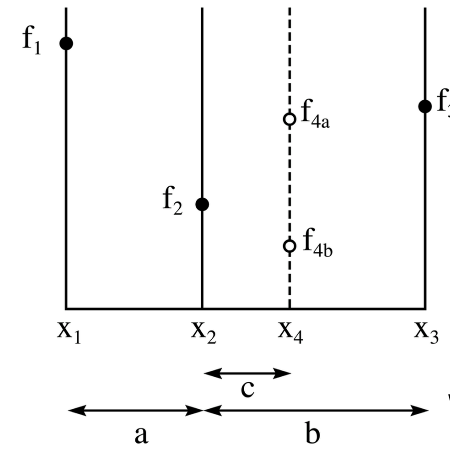
- ω=100 RPM, WOB controlled
- Each material change triggers golden WOB search around lookup setpoint
- Concrete
  - Locates MSE minimum
- Granite
  - 4-5 s filter lag
  - Locates MSE minimum again
  - Much higher WOB



Local Optimum Search (Golden Section Search)

- Golden section search for optimum of unimodal function
  - Previous 3 samples define bounding interval of optimum
  - Define probe point preserving golden ratio (1.618) of triplet spacing; ensures steadily decreasing interval regardless of results

- Concrete results:
  - MSE is relatively insensitive to WOB changes in this regime
  - Indicates initial setpoint is close to optimum



If f_{4a}:

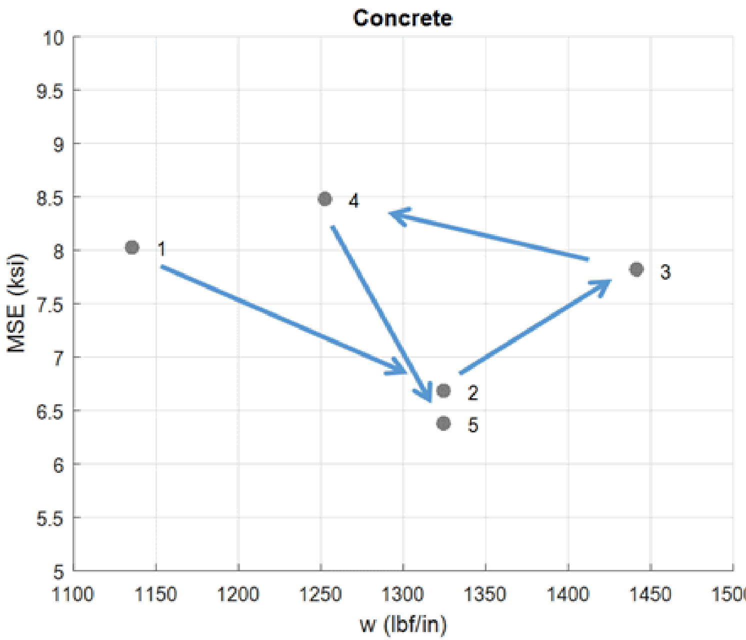
$$\frac{c}{a} = \frac{a}{b}$$

If f_{4b}:

$$\frac{c}{b-c} = \frac{a}{b}$$

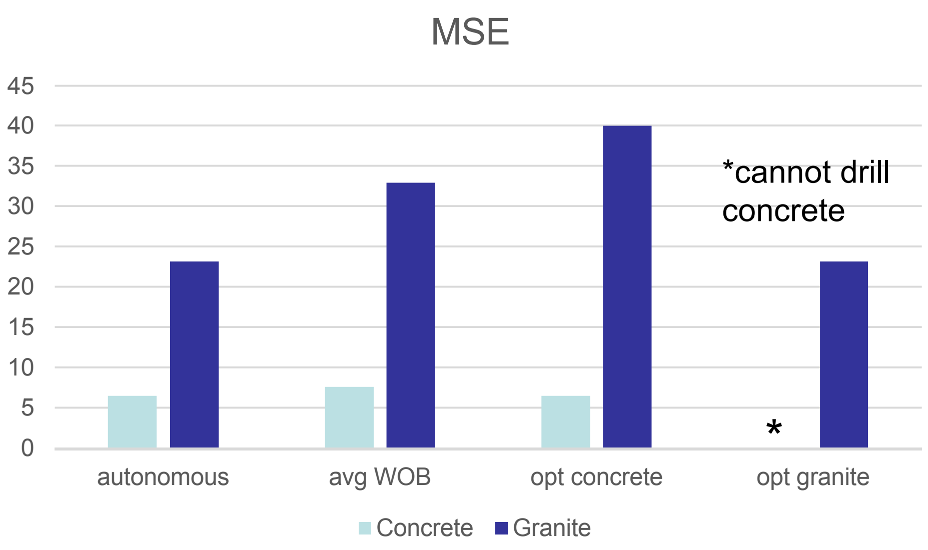
$$\frac{b}{a} = 1.618$$

Wikipedia.com



Comparison to Fixed Control Settings

- Performance, measured by MSE, dramatically exceeds that of any single fixed WOB setting
- Autonomous optimum w:
  - Concrete: 1320 lbf/in
  - Granite: 2780 lbf/in
- Alternatives
  - Intermediate w: 2050 lbf/in
    - MSE higher in both materials
  - Optimal for concrete: 1320 lbf/in
    - MSE almost 2x higher in granite
  - Optimal for granite: 2780 lbf/in
    - Pathological drilling in concrete (phase 3)



To get the best drilling, it is necessary to tune WOB in real-time

Autonomously selected MSE values approach material strength limit, indicating highly efficient drilling

Discussion and Future Challenges

- Key next steps
  - Implement anti-stall control (safeguard for hard-to-soft transitions)
  - Expand material library
    - Greater density of parameter sets will result in increased confusion between materials
    - To what extent will local search optimization compensate?
    - Explore adding Bayesian update to incorporate historical data in estimating rock type
  - Move toward real-world drilling
    - Model wear state of bit and update material parameters accordingly
    - Account for downhole pressure, which also affects drilling model parameters
    - Poor downhole measurement resolution, drillstring compliance, and other non-ideal factors