Development of a Measure While Drilling System

Markus Timusk[1], Greg Lakanen[1], Dale Boucher[2].
[1]Bharti School of Engineering, Laurentian University, Sudbury Ontario
[2]Northern Centre for Advanced Technology, Sudbury Ontario

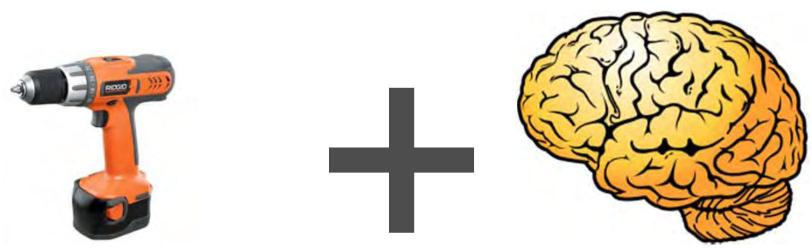
Intelligent MWD System

MWD Planetary Substrate Identification System Development

- Proposed technology is part of a larger NORCAT project involving a TRL 5 prototype of a rover-based drill
  - Can also be mounted on a fixed base (e.g. lander)
- Technology will demonstrate Canadian expertise in planetary drilling for future exploration missions
- Supports the concept of NASA's next generation RESOLVE mission.

Measure While Drilling: Overview

- End objective:
  - Develop additional functionality to planetary drills. From a tool for gathering core samples
    - Decision support
    - Science instrument
  - a robust system architecture that would permit a MWD system to be readily integrated into a NORCAT planetary drill system
  - develop an understanding of which parameters are most useful for MWD



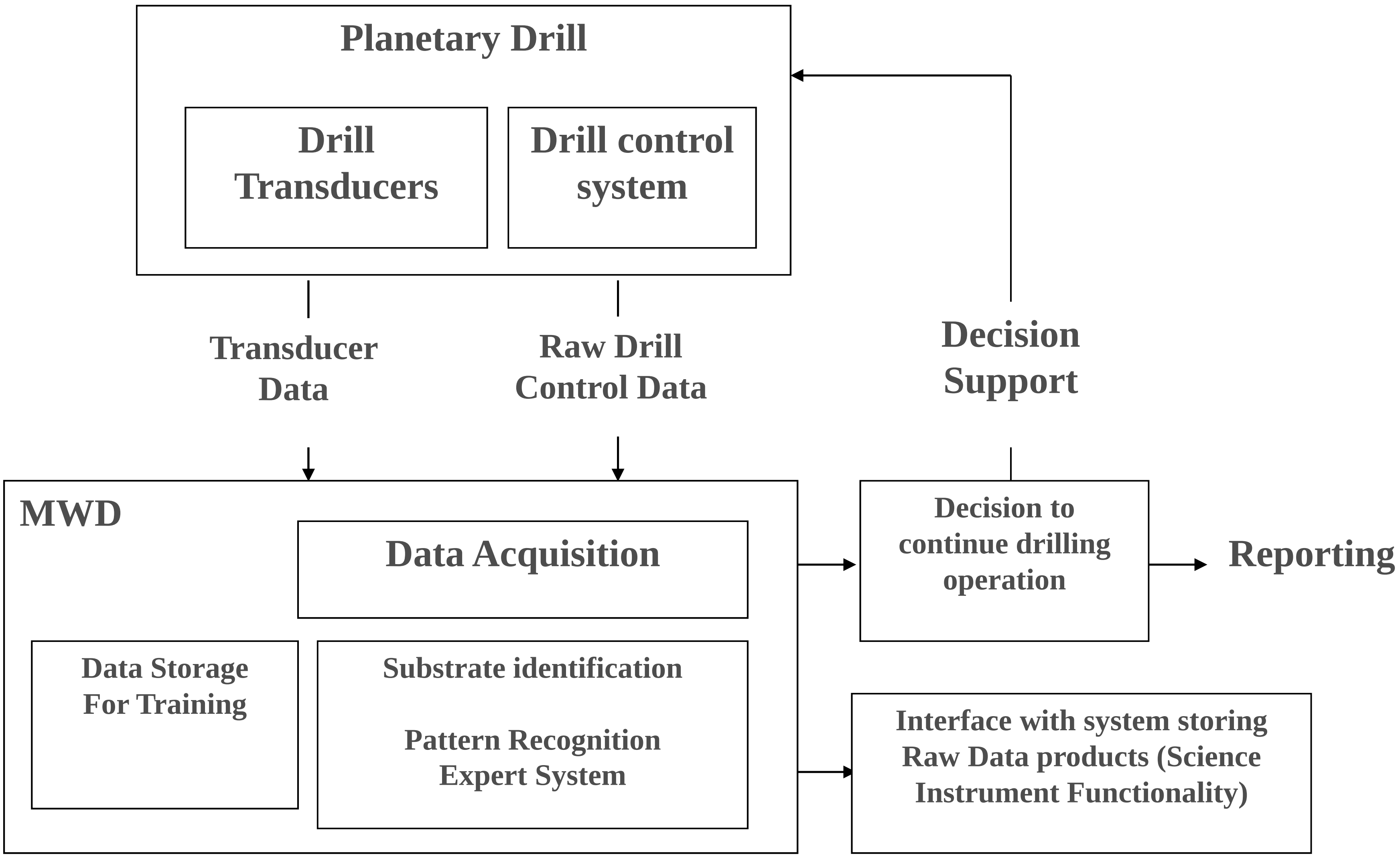
Decision Support Scenario

- In situ substrate identification
  - Rock or ice bearing regolith
  - Decision support: continue drilling or to abort the hole
- Avoidance of Hazardous Drilling Conditions
  - Ex: drill encounters a partially exposed rock protruding into the bore hole
  - This condition can result in accelerated bit wear or damage to diamond cutters.
  - Extend equipment life

Science Instrument Scenario

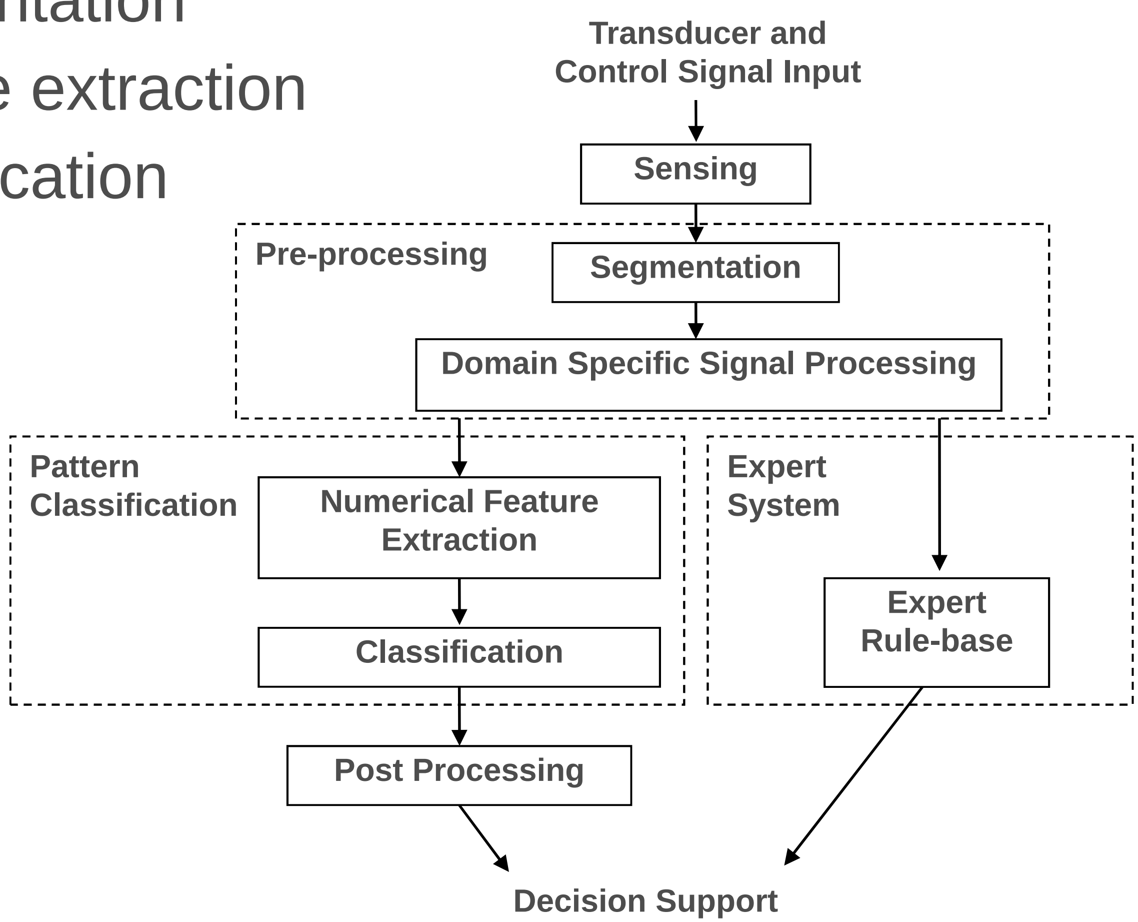
- Use drill to gather key geotechnical and mechanical characteristics of the material (Strength, hardness etc.)
- Data can also be stored and corroborated with data collected from sample analysis
- Data from multiple holes could be used to predict geological makeup of larger areas

Conceptual Implementation



Data Flow

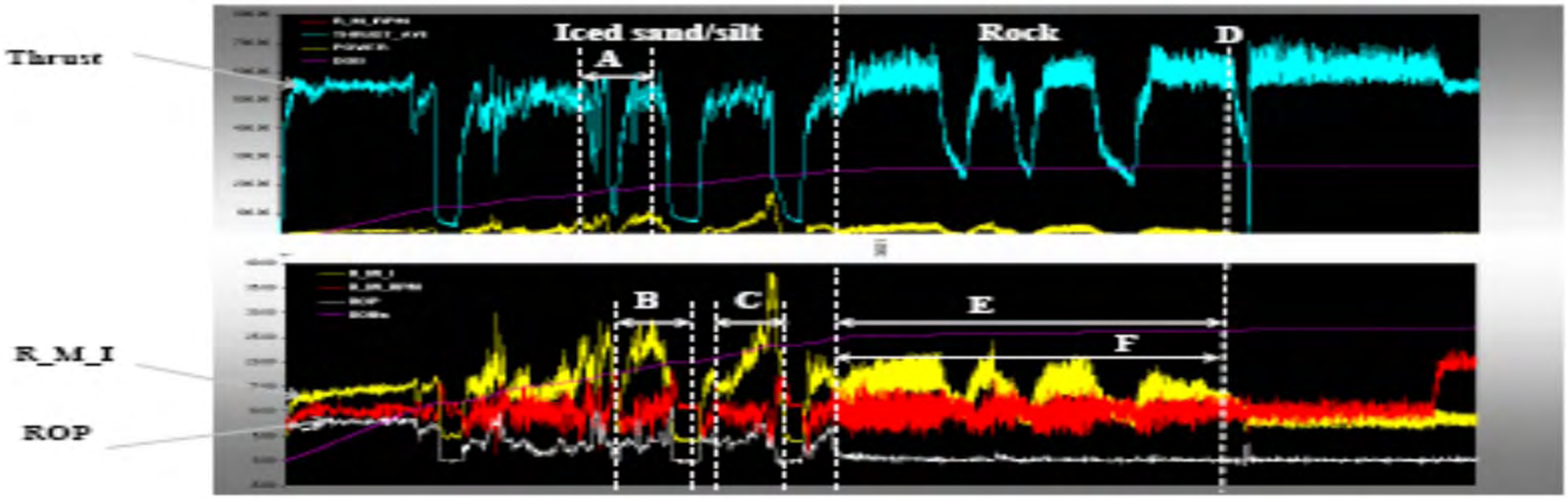
- Map data from the sensor signals to the end goal of substrate identification through:
  - Segmentation
  - Feature extraction
  - Classification



Is this feasible?

Is this feasible?

- Technically feasible based on:
  - Previous findings at NORCAT
  - Literature review
  - Relatively straightforward to incorporate into NORCAT's existing drill systems
- Various researchers have shown that the task of identifying substrates is possible using an instrumented drill
  - Prediction of strata in coal mine using thrust, ROP (95% confidence)
  - Characterise the structural integrity of tunnels before material is excavated
  - Statistical pattern recognition to ID rock types to optimize blasting

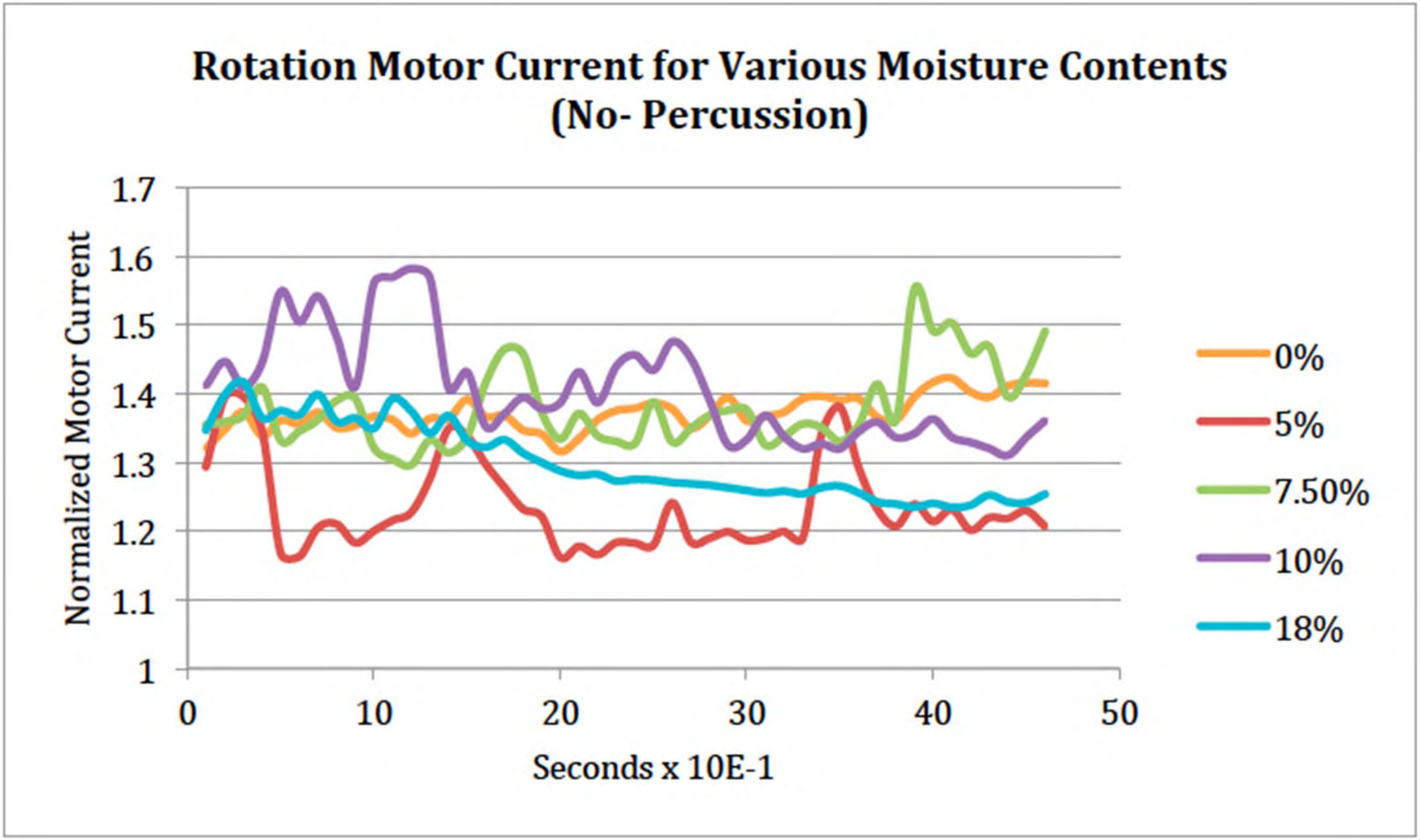


<u>Parameter</u>	<u>Iced Sand/Silt</u>	<u>Rock</u>
Thrust	Significant variations	Relatively constant
R_M_I (current)	Continually ramped up, paused to clear	Lower, comparatively flat
ROP (rate of penetration)	High	Minimal, constant

Initial Investigation: Is this a trivial task?

- Before resorting to:
  - Advanced and more computationally intensive methods of signal processing or high dimensional feature extraction and classification for MWD…..
- The work first investigated the basic response and relationships of the control parameters to moisture content
  - rotation motor current, measured rate of penetration and measured thrust to the varied levels of moisture content and substrate types in the unconsolidated material.

Initial Investigation: Is this a trivial task?



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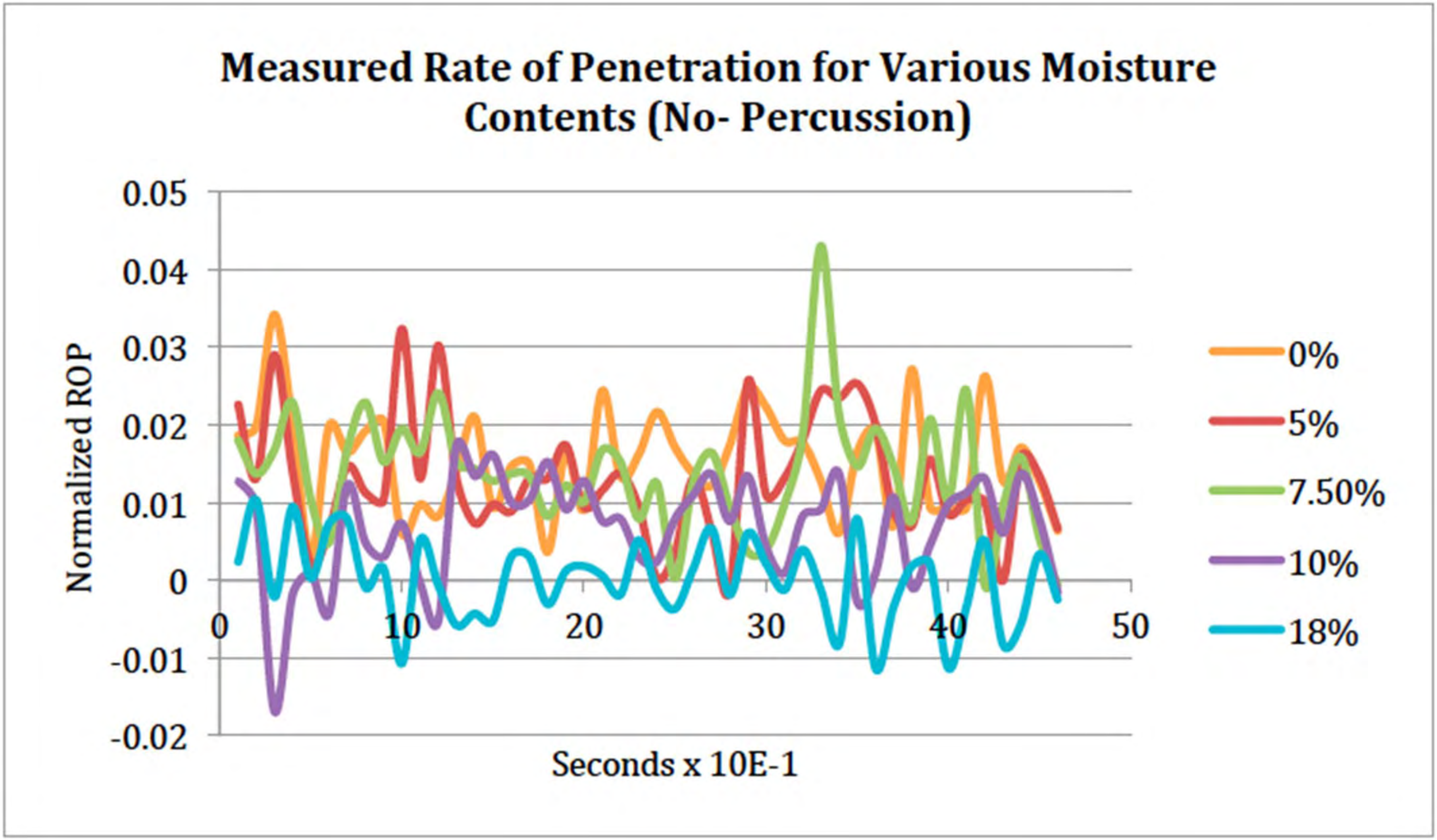

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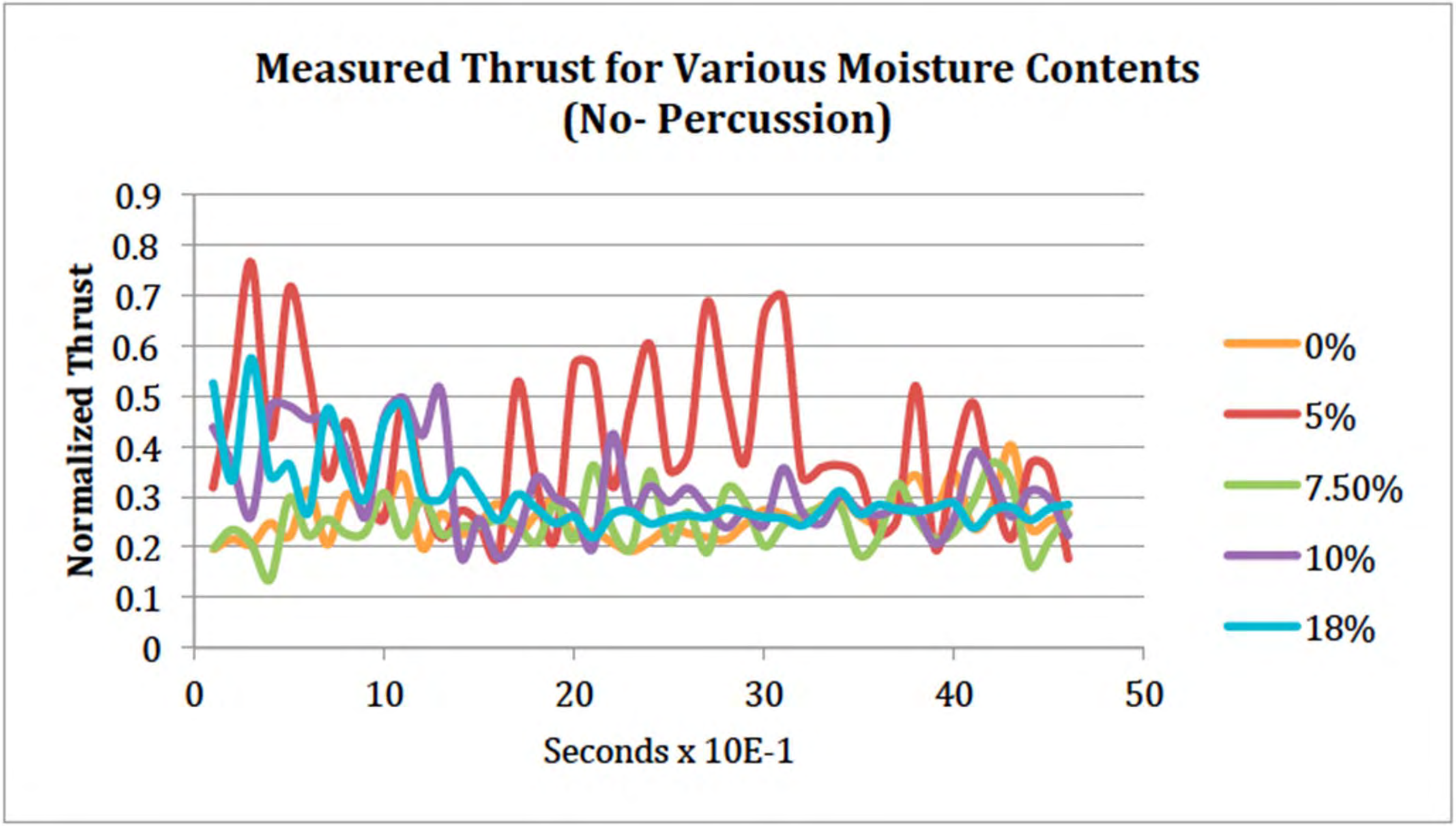
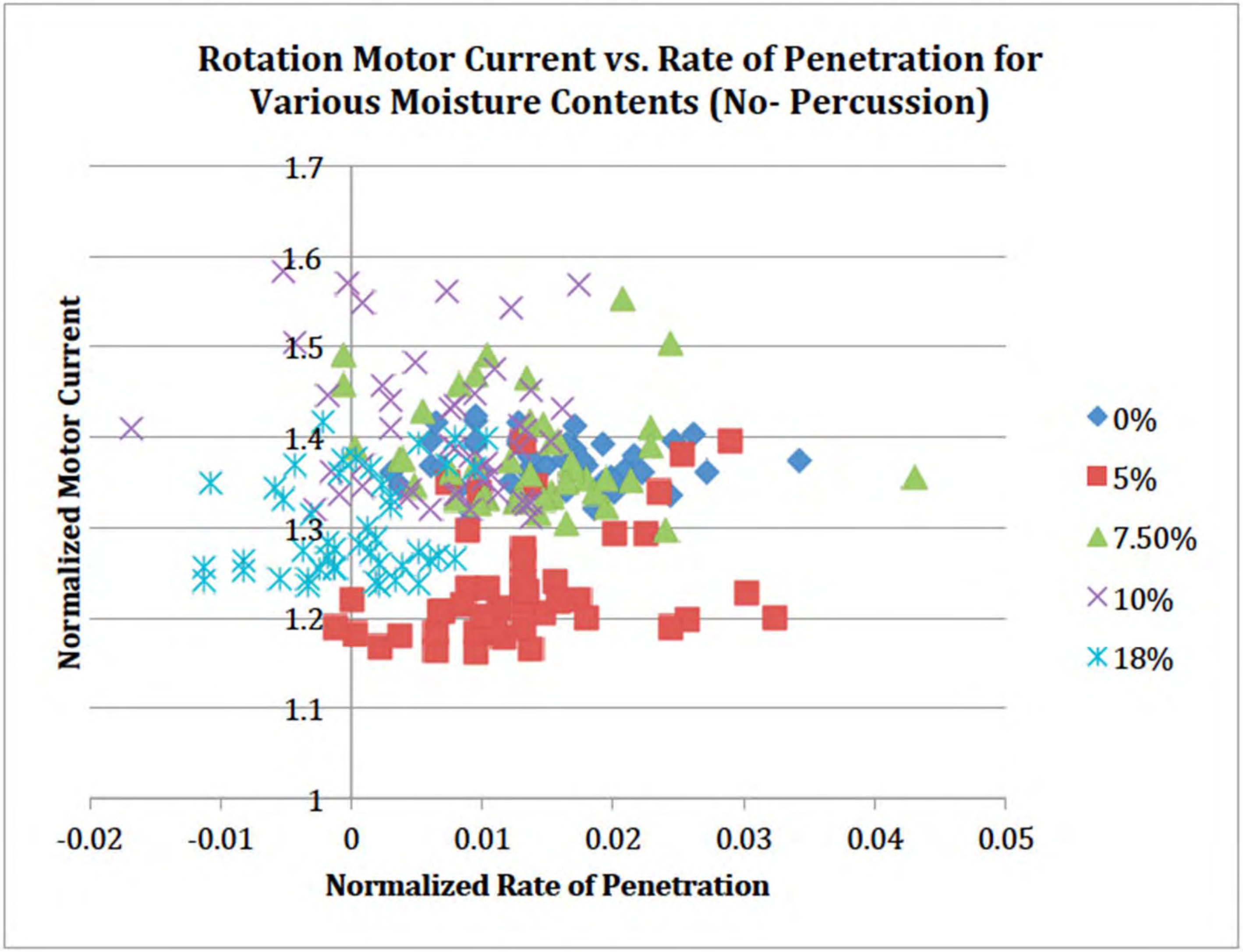
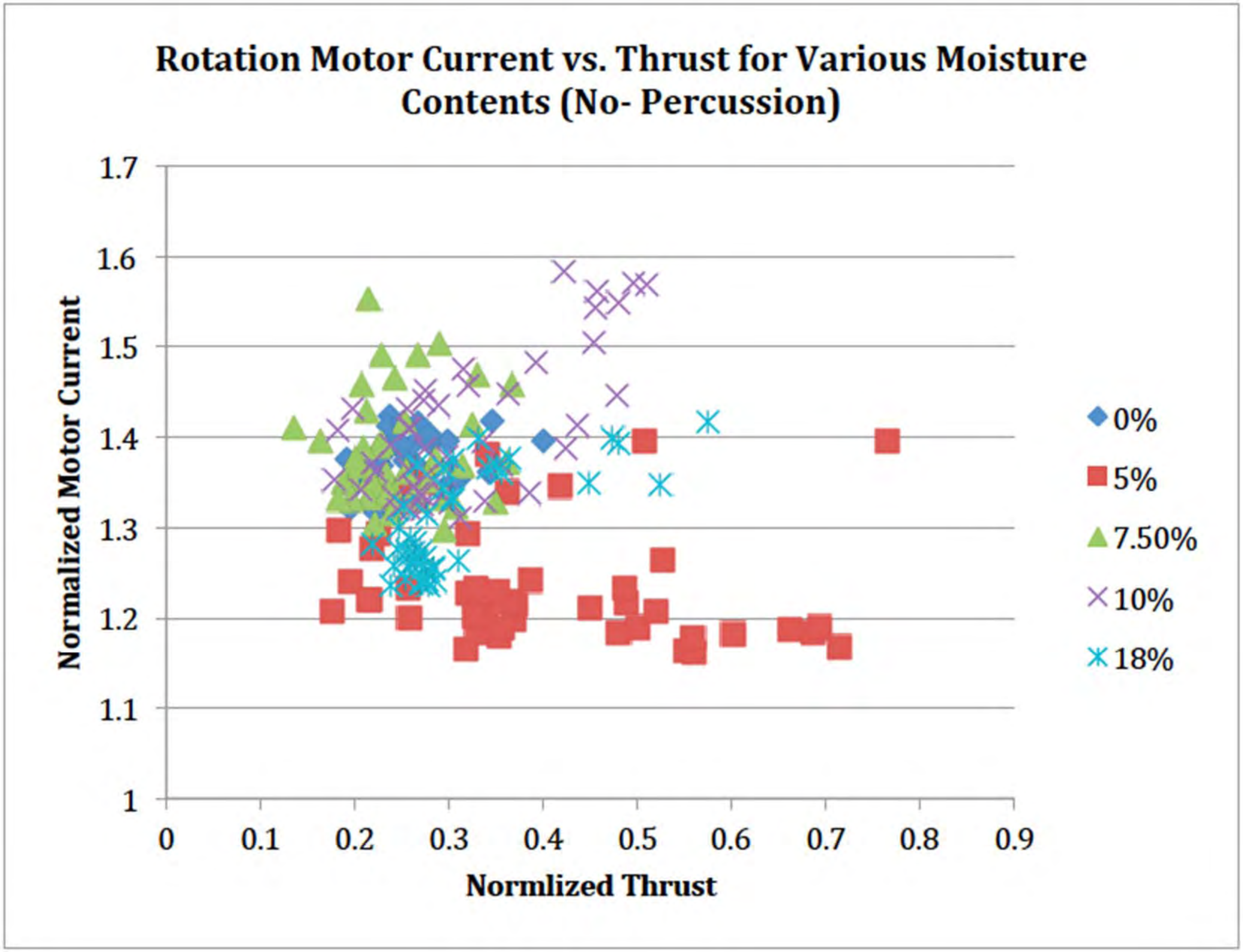




Rotation Motor Current vs. Rate of Penetration for Various Moisture Contents (No- Percussion)
Normalized Motor Current
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
-0.02
-0.01
0
0.01
0.02
0.03
0.04
0.05
Normalized Rate of Penetration
0%
5%
7.50%
10%
18%

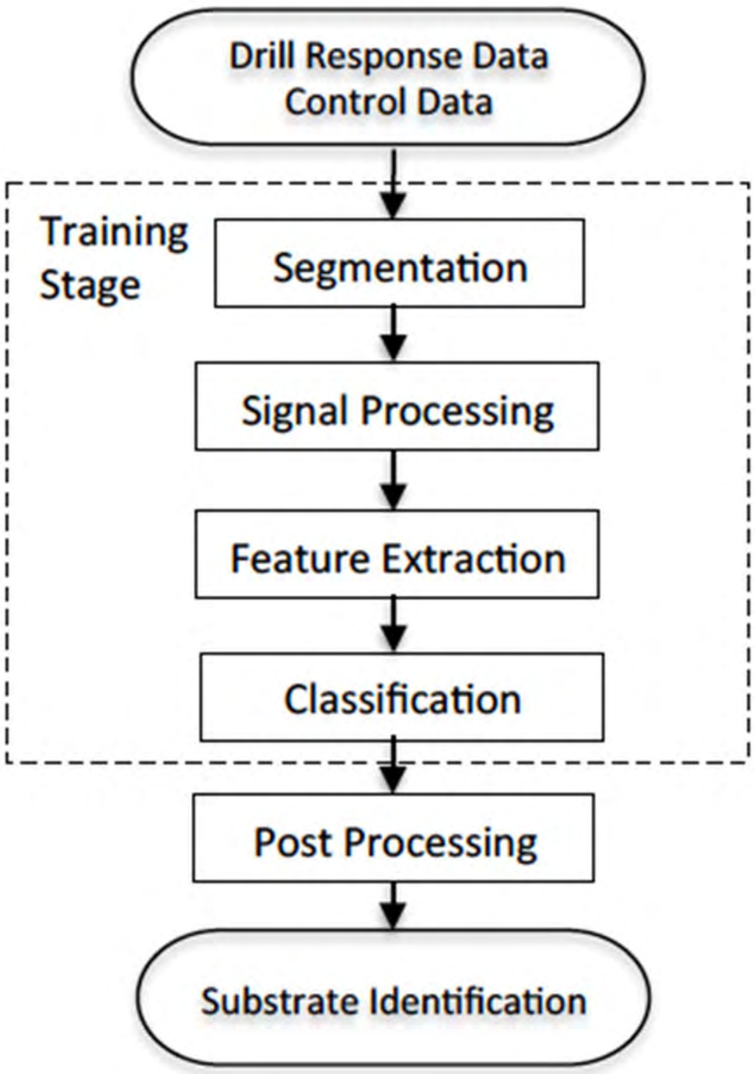


Rotation Motor Current vs. Thrust for Various Moisture Contents (No- Percussion)
Normalized Motor Current
Normlized Thrust
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0%
5%
7.50%
10%
18%

Initial Investigation: Is this a trivial task?

Conclusion:

- MWD is a non-trivial classification problem.
- MWD will require the use of additional:
  - parameters,
  - Features
  - Multi-dimensional classification tools.



Data Collection

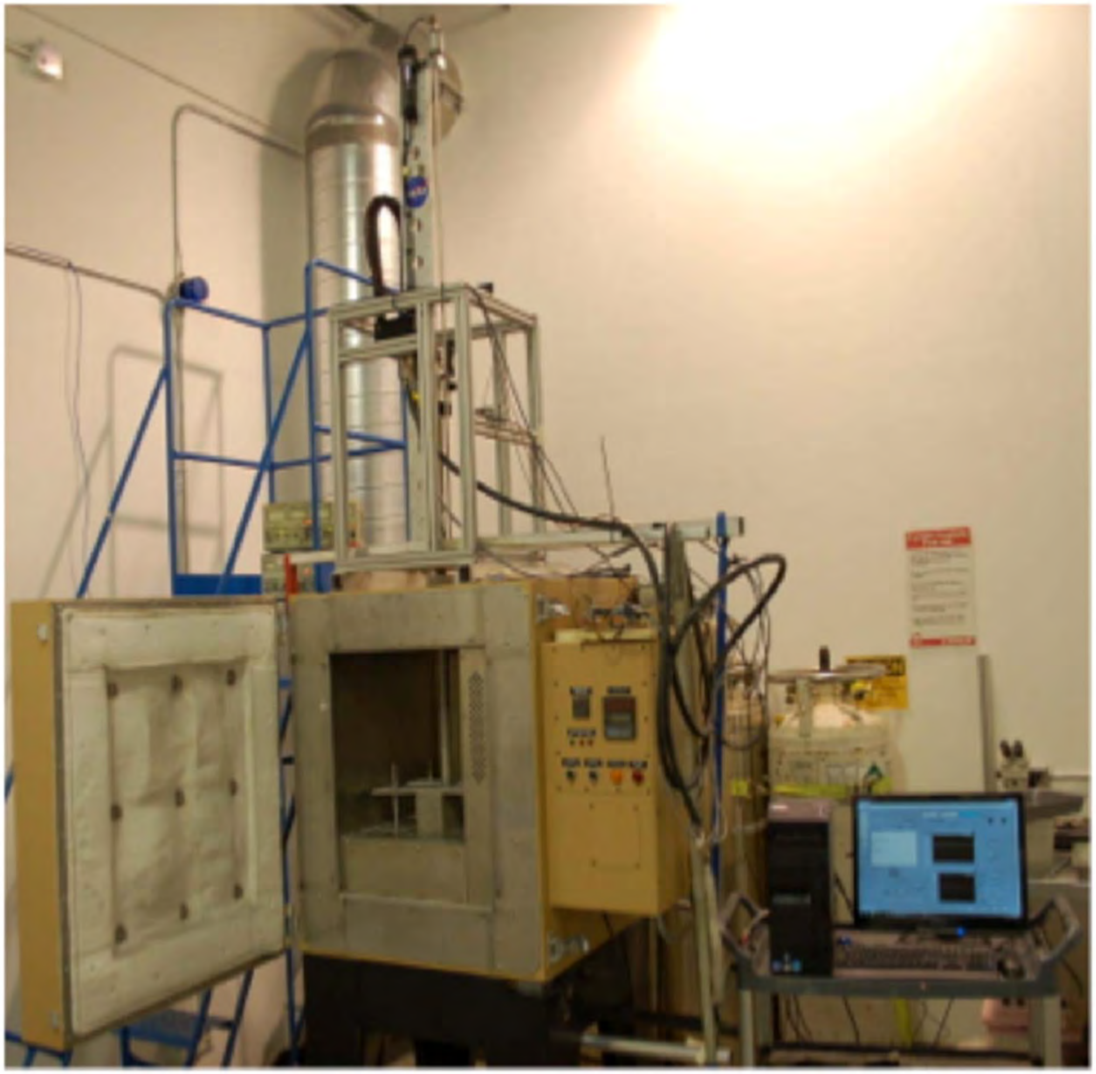
Decision Support System Development: Data Collection

Requires Data That:

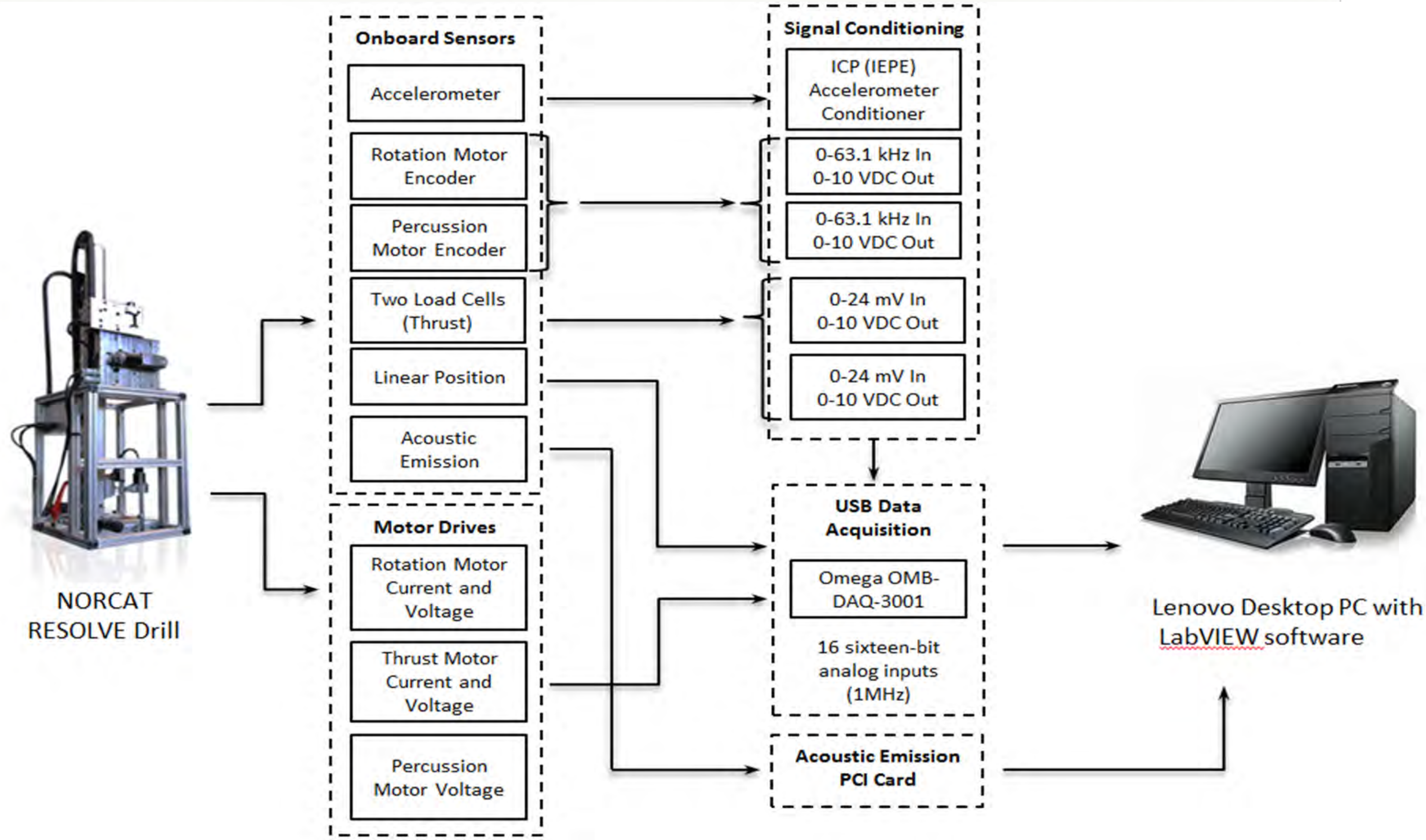
- Characterises the response of the modified NORCAT RESOLVE EBU2 drill penetrating a range of substrates under controlled conditions
- Can be used for training, optimization and testing of classification system
- Can also be used to demonstrate science Instrument capability

Data Collection Setup

- The prepared vessel containing the sample placed in the cryotemper (-175° C).
- The instrumented drill will be placed on top of the cryotemper
- the drill bit accessed the frozen CHENOBI within the chamber by means of the top port in the cryotemper.
- Drilling depth range between 10 to 90 mm.

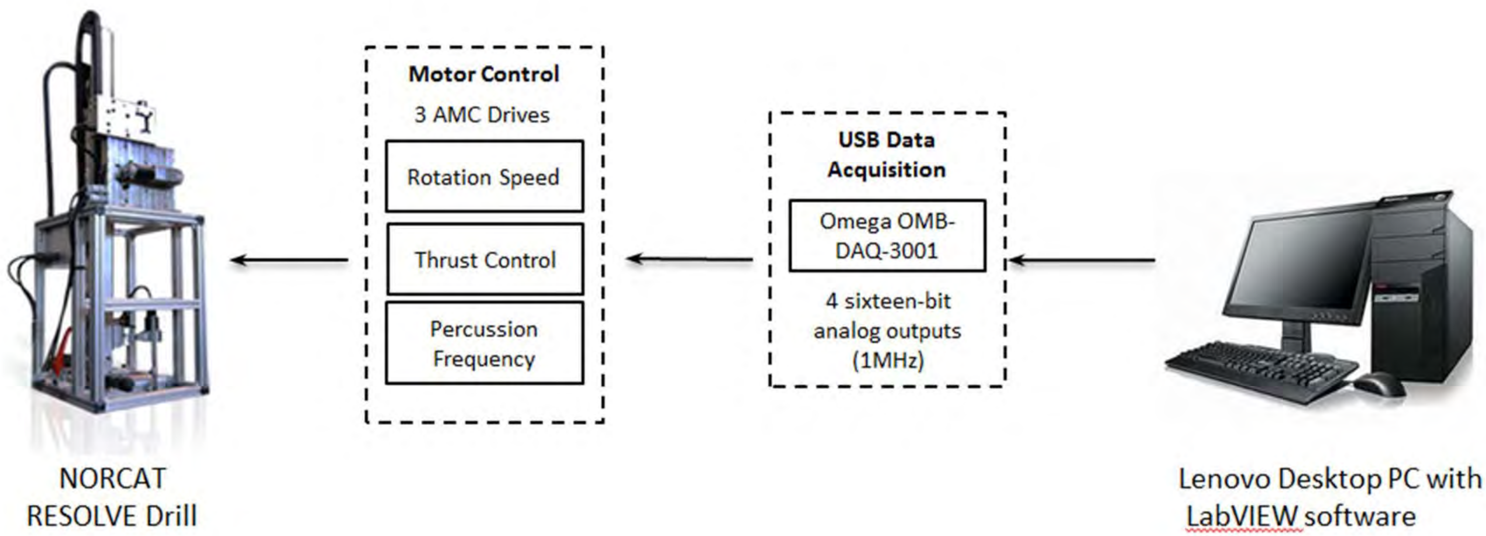


Drill Instrumentation



- Direct instrumentation of the control system of drill and sensors mounted on the drill
- Training data collection and analysis
  - Collection of large, time dependent multivariate data set
  - Sensory and control data collected during supervised drilling of known substrates

Drill Control System

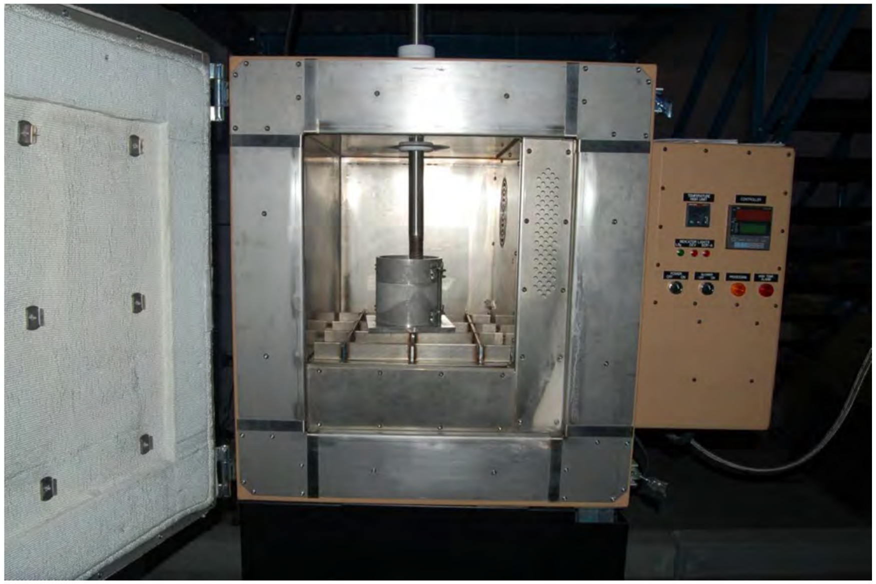


Control of drilling process:

- The instrumented drill will penetrate the sample under specified operating conditions regulated by the MWD control system.
- With and without percussion
- Closed loop (PID) control will be used to control
  - Drill speed (encoder feedback signal)
  - Thrust (load cell feedback)

Samples Tested

- Data collected from drilling of both consolidated and unconsolidated material



Substrates:

- Basalt
- Anorthosite
- Dolomite
- Regolith Simulant
  - compacted Chemically Enhanced OB-1 (CHENOBI) lunar highlands regolith physical simulant
  - 0%, 5%, 7.5%, 10% and 18% moisture content by weight
  - at cryogenic temperatures and standard temperature pressure.

Data analysis

Pre Training Scenario

- The most direct approach to the training and deployment of a MWD system is to train the system to recognize the range of expected substrates under simulated laboratory conditions prior to the mission.
- Once deployed, the system would then compare extracted features from new (unclassified) measurements to features from the database assembled in the laboratory prior to the mission.
- The clear limitation of this approach is the dependency of MWD system on the similarity of data from the (simulated) laboratory conditions to the conditions in-situ.
- This type of system would also not be capable of identifying any data that it was not trained on.

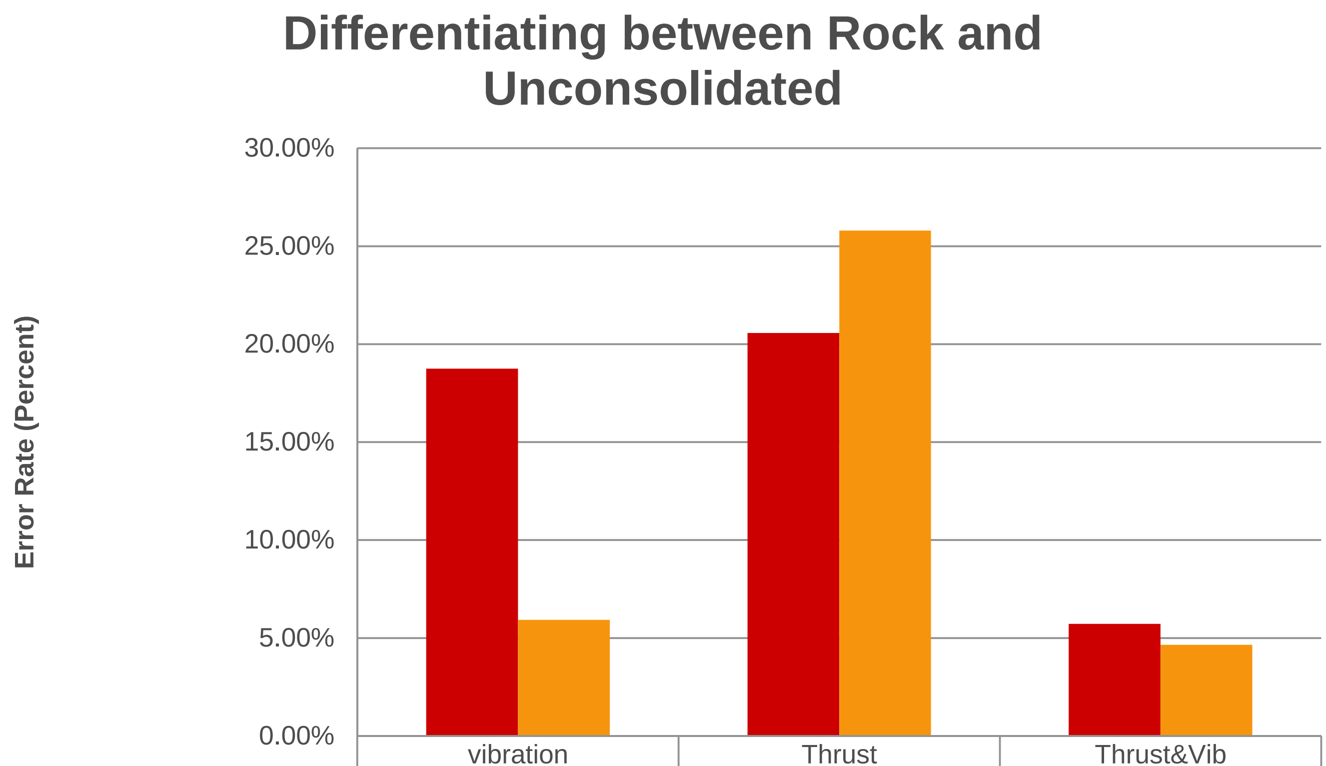
Analysis: Feature Extraction

- Features included drill control parameters (speed, thrust, rate of penetration) and vibration
- The vibration feature vectors were built from six statistical features and an autoregressive model (AR) of the vibration time waveform.
- The features included: RMS, kurtosis, impulse factor, crest factor, standard deviation, absolute mean and the coefficients of an autoregressive model of the tenth order.
- The thrust measurement time signal was processed to form a feature vector (referred to here as the thrust feature vectors) built from 7 statistical features: RMS, kurtosis impulse factor, crest factor, standard deviation, average and absolute mean.

Analysis: Classification

- A range of classifiers were trained in order to determine the separation of the data representing different substrates and drilling modes.
- Classification was achieved via feed forward neural networks, with three hidden layers, trained by backpropogation network training function (Levenberg-Marquardt back-propagation algorithm).
- Future work will involve more advanced features and classification methods.

Preliminary Results

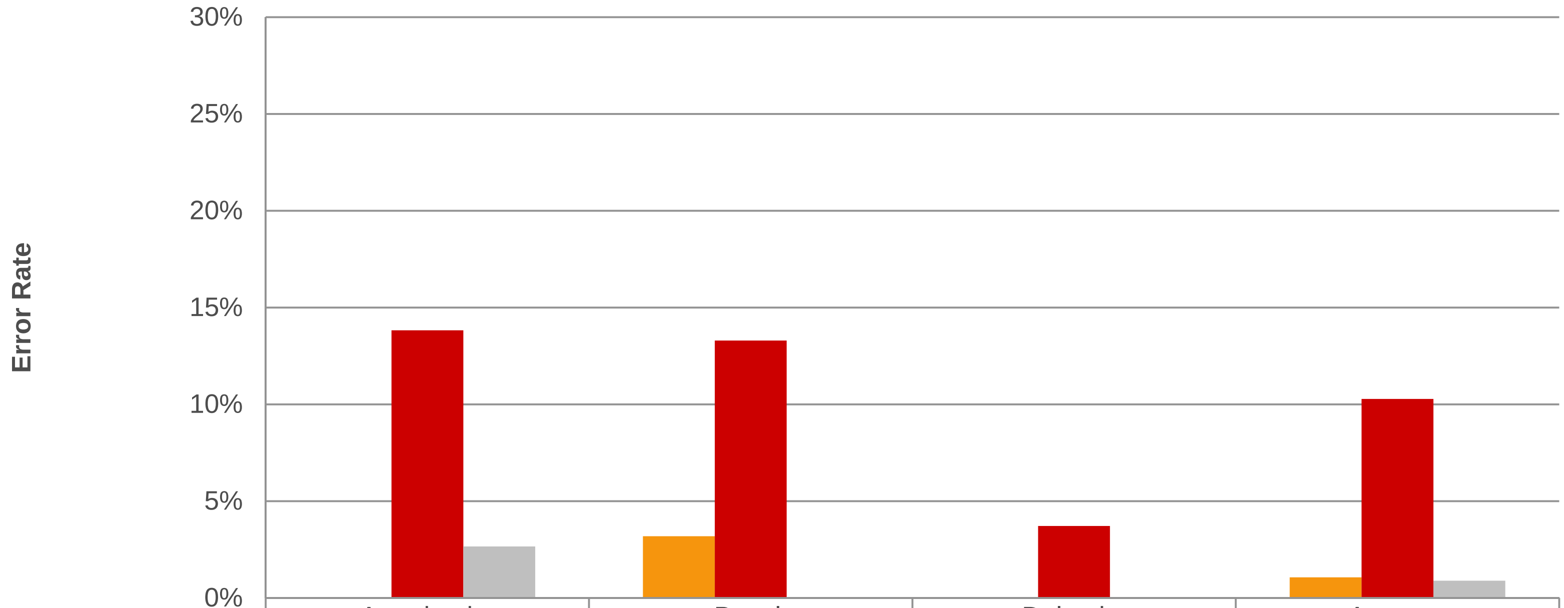


	vibration	Thrust	Thrust&Vib
Tests With Percussion	18.75%	20.57%	5.72%
Tests Without Percussion	5.93%	25.80%	4.65%

- **Initial classification results for drilling response in all materials**

Preliminary Results

Distinguishing Rock Type From Tests Without Percussion

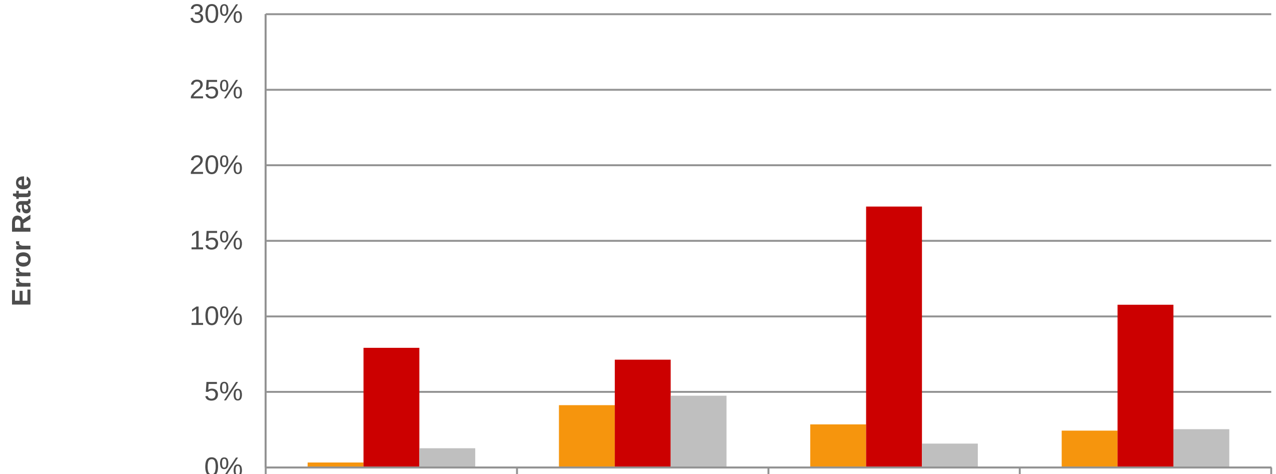


	Anorthosite	Basalt	Dolomite	Average
Vibration	0.00%	3.19%	0.00%	1.06%
Thrust	13.83%	13.30%	3.72%	10.28%
Thrust & Vibration	2.66%	0.00%	0.00%	0.89%

- **Initial classification results for drilling response in rock without percussion**

Preliminary Results

Distinguishing Rock Type From Tests With Percussion

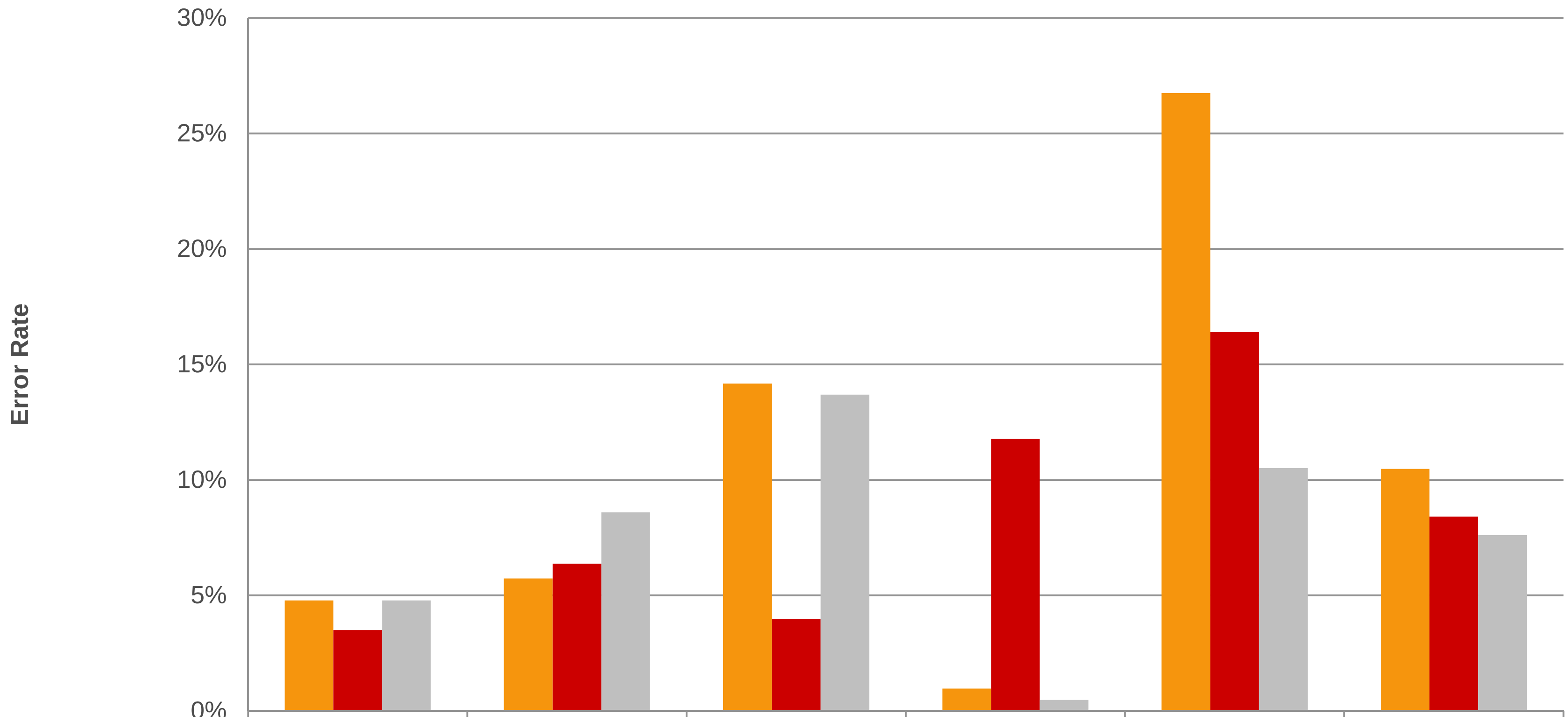


	Anorthosite	Basalt	Dolomite	Average
Vibration	0.32%	4.12%	2.85%	2.43%
Thrust	7.92%	7.13%	17.27%	10.77%
Thrust & Vibration	1.27%	4.75%	1.58%	2.53%

- **Initial classification results for drilling response in rock with percussion**

Preliminary Results: Moisture Content

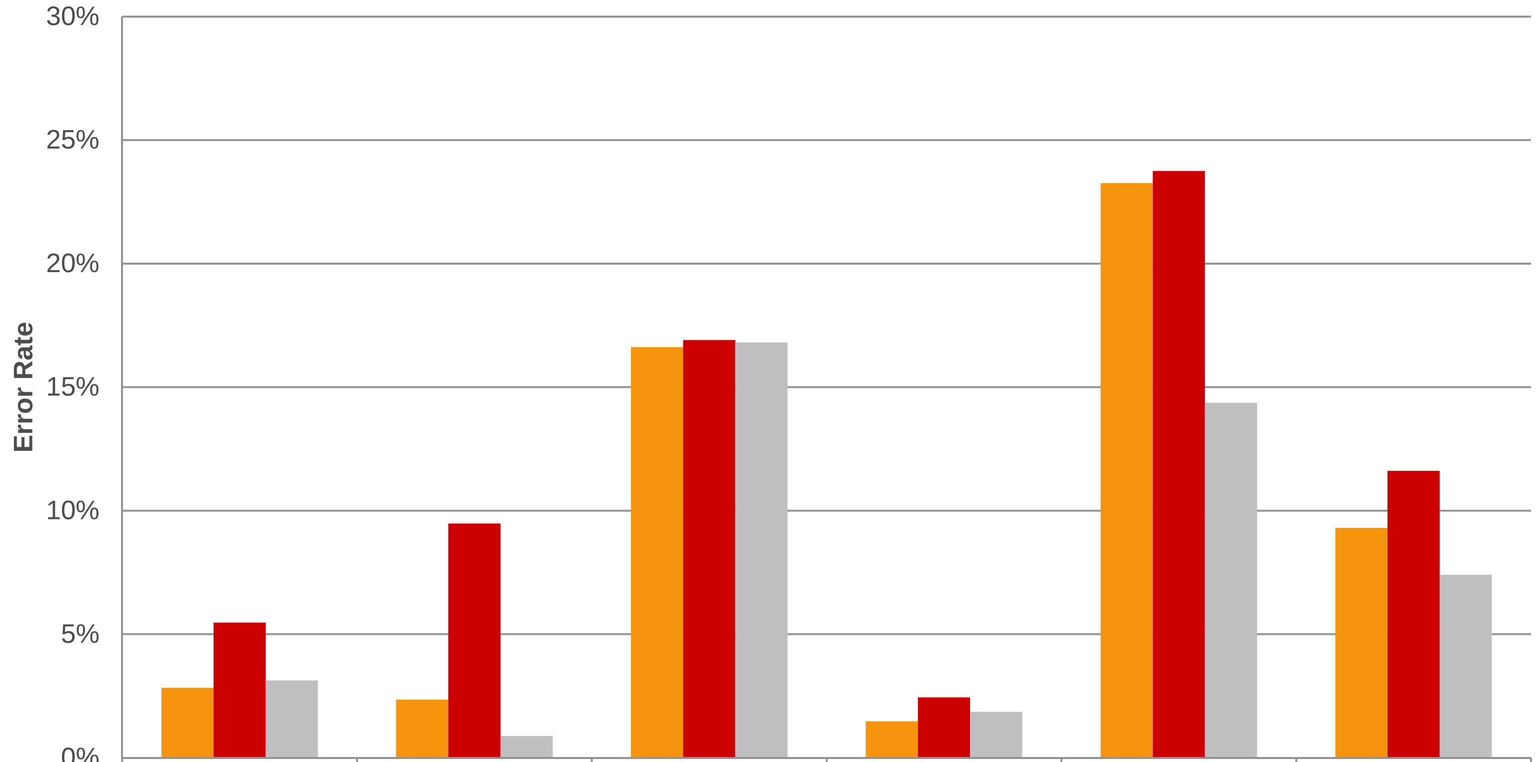
Distinguishing Moisture Content From Tests With Percussion



	Chenobi 0%	Chenobi 5%	Chenobi 7.5%	Chenobi 10%	Chenobi 18%	Average
Vibration	4.78%	5.73%	14.17%	0.96%	26.75%	10.48%
Thrust	3.50%	6.37%	3.98%	11.78%	16.40%	8.41%
Thrust & Vibration	4.78%	8.60%	13.69%	0.48%	10.51%	7.61%

Preliminary Results: Moisture Content

Distinguishing Moisture Content From Tests Without Percussion

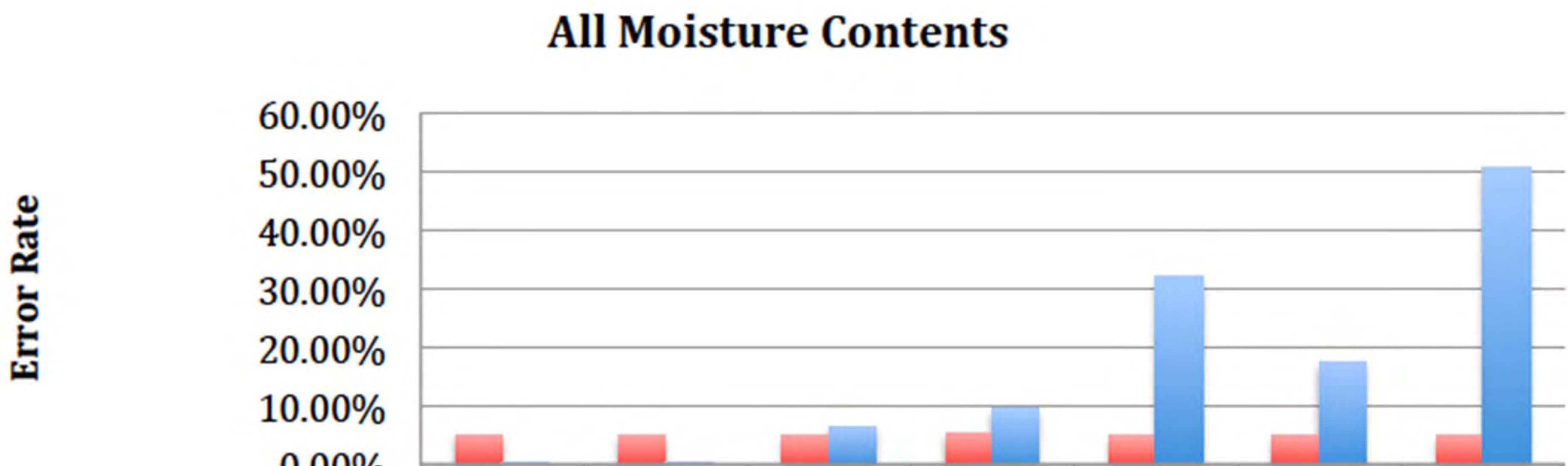


	Chenobi 0%	Chenobi 5%	Chenobi 7.5%	Chenobi 10%	Chenobi 18%	Average
Vibration	2.83%	2.35%	16.62%	1.47%	23.26%	9.31%
Thrust	5.47%	9.48%	16.91%	2.44%	23.75%	11.61%
Thrust & Vibration	3.13%	0.88%	16.81%	1.86%	14.37%	7.41%

In-Situ Training Scenario

- In-Situ Training Scenario: the MWD system depends on the confirmation of material type **during the mission** resulting from the analysis of the captured drill core samples that is processed through the LAVA Gas Chromatograph/Mass Spectrometer and OVEN systems.
- The classification approach of novelty detection offers several practical advantages when applied to the task of substrate identification. These advantages relate to the data available:
- The ability to identify substrates without relying on laboratory simulated training data fault data.
- The ability to classify previously unseen substrates.

Novelty Detection Error Rates for Classifying



	Control and AE 5KHz	Control and Vib 5KHz	Control and Vib AR Model 5KHz	Vibe Stats Only 5KHz	Vibration AR Model 5KH	Control Stats Only 5KHz	Control and Vib 100Hz
False Negatives	5.21%	5.04%	5.01%	5.42%	4.90%	5.15%	5.13%
False Positives Total	0.5%	0.2%	6.6%	9.5%	32.2%	17.6%	50.7%

Overall Conclusions

From the first round of testing (terrestrial pre-training):

- MWD system is capable of differentiating between various ranges of moisture contents of unconsolidated material and identify types of rock.
- This approach would require prior training of the drill in simulated conditions.
- System would be only as good as the training data.

Overall Conclusions

The second round of testing (in-situ training):

- employed the novelty detection approach and assumed that there was no data available in advance of the mission.
- This round resulted in excellent classification results.
- However, the capability of MWD would be limited to the data generated by processing, analyzing samples and confirming substrates during the mission.
- The system would get smarter as it processed more samples.

Conclusion

- The Concept
  - Concept is technically feasible:
    - It is possible to determine rock type and moisture content
  - Could assist with mission decision support
  - Would make a valuable science instrument
  - Could be implemented with minimal additional payload
- Next Steps
  - Further data collection of more samples
  - Pattern recognition system development
  - Optimization of features, signal processing, data compression
  - Pilot System Development
  - System Validation

Acknowledgements

NORCAT

CSA ASC