Mobile Mining Machinery

Monitoring when fault modes are plentiful and sensors few.

Erik Jakobsson, 2022-09-07
Epiroc’s journey towards condition monitoring

Outline

• General application. Why is this hard for us? (And many others?)
• Difficulties with accessing data
  – Ownership
  – Environment
• Value versus cost
• My particular work as a PhD-student
  – Maximize value from single sensor on hydraulic rock drills
Background

The type of equipment we make
Mining

- Mine operator owns infrastructure, machinery, and data.
- Many different machines
- Many different manufacturers of machines
- Limited connectivity
Data access

Difficult for OEMs

- No communication on site / low capacity
- Infrastructure owned by customer (mine operator)
- Production data is considered sensitive
- Customers want data for themselves
- Service data, rarely recorded and/or proprietary
- Etc…

- However, the situation is steadily improving!
Worth it?
Reducing cost and adding value

- Less service cost
- No unexpected breakdown
- Better planning
- Better operation

COST

VALUE

Varying conditions
Harsh environment for sensors
Many Fault modes
Component internal structure
Accessing data
Component ownership
Small series
Automation
Process operation
Increasing complexity
No operator
Condition Monitoring

Different levels

Usage

"Racing, 10%, commuting, 90%"

Cause

Revolutions and measured force

Wear

Pad thickness

Result

Lack of braking
How to monitor when we can’t wait for data?

The only options for an OEM?

- Induced faults
  - Performed during development phase
  - Hard to cover all cases

- Data-driven approaches from previous products
  - Transfer learning
  - Domain adaptation

- Physics based approaches
  - Knowledge incorporated in (manual) modeling of system
The Mine Truck

ARX-model

\[
\begin{align*}
\varphi(t) &= (-y_{t-1}, \ldots, -y_{t-n_a}, u_{t1}^{1}, \ldots, u_{t-n_b}^{1}, u_{t-n_b}^{nb}, \ldots, u_{t-n_b}^{nb})^T \\
\theta &= (a_1, \ldots, a_{n_a}, b_0^{1}, \ldots, b_{nb}^{1}, b_{nb}^{nb}, \ldots, b_{nb}^{nb}) \\
y(t) &= \varphi_t^T \theta
\end{align*}
\]
Usage profiling

Condition Monitoring in Mobile Mining Machinery
Hydraulic Rock Drills
Rock drill fault modes

- Faults not affecting operation (before too late)
  - Fatigue
  - Cracks

- Faults affecting operation
  - Leakages / restrictions
  - Wrong flow levels
  - Pre charge levels

<table>
<thead>
<tr>
<th>Usage</th>
<th>Cause</th>
<th>Wear</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock type, Pressure level, etc.</td>
<td>Stress</td>
<td>Crack propagation</td>
<td></td>
</tr>
<tr>
<td>Rock type, Pressure level, etc.</td>
<td>Cavitation erosion</td>
<td>Worn seal Leakage</td>
<td>Change of oscillations</td>
</tr>
</tbody>
</table>
Data collection
• Subtle changes from faults
• Hard to predict wave propagation
• Variation from different configurations
• Timing changes
Handcrafted features

![Graph showing percussion pressure over time with labels for percussion pressure, forward stroke pressure $P_f$, and straight line fit.]

- Sensitive
- Not sensitive

Condition Monitoring in Mobile Mining Machinery

2022-09-07

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Dynamic-time-warping-converted-features

- Find DTW/synchronization
- Create new "time series"
- Use the new time series for classification in

```
\[ \delta_{ts}(x_a^i, x_b^i) \]
\[ \delta_{amp}(x_a^i, x_b^i) \]
```

![Graph showing time series and dynamic time warping converted features](image-url)
Results, relative features

<table>
<thead>
<tr>
<th>Measured quantity</th>
<th>Same</th>
<th>Different</th>
</tr>
</thead>
<tbody>
<tr>
<td>1NN-DTW, time series</td>
<td>92%</td>
<td>35%</td>
</tr>
<tr>
<td>SVM, time series</td>
<td>93%</td>
<td>35%</td>
</tr>
<tr>
<td>InceptionTime, time series</td>
<td>99%</td>
<td>34%</td>
</tr>
<tr>
<td>1NN-DTW, $\delta_{amp}$</td>
<td>73%</td>
<td>40%</td>
</tr>
<tr>
<td>SVM, $\delta_{amp}$</td>
<td>56%</td>
<td>40%</td>
</tr>
<tr>
<td>InceptionTime, $\delta_{amp}$</td>
<td>79%</td>
<td>53%</td>
</tr>
<tr>
<td>1NN-DTW, $\delta_{ts}$</td>
<td>71%</td>
<td>52%</td>
</tr>
<tr>
<td>SVM, $\delta_{ts}$</td>
<td>26%</td>
<td>27%</td>
</tr>
<tr>
<td>InceptionTime, $\delta_{ts}$</td>
<td>89%</td>
<td>62%</td>
</tr>
<tr>
<td>SVM, $\delta_{amp}$ and $\delta_{ts}$</td>
<td>63%</td>
<td>43%</td>
</tr>
<tr>
<td>SVM, $\delta_{amp}$ and $\delta_{ts}$ + f</td>
<td>65%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Slightly less  A lot better
# The Rock Drill Dataset

<table>
<thead>
<tr>
<th>Label</th>
<th>Letter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NF</td>
<td>No-fault</td>
</tr>
<tr>
<td>2</td>
<td>T</td>
<td>Thicker drill steel.</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>A-seal missing. Leakage from high pressure channel to the control channel.</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>B-seal missing. Leakage from control channel to the return channel.</td>
</tr>
<tr>
<td>5</td>
<td>R</td>
<td>Return accumulator, damaged.</td>
</tr>
<tr>
<td>6</td>
<td>S</td>
<td>Longer drill steel.</td>
</tr>
<tr>
<td>7</td>
<td>D</td>
<td>Damper orifice is larger than usual.</td>
</tr>
<tr>
<td>8</td>
<td>Q</td>
<td>Low flow to the damper circuit.</td>
</tr>
<tr>
<td>9</td>
<td>V</td>
<td>Valve damage. A small wear-flat on one of the valve lands.</td>
</tr>
<tr>
<td>10</td>
<td>O</td>
<td>Orifice on control line outlet larger than usual.</td>
</tr>
<tr>
<td>11</td>
<td>C</td>
<td>Charge level in high pressure accumulator is low.</td>
</tr>
</tbody>
</table>

![Graph depicting data analysis]
Remaining challenges

• Implementation of rock drill monitoring
  – Sensor placement/durability

• Transfer learning and domain adaptation between:
  – Configurations
  – Models
  – Or even from simulation model to real world data

• The gap between the research front and the industry
  – More focus on catching the last 0.1% on some test set, than to generalize model to be useful on more domains