Development of a Semi-Autonomous Scale Dragline Excavation Research Tool

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ABSTRACT

In open pit coal mines of the Bowen Basin and Hunter Valley region, draglines are responsible for the largest share of overburden excavation. These machines operate 24 hours a day, seven days a week. Previous research has calculated that for every per cent increase in efficiency the benefit to the mine is roughly one million dollars per annum. Due to the high opportunity cost for a dragline any downtime is unfavourable. Thus sufficient access to an operational dragline for research purposes is a key problem. One solution to this problem is to use scale models.

There are however many problems associated with implementing a scale dragline. Operator variability has been shown to be as high as 40 per cent. This may be due to many reasons such as; digging style, skill level or fatigue. Using human operators on a scale dragline will generate the same type of variability. Material properties such as particle size distribution, moisture content, rock shape, rock length, overburden composition variability can also significantly impact digging performance. Careful consideration of the material properties is required to achieve similarity between scale models and real scale draglines.

This paper presents the development of a semi-autonomous scale dragline to address these problems. An automated digging algorithm that eliminates the variability of a human operator tackles operator variability. As the dig algorithm will always respond with the same digging style, results are reproducible. The problem of material variability has been eliminated by measuring material properties from a coal mine and accurately reproducing those properties in scale. The combination of a computer controlled digging algorithm and accurately scaled materials produces results that are statistically similar to real full scale dragline results.

INTRODUCTION

This paper reviews the development of a 1:25 scale dragline model. The model is based on a Marion 8050. The implementation of the system was developed in three parts: mechanical and electrical design, software, field data collection and calibration.

The scale dragline system presented is unique as it is the only system that has a semi automated digging system coupled with a representative scale model of overburden material. In order to achieve similarity between field data and scale data, accurate buckets (dimensionally, mass and centre of gravity), accurate muck piles (size distribution) and an autodig controller are required. As a human
operator may introduce error, an autodig controller is used to dig the muck pile. To demonstrate success the results must be statistically similar to that of an experienced field operator.

**LITERATURE REVIEW**

**Scaled draglines**

Previous dragline researchers at the University of Queensland, Rowlands (1991), McClure (1995) and Sharrock (1996) have used scale model draglines. McClure summarises the research:

> The results of a series of research studies since 1984 at the University of Queensland into dragline bucket performance identified the potential benefits of a new bucket geometry ... Further test work is required to identify the optimum bucket shape and even more extensive testing is required to determine the optimum design and set up of the dragline bucket for each material to be excavated. Scale model test work can play a large part in both of these processes due to the relatively inexpensive nature of the test work.

Their research was constrained by suitably priced motor control solutions. The implementation allowed for either a single speed selection or variable speed control selected with a joystick. The researchers were able to compare relative differences in buckets, however in order to develop automation technologies and bucket optimisation, confidence in the scalability of results is required. There is a need to develop a research scale dragline model capable of producing digging data sets statistically comparable to that of real dragline results.

Costello and Kyle (2004) developed a 1/16th scale dragline to calculate the static equilibrium state of a bucket. Ridley (2001) developed a 1:20 scale model to test dragline bucket kinematics and dynamics.

**Automated digging**

Research conducted by CRC Mining has shown that it is possible to scale the operation of electric rope shovels using a custom built robotic arm and produce dipper statistics within ±5 per cent of real data. Lever (2001) used a computer controlled automated digging algorithm. It was shown that this system was capable of re producible, statistically representative digging data sets. The automated digging algorithm was able to reproduce in scale the following data: dig time, dig energy, fill factor, dig forces and payload. It was also possible for the system to accurately predict the performance of prototype dippers.

The CSIRO ICT (Information, Communication and Technologies) centre for autonomous systems have published research into automated dragline digging (Winsteadley *et al.*, 2007 and Dunbabin, 2006). The researchers completed 50 totally autonomous excavation cycles on a 1:10 scale dragline. The results indicate an average cycle time of 63 seconds and a total volume of excavated material of 5.1 m³. The average volume per bucket is 0.102 m³. Scaled up to full sized dragline bucket that volume is 102 m³. The material used in their study is not a scaled representation of the materials excavated by real draglines. These differences and the lack of statistical dragline bucket results would make it difficult to compare with real dragline field data. The main scope of their project was to automate the swing and dig components of the cycle and produce digital terrain maps.
MECHANICAL AND ELECTRICAL DESIGN

The scale dragline is based on the UQ scale dragline design (Rowlands, 1991). The main structure is an A-frame gantry that supports the hoist rope sheaves. The structure is manufactured from tube steel. The side walls are manufactured with plate steel and supported with angle iron (see Figure 1). A perspex side viewing window was also added.

The scale dragline is driven by Parker AC servo motors. The system is controlled by a Gallil motion controller. The system incorporates six emergency stops and maximum force limited by software.

A national instruments data acquisition card is used to measure rope tensions. The tensions in the hoist ropes are measured with in-line sensors and the drag force sensors have been specially designed. The force in the drag rope is measured by a S-beam load cell (see Figure 2).

SOFTWARE

The scale dragline is controlled with Matlab™ software. The low level control class dragline bin utilises the Gallil active x control tool and the Matlab™ data acquisition toolbox. A diagram of the control architecture is shown in Figure 3.
The *dragline bin* class implements the autodig algorithm. This controls the dig strategy so as to produce digs that are statistically similar (dig energy, dig length, dig time, dig payload) to a real dragline bucket. The flow control of the autodig algorithm is shown in Figure 4.

\[ L_1 = \sqrt{L_4^2 - r^2} \]  
\[ L_2 = \frac{\theta_1}{360} \times 2\pi \]

**Inverse kinematics**

The inverse kinematics can be derived if the position of the bucket is known. Given the rotation and coordinate position of the dragline in the reference frame, the lengths of tight ropes may be calculated. Most of the dragline bucket movement occurs in a plane perpendicular to the boom assembly. The plane dissects the troughs of the hoist and drag sheaves. A schematic of the reference plane is shown in Figure 5. Where S1, S2 and S3 are sheave locations and B1, B2 and B3 are bucket locations in the dragline coordinate frame. Equation 1 to Equation 5 presents the inverse kinematic equations with Figure 6 as the reference plan.
As the dragline rope wraps around the sheaves the leaving point of the hoist ropes and drag rope on sheaves changes with bucket position (see Figure 6).

**Forward kinematics**

The forward kinematics are derived to determine the position of the bucket using rope lengths. The angles of the ropes with respect to the sheaves are unknowns. The position of the bucket and the angle of the bucket are also unknown.

The position of the bucket (hoist and drag rope angle, bucket coordinates and tilt) may be calculated if the ropes are in tension. Shekhar (2007) used a vector based approach with a Newton-Raphson solver.
for the system of non linear equations. The forward kinematic equations are presented in Equation 6 to Equation 11 (Shekhar, 2007):

where:
- \( B(θ) \) = bucket angle
- \( B(x) \) and \( B(y) \) = bucket coordinates
- \( r \) = sheave radius
- \( D \) = diameter
- \( H_1 \) and \( H_2 \) are constants

**Vector analysis**

Figure 5 as reference plan.

\[
\begin{align*}
(H_1 + R_1 \times S_1(θ)) \times \cos(S_1(θ)) &- R_1 \times \sin(S_1(θ)) + B_3 \times \cos \theta &+ B_2 \times \sin \theta \\
(B_3 + B(θ)) - B(x) + S_1(x) & &\quad (6) \\
(H_1 + R_1 \times S_1(θ)) \times \sin(S_1(θ)) &- R_1 \times \cos(S_1(θ)) + B_3 \times \sin \theta &+ B_2 \times \cos \theta \\
(B_3 + B(θ)) - B(y) + S_1(y) & &\quad (7) \\
(H_2 + R_2 \times S_2(θ)) \times \cos(S_2(θ)) &- R_2 \times \sin(S_2(θ)) - B_1 \times \cos \theta &+ B_2 \times \cos \theta \\
(B_1 + B(θ)) - B_3 \times \cos(B_3 + B(θ)) - B(x) + S_1(x) + S_1(y) & &\quad (8) \\
(H_2 + R_2 \times S_2(θ)) \times \sin(S_2(θ)) &- R_2 \times \cos(S_2(θ)) - B_1 \times \sin \theta &+ B_2 \times \sin \theta \\
(B_1 + B(θ)) - B_3 \times \sin(B_3 + B(θ)) - B(y) + S_1(y) + S_1(y) & &\quad (9) \\
(D - R_3 \times \text{abs}(S_3(θ))) \times \cos(S_2(θ)) &+ R_3 \times \sin(S_3(θ)) - B_2 \times \cos \theta &+ B_2 \times \cos \theta \\
(B_2 + B(θ)) + B_3 \times \cos(B_3 + B(θ)) - B(x) + S_3(x) + S_4(x) & &\quad (10) \\
(D - R_3 \times \text{abs}(S_3(θ))) \times \sin(S_3(θ)) &+ R_3 \times \cos(S_3(θ)) - B_2 \times \sin \theta &+ B_2 \times \sin \theta \\
(B_2 + B(θ)) + B_3 \times \sin(B_3 + B(θ)) - B(y) + S_3(y) + S_4(y) & &\quad (11) 
\end{align*}
\]

The equations presented for the forward and inverse kinematics only determines the length of the dragline hoist and drag ropes whilst the ropes are under tension. During digging the hoist ropes are slack and the bucket half submerged. Another localisation method is required to achieve bucket position during digging. For example a scanning laser.

**FIELD DATA COLLECTION AND CALIBRATION**

The field trial was performed in order to determine baseline dragline bucket data and compare the performance of the scale autodig algorithm. In this section, the experimental methodology and implementation are reviewed and the results of a field trial are presented.

The objective of the work in the field study was to demonstrate the capabilities of the scale dragline bin to accurately predict the relative performance of different dragline buckets. The proposed approach is to collect bin calibration data from a site dragline with bucket A and then generate predicted performance for bucket B. Field performance data for bucket B will also be collected from
the site dragline to compare with the bin predictions. During the field trial, bucket B was not serviceable, so bucket C was used. However, bucket B was also tested in scale.

One hundred tests of bucket A were completed to calibrate between field data and scale data. Data comparisons between bucket A field data and bucket A scale data are presented in Figure 7. Results are within five to ten per cent. Thirty tests of bucket B and C were completed. Data comparisons between bucket A and bucket B are presented in Figure 7. Data comparisons between bucket A and bucket C are presented in Figure 8. Data points for Figure 7 to Figure 9 are respectively presented in Table 1 to Table 3.

![Figure 7](image_url)

**Fig 7 - Real bucket A data compared with scale bucket A data.**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Bucket A real</th>
<th>Bucket A scale</th>
<th>Avg Δ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload (t)</td>
<td>90.43</td>
<td>91.9</td>
<td>-2.17</td>
</tr>
<tr>
<td>Energy (MJ)</td>
<td>28.33</td>
<td>35.12</td>
<td>+1.13</td>
</tr>
<tr>
<td>Fill dist (m)</td>
<td>14.07</td>
<td>21.3</td>
<td>-4.03</td>
</tr>
<tr>
<td>Fill time (s)</td>
<td>11.5</td>
<td>11.26</td>
<td>+2.24</td>
</tr>
<tr>
<td>t/s</td>
<td>4.59</td>
<td>3.8</td>
<td>+11.43</td>
</tr>
<tr>
<td>J/Kg</td>
<td>276</td>
<td>366</td>
<td>+3.68</td>
</tr>
</tbody>
</table>
The predictions of bucket B and bucket C have been satisfactory based on feedback from the mine.

The plots compare real payloads, fill lengths, fill energy, fill time, tons/second and Joules/Kilogram with scale data. The number in the middle of the plot is the per cent difference between the averages of the real data and scale data for the box plot metric.

**TABLE 2**

*Bucket A real field data versus bucket B scale data.*

<table>
<thead>
<tr>
<th>Metric</th>
<th>Bucket A</th>
<th></th>
<th></th>
<th>Bucket B</th>
<th></th>
<th></th>
<th>Avg Δ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload (t)</td>
<td>Min</td>
<td>Avg</td>
<td>Max</td>
<td>Min</td>
<td>Avg</td>
<td>Max</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90.43</td>
<td>98.9</td>
<td>108.2</td>
<td>92.89</td>
<td>108.72</td>
<td>125</td>
<td>+9.92</td>
</tr>
<tr>
<td>Energy (MJ)</td>
<td>28.33</td>
<td>41.0</td>
<td>54.47</td>
<td>30.12</td>
<td>42.67</td>
<td>51.56</td>
<td>+3.83</td>
</tr>
<tr>
<td>Fill dist (m)</td>
<td>14.07</td>
<td>25.5</td>
<td>34.91</td>
<td>28.64</td>
<td>24.21</td>
<td>28.64</td>
<td>-5.33</td>
</tr>
<tr>
<td>Fill time (s)</td>
<td>11.5</td>
<td>16.1</td>
<td>21.3</td>
<td>11.91</td>
<td>17.11</td>
<td>23.73</td>
<td>+5.85</td>
</tr>
<tr>
<td>t/s</td>
<td>4.59</td>
<td>6.22</td>
<td>8.63</td>
<td>4.18</td>
<td>6.57</td>
<td>9.66</td>
<td>+5.60</td>
</tr>
<tr>
<td>J/Kg</td>
<td>276</td>
<td>415</td>
<td>556</td>
<td>303</td>
<td>392</td>
<td>423</td>
<td>-5.72</td>
</tr>
</tbody>
</table>

The predictions of bucket B and bucket C have been satisfactory based on feedback from the mine.

The plots compare real payloads, fill lengths, fill energy, fill time, tons/second and Joules/Kilogram with scale data. The number in the middle of the plot is the per cent difference between the averages of the real data and scale data for the box plot metric.

**FIG 8** - Real bucket A data compared with scale bucket B data.
The objectives of scaling testing were to:

- develop a scale model dragline;
- accurately scale a dragline muckpile, manufacture accurately in scale three dragline buckets (bucket A, bucket B, bucket C); and
- calibrate scale bucket A with field data and test dragline buckets in the calibrated scale muckpile.

These objectives were achieved.

**TABLE 3**

*Bucket A real field data versus bucket C scale data.*

<table>
<thead>
<tr>
<th>Metric</th>
<th>Bucket A</th>
<th>Bucket C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload (t)</td>
<td>Min 90.43 Avg 98.9 Max 108.2</td>
<td>Min 85 Avg 92.7 Max 100.08 Δ% -3.6</td>
</tr>
<tr>
<td>Energy (MJ)</td>
<td>Min 28.33 Avg 41.0 Max 54.47</td>
<td>Min 33.68 Avg 44.25 Max 58.35 Δ% +7.6</td>
</tr>
<tr>
<td>Fill dist (m)</td>
<td>Min 14.07 Avg 25.5 Max 34.91</td>
<td>Min 15.5 Avg 22.56 Max 26.85 Δ% -11.7</td>
</tr>
<tr>
<td>Fill time (s)</td>
<td>Min 11.5 Avg 16.1 Max 21.3</td>
<td>Min 12.52 Avg 18.91 Max 23.53 Δ% 16.9</td>
</tr>
<tr>
<td>t/s</td>
<td>Min 4.59 Avg 6.22 Max 8.63</td>
<td>Min 4.01 Avg 4.98 Max 6.79 Δ% -19.8</td>
</tr>
<tr>
<td>J/Kg</td>
<td>Min 276 Avg 415 Max 556</td>
<td>Min 391 Avg 477 Max 502 Δ% +14.8</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The objectives of scaling testing were to:

- develop a scale model dragline;
- accurately scale a dragline muckpile, manufacture accurately in scale three dragline buckets (bucket A, bucket B, bucket C); and
- calibrate scale bucket A with field data and test dragline buckets in the calibrated scale muckpile. These objectives were achieved.
FUTURE WORK

A scanning laser has been implemented on the scale dragline. The laser can be used to develop bucket fill estimation to automate the pullout of the overburden and digital terrain modelling (DTM). An accurate digital terrain model allows the development of a totally autonomous dig algorithm. The algorithm would be required to delineate between particles and plan the start of dig position. An example of one requirement of the algorithm is that the machine must not start digging into a solid particle.

ACKNOWLEDGEMENTS

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REFERENCES


Shekhar, 2007. UDD dragline forward kinematics, internal CRC Mining report.