Dragline Automation— A Decade of Development

Shared Autonomy for Improving Mining Equipment Productivity

Draglines are massive machines commonly used in surface mining to strip overburden, revealing the targeted minerals for extraction. Automating some or all of the phases of operation of these machines offers the potential for significant productivity and maintenance benefits. The mining industry has a history of slow uptake of automation systems due to the challenges contained in the harsh, complex, three-dimensional (3-D), dynamically changing mine operating environment. Robotics as a discipline is finally starting to gain acceptance as a technology with the potential to assist mining operations. This article examines the evolution of robotic technologies applied to draglines in the form of machine embedded intelligent systems. Results from this work include a production trial in which 250,000 tons of material was moved autonomously, experiments demonstrating steps towards full autonomy, and teleexcavation experiments in which a dragline in Australia was tasked by an operator in the United States.

Introduction

This article describes the key results from a research program that is now in its 12th year. Our initial inspiration was to automate the operation of a dragline; a task that turned out to be much more complex than we envisaged for reasons not entirely technological. In particular, mine owners have often been slow to address the uptake of robotic technology due to the immense challenges of the mine environment. These challenges range from cultural issues to significant technical issues, including the harsh and continually changing operating environment.

Excavation is the predominant task in open-pit mining and is achieved using draglines, rope shovels, and hydraulic excavators. The latter two load material into trucks for transport, whereas a dragline acts as a pick-and-place robot, moving material from one location to another within its workspace. Draglines (see Figure 1) can move more than 100 tons of material per load at approximately one load per minute. Their operational cost in terms of dollars per cubic meter of material

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moved is an order of magnitude lower than that of shovel/truck and hydraulic-excavator/truck operations.

A natural, and perhaps obvious, consequence of many years of open-pit excavation is that much of the remaining material of economic value is buried deeper than what has been removed to date. Miners refer to a stripping ratio, the ratio of the overburden volume that must be removed to access one ton of this material. In the Australian coal industry over the last twenty years, this ratio has climbed from 2–5:1 to 8–15:1 today. A dragline can only excavate down to 50 m, and with pit depths exceeding 100 m, the overburden must be removed in two dragline passes or by using shovels and trucks to prestrip.

Mines have used several methods to achieve the necessary increase in overburden stripping productivity. First, draglines are routinely overloaded, exploiting the generous design safety margins by using larger buckets. Careful economic analysis has determined the optimal operating load that trades off productivity against machine damage. Networks of sensors monitor stresses on the machine and can even inform the operator if he or she is working the machine too hard. Secondly, operator training and performance monitors have improved the overall skill level of the operator workforce. However, despite a large investment in training and monitoring there is still a gap of at least 20% in productivity between the more and less skilled operators, and also a large variation within a single operator's performance during a shift (which are typically 12 hours).

From a robotic perspective, there has been important prior work in automating excavation machinery. The majority of this research has focused around digging, weight estimation and motion planning, see for example [1]–[4]. Singh [5] provides a good treatment of much of this work using a number of implemented systems to illustrate the state of the art. One of the more impressive bodies of work was conducted at Carnegie Mellon University in the 1990s, culminating in a comprehensive study and experimental evaluation of an autonomous 25 ton hydraulic backhoe-type excavator [6]. This work included the development of techniques to estimate soil hardness and dig forces, which were integrated into an autonomous digging control law, as well as methods for planning dig locations and clean-up operations.

There has been little work by others on the topic of dragline automation, a topic we chose to investigate because draglines are important to the economically significant Australian coal export industry. Draglines are also challenging from a robotic viewpoint due to their sheer size: they are a large 4 degrees of freedom (DoF) robot with a passive final link and a load whose inertia is comparable to that of the robot.

From an experimental and developmental standpoint, dragline automation has also been difficult because of limited access to machinery—draglines are expensive assets, which cannot be removed from production without significant economic penalty. For this reason, much of our experimental program, including retrofitting of equipment, has revolved around existing planned shutdowns of the machines, resulting in extremely constrained time-tables. An additional issue has been managing the risk and expectations of this type of technology; the consequences of a system failure could be astronomical in economic terms, not to mention the possibility of fatalities. A further hurdle has been managing the on-site cultural issues surrounding the introduction of automation.

Our dragline automation work has been carried out on two production draglines and a 1:7 scale-model machine, which captures all the critical geometric and performance characteristics of the full-sized machines. Key results from this work include the installation, development and demonstration of an operator-assist system, called dragline swing assist (DSA), which automates part of the dragline excavation cycle. This work culminated in a two-week production trial in which 250,000 tons of material was shifted by our system. A key limitation of the system was a lack of awareness of the machine's surrounds, an issue that has been addressed through the development of digital terrain mapping (DTM) for draglines and other rotating excavation machinery. By integrating DSA with the DTM technology, we have been able to demonstrate significant steps towards full autonomy. Work in this area has included the development of systems aimed at addressing off-world excavation, including experiments in which an operator in Boston, Massachussettes was able to perform an excavation using our 1:7 scale dragline in Queensland, Australia, via a standard Internet browser interface. Following a brief introduction to how a dragline operates, the remainder of the article addresses these key results.

__Figure 1.__ A Bucyrus-Erie 1350 dragline. For scale, note the large truck in the lower right corner of the photograph. Typical boom lengths are 100 m.

Dragline Operation

A dragline (see Figure 2) comprises a rotating assembly that includes the house (drive motors, controls, and operator cabin), tristructure or mast, and boom. [Boom elevation angle (β in Figure 2) is constant.] The house rotates on a bearing surface on top of the tub, which sits on the ground. A large diameter ring gear is fixed to the tub and the house is rotated by a number of pinions driven by motors in the house. A walking dragline is able to drag its tub along the ground by means of large eccentrically driven walking shoes at the side of the machine. The dragline has three driven mechanical DoF:

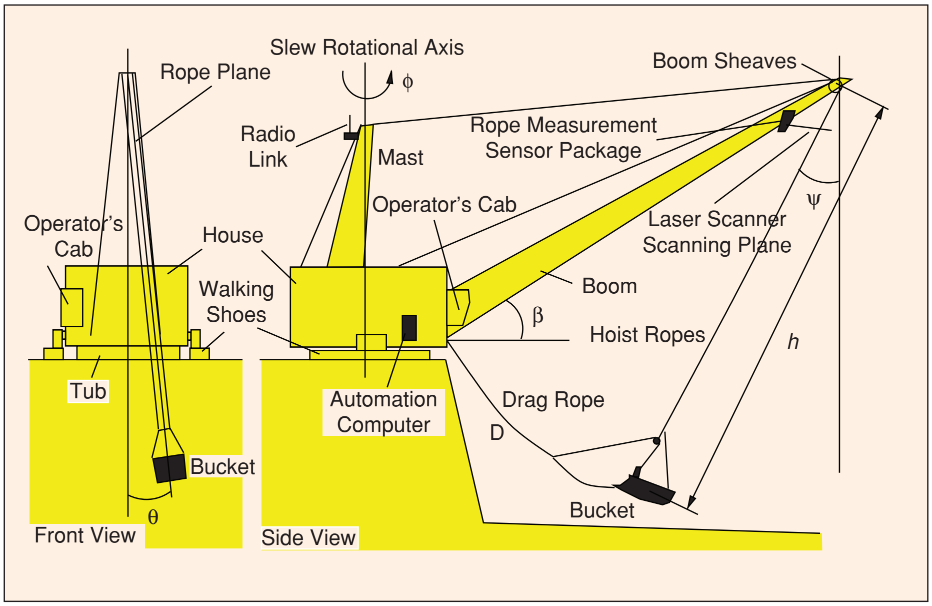


Figure 2. Schematic of a dragline showing the critical states. Note that the hoist and drag ropes are flexible and hence the bucket is free to swing.

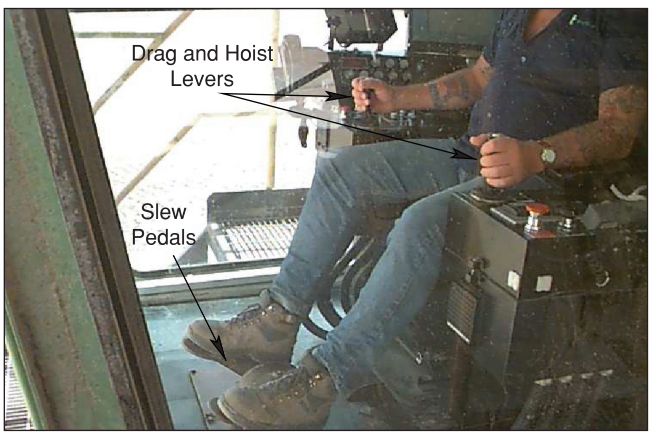


Figure 3. Operator controls. Two hand levers control the drag and hoist axes whilst a pair of foot pedals control the dragline slew motion.

- the house and boom can slew (rotate) with respect to the tub
- the bucket can be hoisted by cables passing over sheaves at the tip of the boom
- the bucket can be dragged toward the house by cables passing over sheaves at the base of the boom.

During digging, the bucket motion is controlled using only the drag and hoist ropes. When the bucket is filled it is hoisted clear of the ground and swung to the dump position by slewing the house and boom. The drag and hoist drives now control the position of the bucket within a vertical plane that contains the center-line of the boom, however, the bucket is free to swing normal to that plane.

With reference to Figure 2, the configuration of the bucket is given by

$$\mathbf{x} = [d,\ h,\ \phi,\ \theta],$$

comprising, respectively, drag and hoist rope lengths, slew angle, and swing angle of the bucket normal to the vertical plane containing the boom. The bucket swing behaves like a pendulum

$$\ddot{\theta} = f(d,\ h,\ \phi,\ \theta),$$

which cannot be controlled directly. The control inputs are

$$\mathbf{u} = [\dot{d},\ \dot{h},\ \tau],$$

respectively the drag and hoist rope velocities and the slew torque, τ. A good deal of operator skill is required to control the bucket's natural tendency to swing.

The operator controls the dragline using a set of foot pedals to slew the machine and a pair of levers to control the drag and hoist ropes, see Figure 3.

Dragline Automation—Early Days

In the 1980s, an innovative project at one Australian mine attempted to automate the operation of a dragline [7]. The approach was to record the signals from the operator controls and then replay them. The results were not what was hoped for, since these signals were based on the operator's perception of the instantaneous machine state, which is a history of the initial condition and subsequent inputs, as well as the goal state.

Our initial take on the problem in 1993 was driven by prior work on vision-based robotic control [8], which we believed offered a way to determine the machine state, an element that was critically missing in the earlier work. A very important state is that of the bucket; a fully laden bucket at full radius has an inertia of about half the rest of the machine and exerts enormous forces on the house and boom. In this early work, we demonstrated scale-model control where we could stabilize a pendulum hanging from a Puma robot using a wrist mounted camera. From here it was just a matter of scale up.

Superficially a dragline is quite different to a robot, due to its size and unusual actuation (by cables and winch drums). However, with the addition of suitable sensors, a dragline can be considered as a 4 DoF robot with one passive link [9], which can then perform controlled motion of its tool (the bucket) along a defined trajectory. It was clear to us that control of the swinging load was the crux of the problem.

A typical cycle takes around 60 s to complete, of which 80% is swinging the bucket through free space and it was here that we focused our attention as time savings in the largest part of the cycle would have the greatest impact on overall cycle time—the only metric of interest to the industry. Also, the free space motion is clearly simpler than pulling a huge bucket through fragmented rock, as is required for digging. The idea was that the automation system would be activated by the operator once the bucket was filled, and the bucket would then be automatically disengaged, hoisted, swung and dumped at an operator set reference point before returning the bucket to a predefined dig point.

Controlling the natural tendency of the bucket to swing requires a good deal of operator skill, and to do this automatically required measuring the angle of the dragline bucket with respect to the vertical plane passing through the boom centerline, $\theta(t)$ (see Figure 2). The bucket is treated very roughly and in every cycle it is pulled through several meters of broken rock. Others have previously attached instrumentation to the bucket [10] in order to measure its state. However, the very nature of the bucket's function (i.e., extreme interaction with the terrain) limits the life, and reliability, of any such instrumentation. Noncontact sensing was thus seen as the preferred option and computer vision seemed a likely candidate as the camera could be mounted high on the boom looking down, and significant lighting was already provided to enable the operators to work at night.

This approach led to the problem of reliable bucket segmentation, which was no easy task considering that the scene was a bucket filled with overburden against a background of overburden, with relative motion between the background, camera and bucket, not to mention problems with changing ambient lighting, strong background texture, shadowing and night time operation. Additionally, real-time results were required and the state-of-the-art hardware of the day was VMEbus 68020 main processors and dedicated datacube image processing hardware. Ultimately, we demonstrated the principle but had to resort to an artificial target on the hoist ropes above the bucket. Nevertheless, by the end of 1995 we were operating on a scale-model dragline with a 10m boom, a 10 times scale up from the Puma system of our earlier testing. We could rotate the house from side to side and the bucket would hang almost vertically with minimal swing [11].

Starting in 1996, the next phase was to install a system on a production dragline, a Bucyrus-Erie 1370 at Meandu Mine near Brisbane in Australia. The limitations of the computer vision approach soon became apparent for automation in a realistic field deployment for which such a system must operate

- 24 hours a day in all weather conditions (including heavy rain and dust)
- at a rate of at least 3 Hz (a control constraint)
- with a large variation in scale as the bucket range varies from 5 to 100 m from the camera.

In addition to the image processing challenges mentioned earlier, camera placement is also a nontrivial issue. We selected a view looking downward from the boom tip, since a horizontal view from the operator's cabin has problems with Sun dazzle (light shining directly into the camera) at certain times of the day. Figure 4 illustrates an image from the downward looking camera—it is difficult enough to spot the bucket manually, let

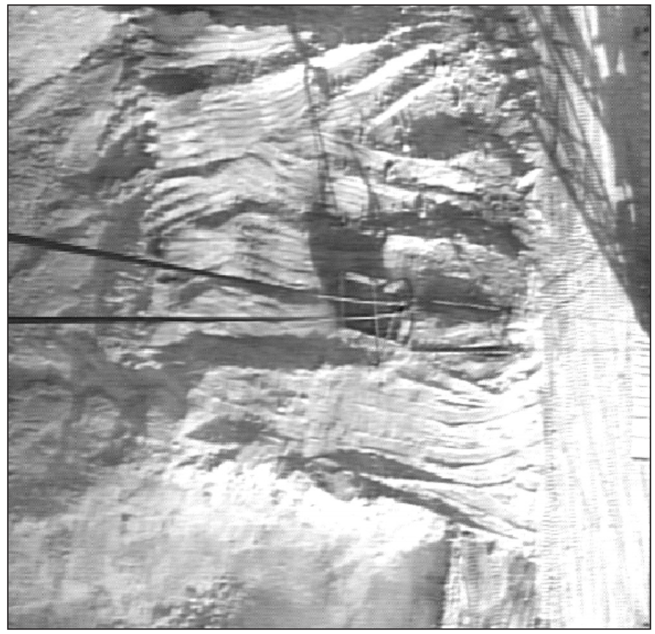


Figure 4. *Image from the downward looking camera on the production dragline shows the complexity of the scene (bucket is in the center of the image).*

alone extracting it automatically using image processing. A large study into the problem [12] established that it was not practical to meet the constraints in the production environment using computer vision.

By this time, Sick laser range-finders were gaining popularity in the robotics community and we realized that such a sensor could be used to track the hoist ropes, rather than the bucket itself, as they move from side to side. We engineered a sensing system with two Sick proximity laser scanners (for redundancy and immunity to Sun dazzle) and a robust Kalman filter based tracker that operated in the presence of false targets such as rain and insects (which are attracted to the huge lights on draglines at night) [13].

We also needed to interface with the operator and to do this we developed our first set of servo-driven active controls—the automation system was able to physically move the operator's controls, but the operator could easily override them. These active controls are further discussed in the following.

At this point, we needed to learn more about what an operator did. Once the bucket is filled (the operator's job in our proposed system) we had to disengage it from the ground, hoist and slew it to the dump point possibly via a nonstraight line path over terrain obstacles, dump the overburden, recover the bucket, and return it to the dig point. This was a lot more than simple swing stabilization. We observed and talked with operators and developed our first control system, a finite-state machine that sequenced a variety of path planners and low-level force and velocity control loops.

An interesting consequence of the dragline's design is that the bucket pose is under-actuated—drag and hoist rope length control its position in the boom plane as well as its orientation. Recently, a new rigging system has been devised, which allows for the direct control of bucket pose [14]. The work described in this article is equally applicable to such an arrangement but our work has concentrated on conventional draglines, which make up the vast majority of the world fleet. On conventional draglines, the bucket pose depends on the position within the plane and also the tension on the drag rope. Dropping the front of the bucket (releasing the drag rope) to empty the overburden was far more complex than the operator made it look. But even harder was bucket recovery, lifting the front of the bucket after it was empty. This is far more subtle than just pulling in the drag rope, which can lead to massive whiplash in the ropes and tens of tons of chains thrashing around and the whole dragline structure shaking. Real skill was required here and the complexity of the task was masked by the high skill levels of the operators we were observing. Nevertheless, by the end of 1997 the system was operating and we had demonstrated the feasibility of the approach through several trials, which had the system building a small spoil pile (the area in which the overburden or waste is piled) [15]. At this point, due to external reasons we were forced to decommission our system.

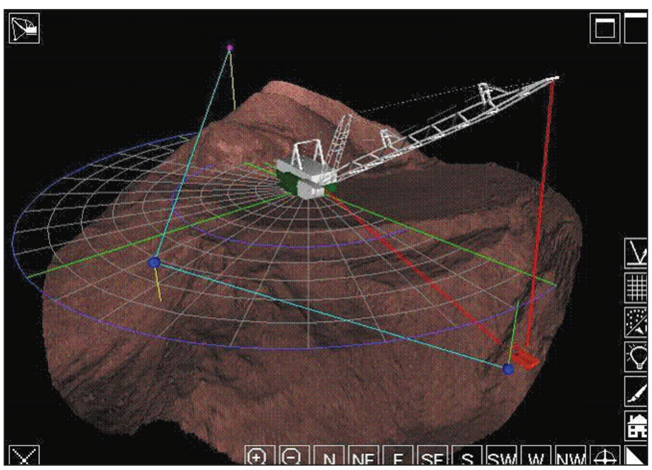


Figure 5. *Operator view of bucket way-points during a production dragline cycle.*

Dragline Swing Assist

In 2001, we made a fresh start at a new mine but on an older dragline, a Bucyrus-Erie 1350. We took the opportunity to rebuild all our subsystems, which included the hoist rope-angle sensor, the servo-driven (active) controls, graphical operator display and off-board communications system [we could dial in via a global system for mobile communications (GSM) modem]. The new system was commissioned in 2002.

This phase of dragline automation resulted in the development of the DSA system. The DSA system is essentially a cruise-control for a dragline whereby it performs the hoist, slew, dump and return components of the excavation cycle. The idea is that the operator fills the bucket and then trades control [16] to the DSA system by pressing a button on the active joystick controlling the drag axis. Once the automation system has control, the bucket motion is then dictated by a set of operator specified way-points, previously entered during a training phase using the active joysticks—passing through the specified way-points ensured a collision free trajectory. The major components of DSA are discussed in the following sections.

Dragline Control

Typically, the drag and hoist drives are velocity controlled, that is the control input is a velocity setpoint, whereas the slew drive is torque controlled [17]. For the drag and hoist axes, the DSA axis controllers are based on nonlinear proportional-derivative loops around rope length. For the torque controlled slew drive, the DSA axis controller closes the loop around position (i.e., slew angle).

Motion Planning

The DSA path planning used in this early investigation was based on the bucket passing through operator specified way-points (or via-points), as it traverses from the dig site, to the dump site and back again. Figure 5 shows an example view of the operator entered way-points overlaid on a measured digital terrain map. In this early form, the control system was essentially operating blind. Failing to pass through any way-point may result in the bucket striking the bench (the bench is the horizontal surface along which the excavation is worked, in this case where the dragline sits) or spoil pile causing considerable damage to the dragline. This placed the onus on the operators to select suitable way-points, ensuring the bucket's trajectory safely avoided any obstacles on its way to the dump point. Thus, the operator chosen way-points were extremely conservative, giving large clearances between the bucket and the terrain.

Another issue was that all the drives have a finite speed capability, which is a function of load, motion direction, tub slope etc; achieving the optimum performance from the dragline motion planning is not always straightforward. The motion planner development underwent three major phases over the years, with each phase utilizing knowledge gained and incrementing the performance and robustness of the dragline's slew cycles.

Active Controls

Our focus in robotic open-pit excavation has been in operator assistance rather than operator replacement. It is important in such a system that the human machine interface (HMI) is intuitive and that the transfer of control does not introduce unwanted effects. In this work, we have used the idea of traded control [16] in which the operator instigates the control system and can also seamlessly reassume control of the system. Here, the seamless transfer of set points is achieved through the use of active controls [see Figure 6(a)]. Active controls have a direct interface to the machine and are capable of being directly driven by a computer or the operator. When the operator reassumes control, the stick position is congruent with the current input to the machine, preventing control input discontinuities. This class of controls also allows novel feedback mechanisms to the operator, restriction of controls requested by the operator, or ultimately enables a computer to drive a machine directly. Additionally, this approach ensures that the assist systems are subject to the same low-level machine interlocks as the conventional joysticks and operator.

Each set of controls was converted to active control through the addition of servo motors to drive the lever or pedal, as appropriate, via toothed belt geared drives coupled by clutches. The clutches disconnect the servo drives so the feel of the controls to the operators when used manually are the same as before conversion. The drag lever has a button inserted in its ball for the operator to conveniently engage the active controls and a button in its cover to switch between the training and operational state. The training state allows the operator to mark way-points through which the trajectory calculated and executed by the DSA system must pass.

The HMI for the DSA system also includes a small screen to display the current status of the system as well as providing an interface for changing the way-points and adjusting the dump height. As operators are already inundated with screens and controls (information overload), the DSA interface was designed to be as unobtrusive as possible; a small touch-screen was located at eye height and within easy reach at the right of the operator [see Figure 6(b)]. This touch-screen was connected via Ethernet directly to the main control computer. Operators found this small screen with simple displays easy to operate.

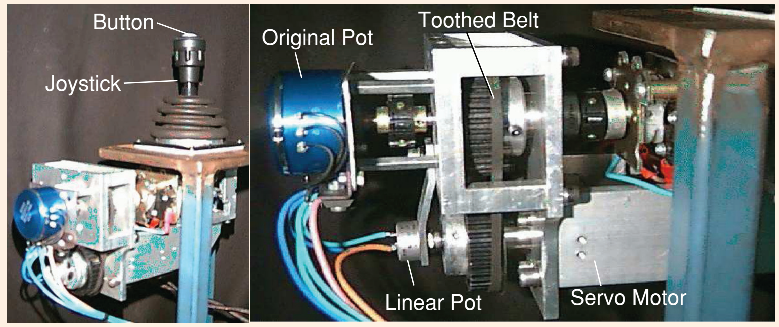


Figure 6. *Some of the elements of the HMI for the DSA system: (a) active joysticks, (b) operator touch-screen.*

The Big Dig

In 2002, a two week experimental evaluation of the DSA system was conducted on the Bucyrus-Erie 1350 dragline. The purpose of the test was to benchmark DSA against operator performance on the slew, dump and return phases of the excavation cycle [18].

A total of 12,235 cycles were recorded during the trial: 3,042 with DSA and 9,193 manual cycles. Our target was in fact 10,000 automated cycles but maintenance and operational issues during the trial period precluded this. Nevertheless, this number of automated cycles far exceeds, to our knowledge, any previous operational testing of a robotic excavation machine with approximately 250,000 tons of material moved autonomously over the two-week trial.

Results

Figure 7 shows a sample of the trial results illustrating the percentages in which the performance (cycle-time) of the DSA system was better than a skilled human operator, binned into slew-angle range. The production trial clearly demonstrated that it is possible for a computer to emulate all of the essential operator skills: disengaging from the bank, dumping and bucket recovery. Critically, it was shown that

- the system was able to match or exceed operator performance in some, but not all, cycles
- return time was significantly better than swing time
- subjectively, the system has a skill level equivalent to an operator with six months training; particular skills such as bucket disengage, dumping and recovery were performed consistently well
- the system was highly reliable; there were no hardware or software failures over the duration of the trial
- the system's operator interface was intuitive and was readily accepted by the operators.

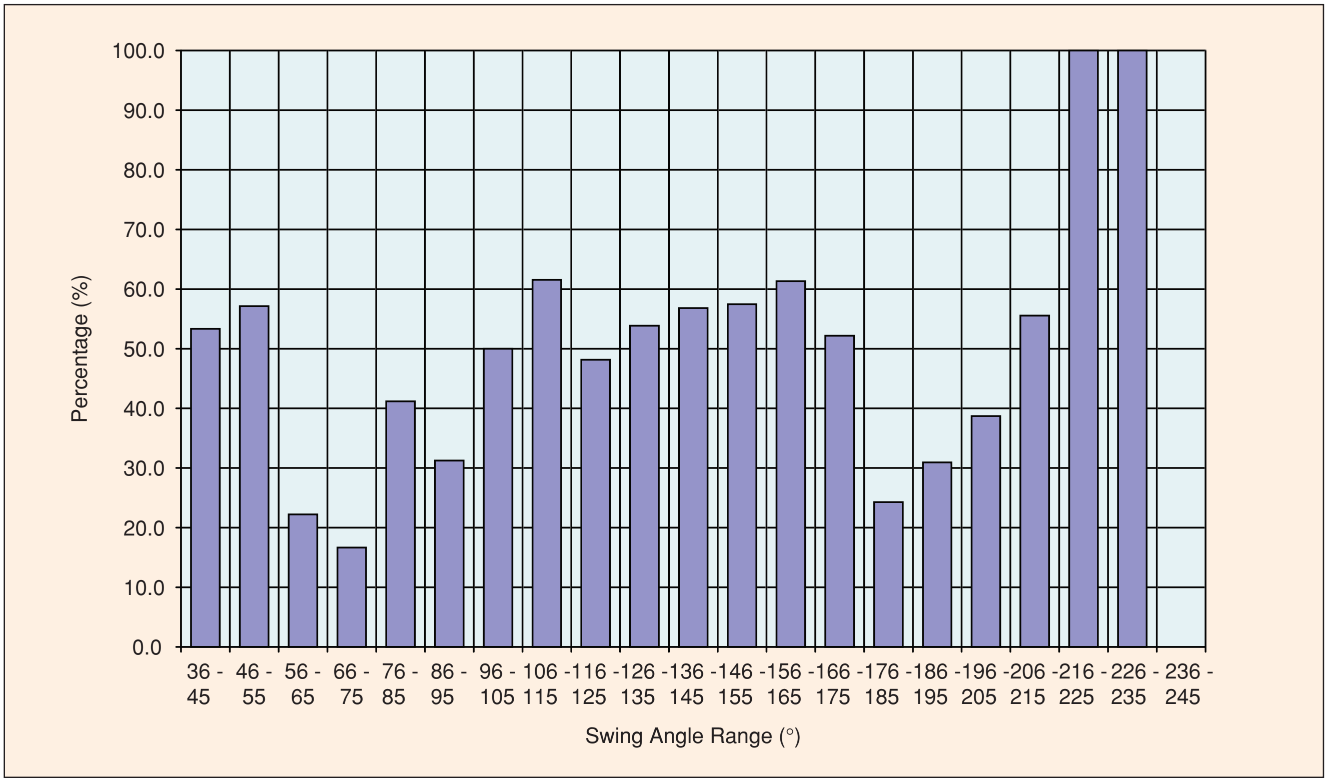


Figure 7. *Histogram of percentage of DSA cycles better than mean operator manual cycle times, binned into slew angle range (two-point paths only).*

Figure 8. *The Riegl LMS-Q140i laser scanner.*

Additionally, although no specific maintenance benefits can be extracted from such a short trial, anecdotally, mine owners observed that the DSA system was much gentler on the dragline. In other industries, the introduction of automation systems has resulted in reduced maintenance costs and it is anticipated that similar benefits will accrue after the introduction of these types of systems to draglines, and mining machines in general.

Although the trial was very successful, the system was hindered by the conservatism of the operator selected waypoints. This meant that the DSA system had to hoist the bucket significantly higher as compared to a human operator who, through observation, can skim much more closely to the surrounding terrain. In summary, this limitation results in a 3–7 s time penalty (5–10%) on each cycle for the DSA system as compared to manual operation. Additionally, post-trial data analysis revealed a software error, subsequently corrected, in a particular class of paths, which added several seconds to some of the DSA executed cycles. A more comprehensive analysis of the production trial is provided in [18].

Reducing the conservatism on hoisting to that typically employed by human operators would nominally make the DSA performance equivalent to that of a skilled operator. In order to realize lower hoist conservatism on the production dragline, it must be given the ability to perceive its surroundings. Providing this situational awareness is the topic of the next section.

Dragline Spatial Perception: Terrain Mapping

DTM can impact on mine operations in two primary ways: as an aid to improving and visualizing production monitoring and planning; and as a means of providing situational awareness to machine automation tasks. The work reported here began through addressing the latter of these potential applications but it was quickly realized that the results from this research could also be readily applied to the production monitoring task.

This section describes the development of our laser range-scanner based DTM technology, which has been operating trouble-free in a production dragline environment for over three years. A more detailed explanation and analysis of the work described in this section is provided in [19].

Choice of Mapping Sensor

There are three general classes of sensor that may be capable of providing range data to a DTM system: stereo vision, radar and laser scanners.

Stereo vision is attractive for this application because it is a true 3-D sensor, i.e. it is not necessary to integrate one-dimensional (1-D) range data over time in order to construct 3-D data—data covering a wide area is collected at one instant in time. However, the large range operation required (>150 m) implies a large camera baseline, which brings with it the problems of rigidity and camera calibration. As our previous experience has highlighted, computer vision methods are difficult to use effectively in this environment due to poor visibility and the requirement for good lighting (particularly at night). Radar is also an attractive sensing option but at the time of development, there were no commercially available systems appropriate for this task. More recently, suitable radar technology has become available and been tried in this environment [20].

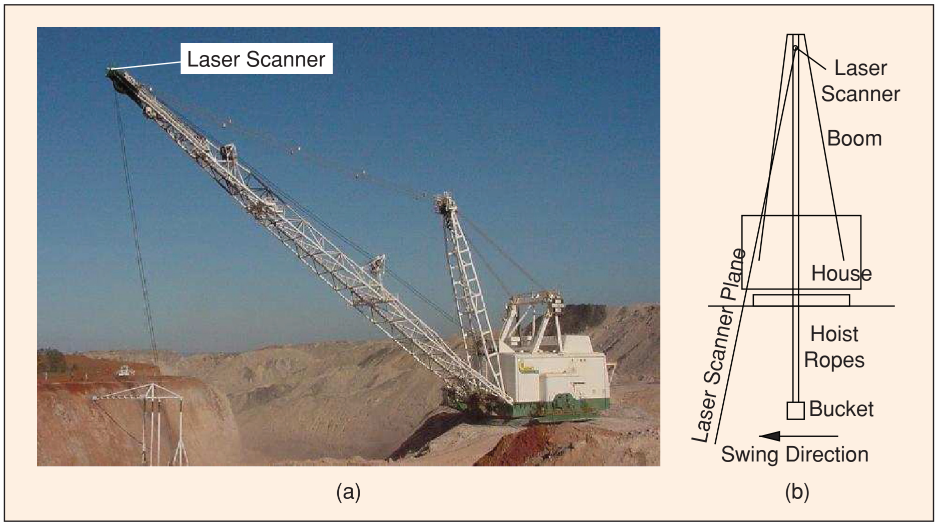


Figure 9. (a) The laser scanner is mounted at boom tip and (b) is mounted so that the scanning plane normally avoids the bucket.

Instead, we chose to pursue commercially available infrared laser range-scanner based technology and chose a single-axis laser scanner with which we had gained significant experience in this challenging environment. The selected system was the Riegl LMS-Q140i (Figure 8). These systems are eye-safe and possess excellent angular resolution (0.1°), ranging characteristics (>150 m, even in sunlight) and an update rate of 10 Hz. These characteristics lead to a theoretical spatial resolution of approximately 0.02 m^3 for a dragline slewing at 4°/s. Additionally, these sensors are capable of seeing through rain and, to a limited extent, dust by using the last return principle where the range to the last significant object encountered is reported.

The success of this particular application of this class of sensor has much to do with the mounting arrangements and nature of operation. Over three years of trouble-free operation of this and the hoist rope tracking lasers attest to the suitability of these sensors in this environment.

Implementation

The DTM laser scanner was mounted at the boom-tip looking down, giving the system an eagle-eye view allowing it to see over the spoil piles and into voids not visible to the operator, see Figure 9. This mounting position (at which the velocity can reach 30 k/h), together with the mounting shroud, shown in Figure 10, has the further advantage of providing turbulence, ensuring that dust is prevented from settling on the scanner optical window. However, from this position, the scanning plane can occasionally by intersected by the hoist and drag ropes as they swing under the boom. To overcome this, the laser was mounted at an angle of 10° to the vertical, see Figure 9, which results in fewer cases of the drag and hoist ropes restricting the view of the scanner.

Figure 10. The laser scanner mount at the dragline's boom tip.

The boom tip also moves with load; to ensure that each laser scan is processed in a common coordinate frame, an RTK-GPS receiver was mounted on the boom tip and used to translate the laser scans into the common reference frame. This also proves useful for reconciling the collected DTMs with the mine plans.

The laser scans are collected as the dragline rotates with the angular position of each radial scan measured using an encoder on the slew drive of the dragline. Combining the bearing and angle data from the laser with the angular position of each scan, the Cartesian position of each point on the

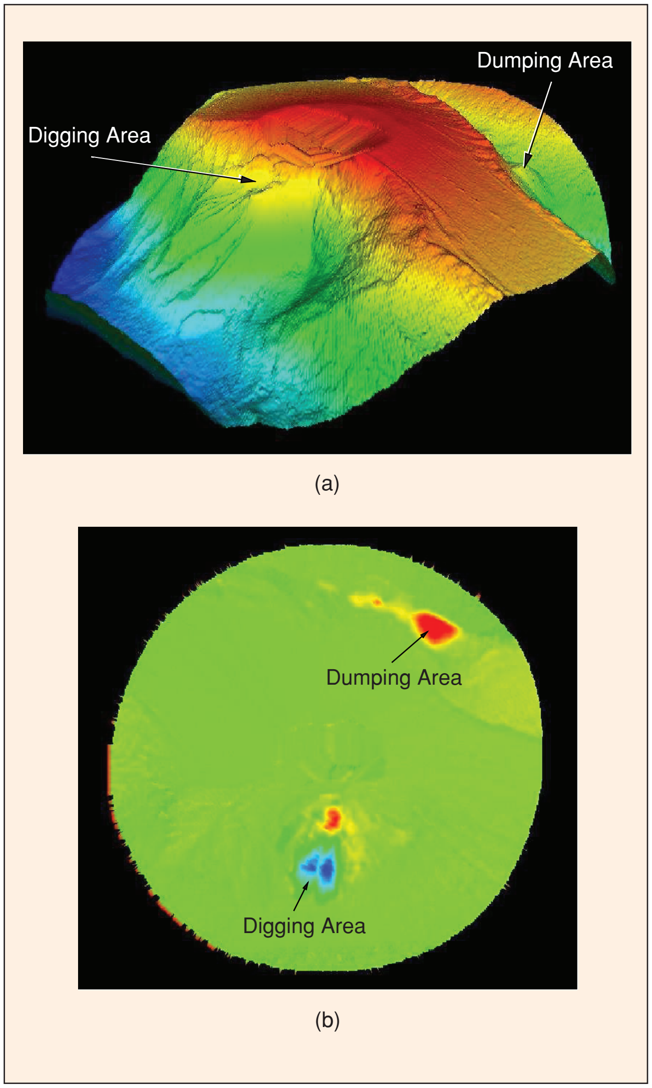


Figure 11. A DTM and a difference image from a DTM taken 30 min earlier. Note that in the difference image, blue indicates areas where material has been removed, and red indicates areas where material has been dumped. (a) A 3-D view of a DTM where material has been removed. (b) The difference DTM between the DTM of (a) and one taken 30 min earlier.

ground (x, y, and z) can be determined. The data is then transformed into a height-encoded occupancy grid where grid cells containing more than one data point (common near the center) are assigned the value of the highest data point within that cell. There can also be cells that are missing data, whether this is due to no laser return from that point (due to surface reflectivity properties) or because the laser did not illuminate that point (due to the high-speed motion at boom tip). The missing data can be filled in using simple interpolation techniques. This approach provides the most conservative estimate of the terrain profile, which is critical if the DTMs are to be used by the automation system for collision avoidance. The grid size that we have found appropriate for this task is 0.5 m × 0.5 m.

In-Field Terrain Mapping

Figure 11(a) shows a measured DTM created from a single 360° rotation of the dragline. Critical dimensions can be easily measured such as spoil pile height, bench width and excavation depth. DTMs are georeferenced using the RTK-GPS allowing maps taken at different times to be compared. This allows for the determination of where material has been excavated and dumped, along with volumetric estimations. Figure 11 shows a terrain map and a difference image from two DTMs, which clearly shows the distribution of material movement over the time between DTM collection (30 min in this case).

Toward Full Autonomy

The DSA work described earlier developed operator enhancement technologies targeted at the slew-dump-return phase of the dragline excavation cycle, keeping the operator in-the-loop. However, a recent project [21] gave us the opportunity to explore automation of all phases of the excavation cycle, including digging, as well as integrating the DSA and DTM technologies. The goal of this exercise was to demonstrate very remote teleexcavation, dealing with large latencies between the operator and the machine, as would be encountered for off-world operations.

Teleoperation has been an active field of research and commercial activity for a number of years as it offers a means of isolating an operator from hazardous or un-inhabitable environments while retaining the reasoning powers of the human operator. The level of operator interactivity required depends on the task at hand, the level of structure in the environment and the level of knowledge about that environment [22]. An additional consideration is the latencies in the system.

For lunar applications, round-trip message time is of the order of 2 s while for Martian operations, it is of the order of 19 min. The architecture of the testing environment is illustrated in Figure 12. Importantly, this architecture has a facility for adjusting the latencies in the system in order to determine its effect. Because the communications mechanism is the Internet, testing can be conducted from almost anywhere in the world.

Our approach was to allow the operator to specify high-level tasks through a graphical user interface (GUI), e.g., to collect a DTM, and then to select the excavation dig and dump regions based on the online generated DTM, see Figure 13. The operator then commands the machine to perform the entire excavation, including repeated autonomous dig-slew-dump-return cycles, to achieve the operator selected excavation plan. The machine then executes this plan, reporting its progress and status to the operator. This approach has the ability to cope with large latencies in the communication links to the dragline by giving the machine sufficient autonomy to deal with the control and motion planning tasks.

This section outlines preliminary experimental results, on the scale-model dragline, which have realized these activities with demonstrations of fully autonomous dragline excavation tasks, including operations directed from the other side of the world. It should be recognized throughout this discussion that an operator is planning the excavation site and monitoring the machinery and can order a halt to the operations, albeit with significant time delays.

Autonomous Digging

For very remote teleexcavation, automating the digging phase is critical, as the significant time delays preclude the use of direct joint-level control or force feedback type systems. Two key issues for draglines are overloading of the main structural elements and stalling the hoist and drag motors whilst the bucket is digging material (bucket stall). Any autonomous system needs to consider these issues to ensure reliable and damage free operation.

Digging is perhaps the hardest phase of the excavation cycle to automate as it involves forceful interaction with the terrain. Of particular concern to mine owners is the damage that can be imposed on mining machines from overloading. These machines are very powerful and can literally tear themselves apart. For these reasons, it is the digging phase of operations that is least likely to be taken up in a commercial sense in the near future. However, in realizing reliable, autonomous digging, the potential benefits to machine health are hard to ignore.

Autonomous digging requires the planning of a bucket trajectory to effectively fill the bucket whilst avoiding over-stress of the machine. In this investigation, at the commencement of each dig task, the profile of the terrain in the dig plane is measured with the laser scanner and the motion of the bucket through the soil is determined to achieve complete bucket filling at the disengage point.

Bucket stall can be characterized in either the hoist or drag axes as an increase in drive motor current with little or no motion along that axis. If no corrective action is taken to unstall the bucket, the motors could over-heat and/or the motor safety protection could be tripped, which may shutdown the drive. Here, we detect the onset of stall, and automatically modify the dig path appropriately to avoid this condition.

Using Environmental Knowledge

Integrating the DSA and DTM systems allows for the calculation of the parameters for an optimal (shortest), collision-free path, which ensures that the bucket clears all obstacles in the surrounding environment. This trajectory can then be adjusted automatically as the excavation proceeds, ensuring collision-free operation. In addition, the DTM can be used to recognize objects in the environment allowing for precision

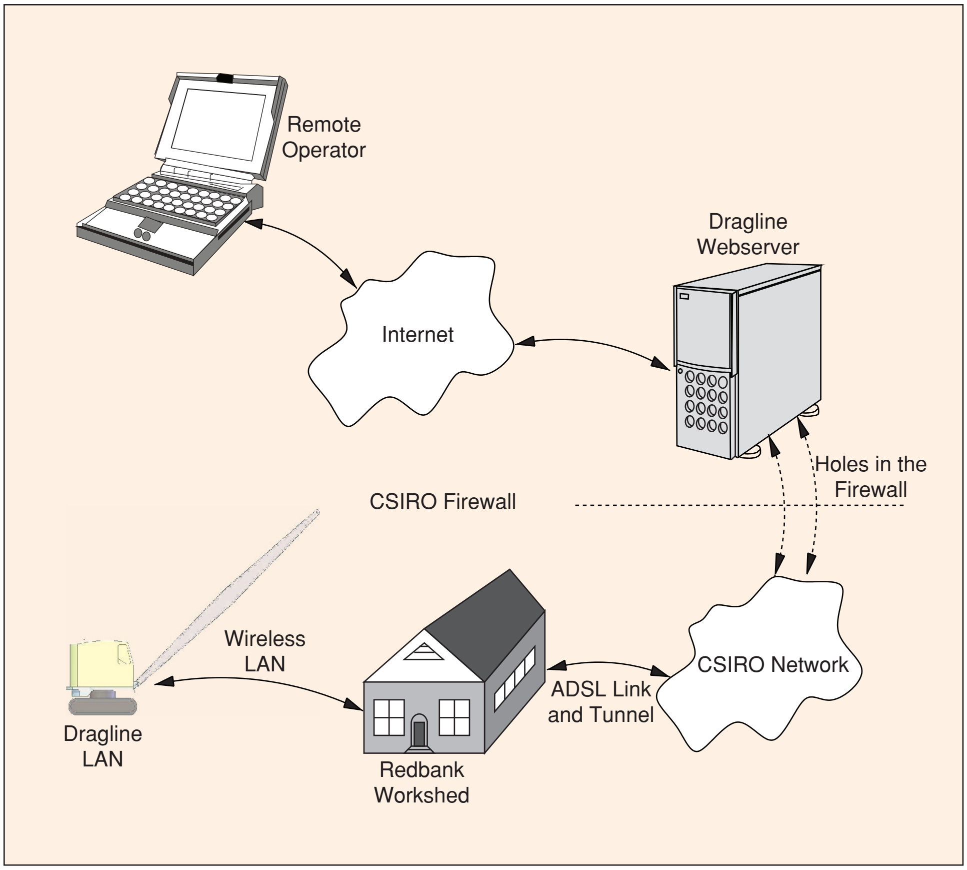


Figure 12. *A schematic of the system/network architecture providing communications between the outside world and the dragline in Brisbane, Australia.*

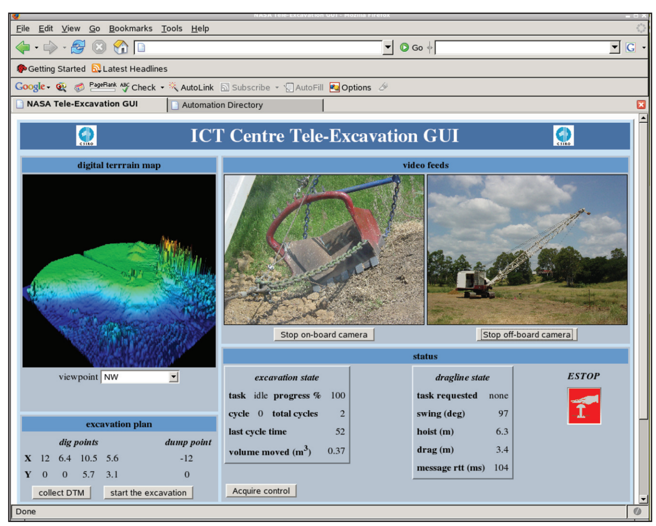
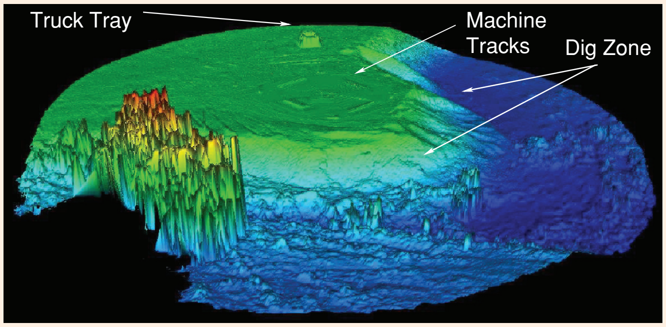


Figure 13. *Screen-shot of the GUI showing the functionality. The DTM of the site is shown in the left image in which a small spoil pile that the system has built can be seen.*



(a)

(b)

Figure 14. *Precision loading of a scale truck tray. (a) Digital terrain map of dragline surrounds. (b) Bucket being autonomously emptied into a truck tray.*

dumping operations. Figure 14(a) shows a measured DTM of the model dragline surroundings where a scale truck tray is visible, while Figure 14(b) shows the tray being autonomously filled by the DSA system.

Complete Autonomous Dragline Cycles

In late 2005, the digging, dumping, DSA, and DTM systems were integrated on the scale-model dragline, with an experimental demonstration, which included 50 consecutive cycles. Here the system was instructed by a remote operator via a GUI to dig in a 4 m long 15° wedge, and dump the material at a slew angle point approximately 120° from the dig zone. Only the dig and dump coordinates and number of digs were specified to the dragline's on-board controller.

The system successfully completed the 50 consecutive cycles without any intervention by the operator. The average cycle time was approximately 63 s with the entire mission taking 52 min to complete. Digital Terrain Maps were captured before and after the experiment from which it was determined that approximately 5.1 m^3 of material was moved during the 50 autonomous cycles. Figure 15 shows an image of the spoil pile generated at the dump location after 50 cycles.

Remote Operator Interface

The most recent version of the operator interface was developed as a highly dynamic Web page, providing seamless updates of the excavation state, video-feeds, a DTM, and the functionality required for an operator to command the machine. This browser-based GUI allows the operator to control the excavation by specifying the high-level tasks outlined previously. Rich user interactivity is provided in the interface through the use of AJAX-like techniques, which provide a means of asynchronous communication between the browser and the server, which, in turn, was able to communicate with the dragline control system directly. Figure 13 shows a screen-shot of the GUI as viewed using a Firefox Web browser.

Experiments included several demonstrations of the technology in which an operator remotely directed an excavation from the Massachusetts Institute of Technology, in Boston, tasking the machine located at Brisbane, Australia. Here, all the required tasks for excavation were directed remotely including: collecting the DTM for planning the excavation, specification of the excavation dig and dump sites, and the execution and subsequent monitoring of the excavation.

Subjectively, although the system can theoretically deal with very large latencies, operators were uncomfortable with delays of more than several seconds as it was difficult to gauge whether the machine had actually received a high-level demand—the time between pressing a button commanding a task, and waiting for the machine to acknowledge and update the web page could be somewhat uncomfortable. However, all of the remote excavations were performed successfully, with minimal operator training required. Of course, further operator training and an awareness of the tasks the machine is performing, along with knowledge of the system latencies and performance could only aid an operator's perception of the system.

Discussion

The development of the DSA system and the surrounding technology has resulted in significant demonstrations of the application of automation technology to the mining industry. Although some of the technological issues have been difficult, more significant were the cultural issues surrounding automation. Furthermore, gaining access to these expensive machines, which are in production 24 hours a day, seven days a week, proved to be a major issue throughout this work—when we did gain access we had to get it right as there was little room for mistakes.

In production environments, we have now developed, fitted, and tried the DSA system on two different draglines; a Bucyrus 1370 at Meandu Mine, Tarong, and a Bucyrus 1350 at Callide Coalfields Boundary Hill mine, Biloela, both in Queensland, Australia. In both cases, the key to successful projects was two fold. First, commitment by the mine owners to the projects was crucial. In particular, allowing us access to the machinery and entrusting the operation of these massive machines to an automation system. A related issue on this point is that the mining industry can be quite transient and in many cases, it was difficult to maintain momentum due to the loss of the site-champion for the technology on the mine site. The second critical element was the involvement of the dragline operators in the projects from the start. An example is the active controls in which the operators were introduced to the concept through training in a mock-up operator chair prior to installation of the controls on the draglines. With this hands-on introduction, and with the knowledge that DSA is not aimed at operator replacement but rather operator productivity improvement, acceptance of the DSA concept and the active controls was very good.

We have taken the DSA technology to a precommercialization stage. Issues for the future include taking the next step and getting this technology into regular use in the mining industry. This is no easy step, as the implementations to date have required rather visionary mine owners. However, the potential benefits in terms of productivity and maintenance are significant. In addition, in Australia at least, there is a growing shortage of skilled workers willing to live and work in isolated mining towns. With the ever increasing demand for resources, one of the few ways of overcoming this skills shortage is through the application of automation and teleoperation, and this seems to be inevitable for the mining industry.

Figure 15. *Photo of spoil pile after 50 autonomous cycles with the scale dragline in the background.*

Conclusion

The ultimate aim of mine automation is to remove humans from the hazardous areas of the mining environment where the work will instead be performed by autonomous machines, supplemented with high-level input from miners. Such a vision is still many years from reality but in the interim we continue to make small steps toward our goal. The autonomous dragline work has demonstrated the major steps we have taken over the last twelve years to develop systems that allow the autonomous operation of mining equipment. In this process, we have recognized the importance of skilled operators and sought to augment their abilities by automating the repetitive aspects of their role. At least in the foreseeable future, this is the most viable approach for the roll-out of these types of technologies in production mines.

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Keywords

Mining automation, dragline, active controls, traded control, shared autonomy, terrain mapping, autonomous operation.

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