Remote controlled short-cycle loading of bulk material in mining applications

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Abstract: High-capacity wireless IP networks with limited delays are nowadays being deployed in both underground and open-pit mines. This allows for advanced remote control of mining machinery with improved feedback to operators and extensive monitoring of machine status, wear and fatigue. Wireless connectivity varies however depending on channel impairments caused by obstacles, multi-path fading and other radio issues. Therefore remote control and monitoring should be capable of adapting their sending rates to handle variations in communications quality. This paper presents key challenges in advanced remote control and monitoring of working machines via high-capacity wireless IP networks in mining environments. We reason about these challenges in context of underground short-cycle load, haul and dump operation with large-volume built wheel-loaders and present a generic communication solution for an operator assistance concept capable of adapting to varying communication properties.

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1. INTRODUCTION

The mining industry has since the early 2000’s tried to exploit recent advances in ultra-high-frequency (UHF) technology, especially cellular phones, wireless local area network (WLAN), UWB and radio frequency identification (RFID) (Forooshani et al. 2013). This trend is driven by needs for improved safety and efficiency. For example, in the United States with a total of 14,885 mines in operation (2006), the Mine Improvement and New Emergency Response Act of 2006 (MINER Act) stipulates that by July 2009 underground mine operators must install wireless two-way communications and tracking systems that will link surface rescuers with underground workers (MMWR 2009).

In Sweden, Boliden Group has in their underground and open-pit mines deployed IEEE 802.11ac wireless networks for communications as well as real-time localization of both workers and machinery (Nilsson 2014). In addition to better safety these networks facilitate effective voice communications as well as remote controlled and monitored machinery. This paper presents key challenges in advanced remote control and monitoring of such machinery, and presents a generic communications solution for industrial working machines. We reason about these challenges and communications solution in context of underground short-cycle load, haul and dump operation with large-volume built wheel-loaders in Boliden underground mines.

Remote controlled mobile machinery such as Load Haul and Dump machines (LHDs) has been used in industrial applications for more than ten years (Gustafson 2011). Such machines have early on been remote controlled and partly autonomous because of the harsh working environment in mines and to enable excavation at times when personnel cannot be present in the machine, e.g. directly after blasting and during ventilation. The productivity of remotely operated LHDs is however not in parity with on-board operation. One specific weakness is lower average payload of remote excavated buckets (Andersson 2013).

The variation in the fragmentation of blasted material to be excavated in underground hard rock mines is significant higher compared to material is of granular type. The challenges for efficient remote controlled or autonomous excavation are therefore higher in underground hard rock mines (Filla. et al. 2014 and Marshall, et al. 2008).

Autonomous loading of bulk material is considered to demand further work and research (Hemami and Hassani 2009). We consider operator assistance functions for remote control with skilled operators as a more viable approach than fully autonomous loading in the short to mid term, as well as an important step to collect experience to refine fully autonomous loading for improved productivity.

Shortcomings of remote operated LHDs are relevant also for high-volume produced wheel-loaders such as construction machines, which in many cases are to perform similar work as for ore excavation in mines. In some cases, such wheel-loaders are even used for underground ore excavation when specialized machines are avoided for reasons such as extensive need for mobility and flexible manoeuvring.
Efficient remote operation depends on reliable and predictable wireless communications. Remote monitoring is further essential to assure that machine issues are properly tracked although personnel are not on-board machines. It is then important to stress that remote control and monitoring systems can adapt their sending rates and handle temporary communications capacity reductions or even complete loss of connectivity as well as delay variations.

Adequate remote operator stations with support for testing during development and operator training are essential for efficiency reasons and to avoid machine damage due to misuse. Such station need to support evaluations and training related to adaptive operator assistance, which needs to be designed for intuitive usage to avoid operator mistakes.

The rest of the paper is organized as follows. Section 2 present and reason about challenges related to underground short-cycle loading. Section 3 discusses means of adapting remote operation in context of the different sequences conducted in such loading operation. Section 4 presents a generic communications solution supporting adaptive remote operation, while Section 5 describes our system implementation and testing. Section 6 concludes the paper.

2. KEY CHALLENGES

An overall challenge in operating remote controlled working machines is how to perform the work safely and fuel efficiently with high productivity without causing unnecessary wear and fatigue on the machine. This is because the remote operator typically lacks motion feedback and is limited to rely mainly on video to operate the machine, which leads to an information gap compared to the on-board operator in the cabin of the machine. Hence, the remote operator has to base the control of the machine on information with less content and inferior quality.

System design, encompassing wheel-loader, operator and application, has a large impact on energy efficiency and productivity (Frank et al. 2012). This is due to the complex nature of the construction equipment operations and interactions between machine and operator. Tests show performance differences between operators in the magnitude of several hundred percent. These differences mainly depend on the operator’s ability to plan the operations. The work-cycle of a skilled operator is typically performed smoothly with a minimum of (unnecessary) machine movements. Skilled operators also ensure that bucket filling is performed energy efficient while achieving large bucket loads.

To minimize issues with low fuel efficiency and poor system performance, several approaches are possible. One is training of operators which has by general experience from operator training shown to be an effective tool to improve fuel efficiency and productivity. Another approach is on-board systems that measures and informs the operator of in-cycle performance and even suggests corrective actions.

The operator impact on system performance is highly relevant when controlling operations remotely. Challenges on system performance in terms of for instance delays in control and feedback will need to be overcome, especially at locations where wireless connectivity is unreliable. The remote operation under such circumstances further motivates targeted training of operators, involving practising with remote operated machines, through simulations, or a combination of both. With remote operations increasing the complexity of operations, higher demands will also be put on operator performance feedback and functions for assistance and guidance.

Consequently, an important challenge related to safe and energy efficient operation while avoiding misuse is how to select the best combination of different feedbacks. Visual, sound, tactile and possibly motion feedback should be combined to make the best of a remote operator’s abilities. Also, the best combination of decentralized control loops to be closed locally at the machine and loops to be closed by the remote operator need to be determined. For example, local control loops can assist in achieving large bucket loads at low energy cost. Selecting where to approach the pile of material to be loaded may on the other hand involve a control loop closed by the remote operator taking decisions based on video feedback.

Two challenges in operator assisted and autonomous underground loading of fragmented rock in comparison with a skilled manual driver are (1) obtaining high average bucket weight at low average cycle time and (2) avoiding collisions with the walls in narrow tunnels and nearby working machines (e.g. trucks).

With blasted rock, the size distribution of the material varies a lot, implying that the optimal control strategy for an automatic loading function might vary from one scooped bucket to another. Figure 1 (left part) shows a pile of blasted rock with varying rock sizes, and a snuffbox with diameter 7.5 cm. According to experience at Boliden the rock size can vary between a few mm to almost 50 cm.

Figure 1 Blasted rock and draw point in cut-and-fill mine

The un-loading of the bucket on a truck in case of short-cycle loading is challenging in several respects. For example, the truck might be at different positions from one bucket to another, the truck might need to be moved during un-loading, and the height of the tunnels can impose constraints on bucket manoeuvring.

3. ADAPTIVE REMOTE OPERATION

For the adaptive assisted operator approach, we consider the specific case of underground short-cycle load, haul and dump operation with bigger-sized and large-volume built wheel-loaders to be important. This is because it comprises of the
challenging task of bulk material loading in a unit operation, which has been well explored with LHD-machines (Gustafson 2013). The type of unit operation commonly performed by LHD-machines involves hauling the loaded media to a remote dumping location. Such longer hauling exercise is not a part of the short-cycle load operation. Instead, a dumper truck is typically present in the vicinity of the machine, and the complete load cycle takes place in a small time frame of 25-30 seconds (Filla 2011).

In short-cycle loading the steps performed by the wheel-loader in one operation cycle are as follows: 1: Approach the pile, 2: Loading, 3: Retract from the pile 4: Approach the dumper, 5: Dumping, 6: Retract from the dumper (Figure 2).

![Figure 2 The short loading cycle](image)

When approaching the pile, a good loading spot needs to be located where the machine navigates to while placing the bucket in the right position. Although different machine vision approaches to automatically identify the best loading position have been studied (Sarata et al. 2005, Magnusson and Almqvist 2011), we believe that this step should be performed by the remote operator specifically in this case of loading of blasted rock in the underground mines. This is because of great variation in the size distribution of blasted rock and the narrow space for maneuvering, which complicates the selection of loading spots. One should also keep in mind that the narrow tunnels limits the options regarding the best loading position. It might even be so that the loading has to be done with a significant articulation angle of the loader if the blasted rock is located in a curved part of the tunnel.

Even though short delay and high-resolution video feedback possibly with some depth perception are highly desirable, the remote operator may, in cases of limited wireless capacity, need to cope up with lower resolution video and longer delays. Operator assistance functions that can aid the remote operator to select the best possible loading spot could potentially help in such cases, while also constituting a step towards fully automatic operation.

Although the loading sequence is clearly challenging due to the variation in size distribution of the material to be loaded, we envision the full automation of this step while achieving high average bucket weights. Possible automatic control methods for the loading step include compliance control (Sarata et al. 2004), feed-forward control (Maeda 2013), and artificial intelligence approaches like rule based fuzzy logic (Wang 2004).

Since a strict position control can only be realized in free air and not while traversing through a pile, compliance control argue for modifying the trajectory of the bucket on the fly in compliance with the resisting forces on the bucket. The idea behind the feed-forward control is to model the complex and stochastic interactions of the bucket with the pile as a disturbance to the loading process (Dadhich 2015).

Iterative learning methods combined with artificial intelligence based control is one of the candidates to perform the loading operation autonomously. A common idea behind these artificial intelligence based methods is to code the intelligence of an expert operator into a computer algorithm (Dadhich 2015).

An autonomous function for loading may depend on remote supervision acting as an outer control loop for adjusting and selecting from different alternative solutions. For example, settings for a solution based on an adaptive fuzzy control may require continuous inputs from the remote operator to perform loading with high bucket weights. High-resolution video, audio and other feedback data (vibration and tactile) would also be desired for such a remote operator task. Hence, limited wireless capacity may impact on the performance of the remote supervision of automated loading.

As noted in Section 2, blasted rock characteristics might vary from one scooped bucket to another, which requires different control strategies for the bucket filling. Selecting the optimal control strategy for a particular rock profile and use it for all loading cycles is hence likely to give lower bucket weights than adapting this strategy based on available inputs. We argue for that the adaptation of the control strategy for automatic loading is a key function for remote loading to achieve high average bucket weights. Such adaptation could be based on the visual and tactile feedback to the remote operator, the measurements on the machine for the local control, or a combination of these inputs.

The sequences, 3, 4, 5 and 6 (Figure 2) which are, retracting from the pile, approaching the truck, dumping and retracting from the truck can be automated by using the already advanced research in the field of localization, navigation and path planning (Dragt et al. 2005, Filla. 2013). Mines in which the cut-and-fill caving method is used are however often very tight and narrow at draw points, making these sequences hard to automate. Examples of such mines are the Boliden Kristineberg and Kankberg mines (Boliden 2015).

Figure 1 (right part) shows a draw point in the Boliden Kankberg underground mine. At this draw point for every loading cycle, the truck needs to move forward to leave space for the wheel-loader to load where after the truck reverses to take position for dumping. These interactions between the wheel-loader and the truck in the tight and narrow environment illustrate the maneuvering difficulties in making short-cycle loading fully autonomous.
These difficulties in maneuvering at tight and narrow draw points motivate the need of assisted remote operation aiming at semi-autonomous solutions in the longer term. Desired operator assistance functions aiding the remote operator in maneuvering include collision detect systems and relative localization solutions, for example needed to position the wheel-loader correctly towards the truck for dumping.

As discussed, wireless capacity and delay can have impact on the remote operation of wheel-loaders performing short-cycle loading in mines. Degraded communication properties will result in limited remote controllability, feedback or a combination of both and in such cases, the machine control should move towards a safer operation. This means that to avoid the risks of accidents as well as unnecessary wear and fatigue on the machine some pre-defined functional restrictions can be forced on the machine depending on the operation mode. Possible restrictions can be on the parameters such as maximum speed and limited power defined by the maximum RPM of the engine.

Restrictions targeting the safe operation should aim for a good balance between energy efficiency, productivity and safety without risking the wear and fatigue on the machine. For example, all the steps in the short loading cycle involving navigation may benefit from different restrictions put under varying communication properties depending on how the operator assistance functions are designed. A trustworthy collision detect function build to avoid collisions with the tunnel walls may motivate higher speed in retracting sequences, while the sequence 4 (Figure 2), i.e. approaching the truck needs to be performed at a much slower speed due to the complexity and the risk of damaging the truck if a collision occurs.

By measuring the available wireless capacity and the delay in the uplink and the downlink to the machine, constraints in the communication that affects the type and the quality of available feedback to the operator as well as the remote controllability can be detected. Such information can be used to impose pre-defined functional restrictions and adapting the control strategy for the loading. Therefore, the communication solution needs to be capable of measuring the data forwarding quality, adjusting the transmissions accounting for detected variations, and reporting to the operator assistance functions on the machine.

4. A GENERIC COMMUNICATION SOLUTION

The generic communications solution that we propose for adaptive operator assistance is based on the SCTP protocol (Fu and Atiquzzaman 2004), active measurements of communications properties inspired by IPPM (Fabini and Morton 2014), and machine localisation obtained from WLAN positioning. The IEEE 802.11ac wireless networks deployed in Boliden mines supports real-time localization of both workers and machinery (Nilsson 2014). A key function of the system is to keep track of personnel. The solution includes a graphical interface with a map of the mine on which positioned items are presented (Mobilaris 2015). Tracking personnel is important for security reasons, e.g. to make sure that everyone presently in an underground mine are inside a rescue chamber in case of an accident. For this application the present positioning resolution of around 50 meters is sufficient. The accuracy can be further improved e.g. using path loss modelling and RFID tags with known exact positions (Osipov and Kleyko 2015). Thereby, applications of the system requiring better positioning accuracy become possible.

With positioning resolutions in the order of a few meters, measurement results for wireless capacity at different locations can be compiled into statistics for discrete locations. That is, measurements for positions in the same area of say 10 square meters in a tunnel can be used to predict the wireless capacity at that particular place. This predicted capacity could then be used to adapt beforehand in a controlled manner the control and feedback data rates, and if necessary because of previously experienced wireless capacity limits, force functional restrictions on a remote operated machine.

The continuous measurements of wireless capacity can capture throughput, delay and delay variation (a.k.a. jitter). This information can be used to adapt control and feedback data rates in case not adapted beforehand, e.g. because of not previously seen degradations in wireless capacity, or in absence of a wireless capacity prediction solution. In this context, it is important to notice that several big machines operating in the narrow tunnels might have a disturbing influence of the communications capacity.

In case of degraded wireless uplink capacity from a machine, video feedback need then move to lower resolution, reduced number of frames per second, or a combination of both. Should downlink capacity become degraded, the rate of control signals needs to be reduced. As noted in Section 3, such reductions in feedback and control may need to be accompanied by functional restrictions forced on the machine to ensure the safe operation.

Although measurements and predictions can be used to force restrictions on remote operated machines, they still face increased risks of being damaged from collisions and become subject to more wear and tear than manually operated machines. Therefore, we argue that extensive remote monitoring should be seen as a vital part of the communications solution.

Wireless communications in mining, industrial and construction environments may constitute more than one wireless infrastructure. 802.11 networks may for example be complemented with cellular data systems such as the 3GPP LTE (3GPP 2015), and CDMA at the 450 MHz frequency bands (CDG 2015), offering coverage also at distant and sparsely populated locations. This means that the communications solution needs to support switching between different networks. We further advocate applying TCP-friendly congestion control and avoidance to all transmissions. This is to avoid saturating the wireless networks causing throughput degradations and longer delays.
Our communications solution can be seen as a middleware providing generic functions for machine automation. Figure 3 shows the block diagram for its components and their interconnection when instantiated in machines. The instantiation at control sites are basically the same, except that the machine restrictions application does not force restrictions to the machine. Instead it may inform remote operators of that restrictions currently are in effect.

The communications solution is based on two SCTP socket associations (i.e. connections between machine computer and computer at control site), one for feedback and control and another for monitoring data. Both these SCTP associations can be multi-homed in case several networks are available. The multi-homing feature allows a single association be associated with more than one IP address. This allows for switching between networks using the SCTP built-in functions for multi-homing (Stewart 2007).

The lifetime of an SCTP message determines how persistent the transport service should be in attempting to send the message to the receiver (Stewart et al. 2004). The lifetimes of feedback and control messages are preferably set short to avoid retransmissions, which would delay the message delivery. This is because such messages typically become useless when delayed.

The lifetimes for monitoring messages should be set to values decided by the monitoring application to allow for different preferences on assured delivery. Also, monitoring messages may need to be throttled in times of reduces wireless capacity to ensure that feedback and control messages are received at best speed. The setting of the lifetime for each message and the throttling of message streams are performed by the functional block located in between the local loop interface and the SCTP sockets (Figure 3).

The experimental system is installed and tested in a Volvo L110G wheel-loader. The means to control the machine are via two electronic breakout units designed and implemented for this purpose (Häggström 2013). These units allow the Controller to send commands to the Electronic Control Units (ECUs) of the machine as well as receiving observed data communicated with the connected ECUs. That is, they can intercept signals on the cabling to and from ECUs. The machines are thereby made remote controlled from a Control Rig from the Swedish Company Oryx Simulations. This rig has the same controls as in the machine.

Using the experimental system we have measured the total delay from remote stick movements to when actuations take effect on the machine. The resulting total delay for lowering the boom was close to 430ms with hydraulics and mechanics accounting for close to 300ms. In this test the communications delay was about 20ms, which illustrates that delays can appear in many steps from remote control actions to when the machine actually reacts.

The video solution used in these tests gave more than 100ms delay. With this delay in visual feedback and the delay for controls of almost a half second, it became very difficult to perform tasks such as short-cycle loading efficiently based on remote control. Reducing delays to become short enough may not be possible. Video delays will remain although they can be made shorter, and the same goes for the hydraulics and electronics in the machine. Assuming the visual feedback and machine actuations will remain at levels still causing difficulties, we believe that operator assistance functions related to forced functional restrictions on the machine are essential to ensure the safe operation at remote.

6. CONCLUSIONS

Modern mines will be equipped with high-speed wireless networks. Mining companies like Boliden have already in their underground and open-pit mines deployed IEEE 802.11ac wireless networks for communications as well as real-time localization of both workers and machinery. An important usage of such networks is the remote control and operations of mining machines. Remote operations of such machines is motivated by the harsh working environment in mines and needs to enable excavation at times when personnel cannot be present in the machine, e.g. directly after blasting and during ventilation.
In this paper we have presented key challenges in remote controlling wheel-loaders used for short-cycle load, haul and dump of blasted and fragmented rock. We have identified possible approaches for automated loading and defined a concept of forcing functional restrictions on machines to ensure safe operations in situations of reduced wireless capacity. We further present a generic communications solution, which is partly verified with a test implementation. Delay measurements made with this experimental system illustrates the need for adaptive operator assistance functions such as the functional restrictions suggested in this paper.

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