RESEARCH REPORT

A Survey in Automation of Earth-moving Machines

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A Survey in Automation of Earth-moving Machines

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Abstract

The earth-moving machines are used in many industries such as mining, construction, forestry, agriculture and cleaning. In underground mines, wheel loaders or LHD machines are used to move the blasted rock to a dumping site or onto a dumper truck. In presence of a nearby dumping truck, the wheel loader is said to be operating in a short loading cycle. This research work concerns with moving of fragmented rock by a wheel loader in a short loading cycle. Three decades of research efforts in automation for bucket loading operation has not yet yielded in any commercial fully autonomous system for this application due to the complexity of bucket-environment interactions. In this report, the challenges in automation and remote-operation of earth-moving machines have been highlighted. A survey in different areas of research within the scope of the project is conducted and knowledge gaps have been identified to give the direction to future work. A plan of actions is made to conduct the proposed research starting from a basic remote control setup to a more advanced assisted remote control operation for a wheel loader in short loading cycle.

Preface

This report is the first step in the WROOMM (Wireless and remote operation of mobile machines) project which aims for advances in the remote control of earth moving machines in underground mines. It has been funded by the Swedish government agency Vinnova and is planned to be done in close collaboration with industrial partners. The industrial partners for this project are Boliden, Volvo CE, Oryx Simulations, ABB and SICS.

Contents

Chapter 1

Introduction

An earth-moving machine describes a big set of industrial machines used in construction, mining, forestry, agriculture, cleaning and many other industries. An earth-moving machine have two parts: one is the vehicle (i.e. the main body) and other being the robotic mechanism which is mounted on the vehicle. Many kinds of earth-moving machines are available with different combinations of the vehicle and the robotic mechanism. The robotic mechanism typically have a robotic arm (a combination of links and joints) powered by a hydraulic system and the tool.

Wheel loaders and excavators are two common examples of mobile earth-moving machines which are shown in Fig. 1.1. An excavator (Fig. 1.1 a) has three joints for the bucket, boom and stick while the wheel loader (Fig. 1.1 b) has two joints one each for the bucket and the boom. For these machines, the vehicle can be wheeled as in the case of a wheel loader or tracked as in the case of an excavator. In the case of wheeled vehicles, the vehicle can also have two bodies connected with an articulated joint.

The wheel loaders are extremely versatile machines often used as multi-purpose machines at production sites [1]. A few applications where wheel load-

(a) Excavator (b) Wheel loader

Figure 1.1: Two common mobile earth-moving machines (Source: Volvo CE)

ers are used everyday are transportation of soil, ore, snow, wood-chips and construction material. Based on the specific application, wheel loaders can have different tools. The most common tools for the wheel loaders are buckets and forks and, depending on the properties of material to be loaded, many different choices of buckets are also available.

Wheel loader have extensive use in the mining industry where they are used to transport ore both in open-pit mines and underground mines. In underground mines, special type of wheel loaders are used which are known as LHD (Load-Haul-Dump) machines. Fundamentally, LHD machines are same as wheel loaders except that they are adapted for the low ceiling in the underground mines.

In this report the focus is on automation of earth-moving machines such as wheel loaders and LHD machines. Automation of such machines has been an active area of research over the past three decades [2]. As claimed in [3], despite a lot of research in this field, a fully automated system of a mobile earth-moving machine has never been demonstrated. This indicates that the problem of automating the earth-moving process is challenging.

The difficulty in automating the whole process can be attributed to the fact that it is impossible to accurately model the earth-moving process, especially the interaction between the tool and the environment. The properties of media to be excavated or moved is central to the problem. Examples of different media are snow, soil, wood chips, fragmented rock, mud etc. Autonomous excavation of soil is a well studied problem and yet fully automated excavators are rare [4].

Since full automation of the earth-moving process is difficult, researchers commonly aim for small steps in moving towards automation. In [5], a five step approach is suggested from a full manual operation at step one to a full autonomous operation at step five. In [1], another nomenclature for these steps is proposed. The five steps to full automation tailored for mining industry are listed below, stressing the point that remote control issues are important when moving from in-sight tele-operation to remote-operation of mobile earth-moving machines. This is because the remote operation introduces more uncertainties in the form of delay and loss of the communicated data over the network. The five steps towards fully autonomous operation are:

- Manual operation: The operator is sitting in the machine manually performing all the tasks.
- In-sight tele-operation: The operator is outside the machine but still inside the mine in the vicinity of the machine performing all the tasks by a hand held remote.
- Tele-remote operation: The operator is in a control room outside the mine still performing all the tasks by the help of a remote and audio-video feedback from the machine.
- Assisted tele-remote operation: The machine performs many tasks by itself by the use of operator assistance functions (sec. 1.2). The operator interferes in the tasks where human supervision is of importance.

- Fully autonomous: The machine performs all tasks by itself. The operator is only present to take care of emergencies and to handle failures.

Most commonly, the mobile earth-moving machines performs the following three tasks during one cycle of operation.

1. Loading
2. Navigating
3. Dumping

Since this cycle in many applications is repeated thousands of time, it is important to ensure that efficiency is respected in each step. Also, the safety of humans and the machine are the main priorities. The requirements for safe and efficient remote-operation of a wheel loader are discussed in chapter 2.

The mobile earth-moving machines transport material (soil, fragmented rock, gravel etc.) from one place to another. The distance between the source of the material to its destination can be from a few meters to a few hundred meters. This differentiation creates two classes of operating cycles, the long distance cycle and the short loading cycle. In the long distance cycle, there is a significant distance between the loading point and the dumping point and thus a larger amount of time is spend in navigating. In a short load cycle, the dumping site is in close proximity of the loading machine which may be in the form of a dumper truck or conveyor belt. The focus of this work is on the short loading cycle because that puts strict constraints on the timing of the operation cycle of the earth-moving machine.

1.1 Short loading cycle

In a short load cycle, a dumper truck is typically present in the vicinity of the earth-moving machine. Most commonly, the mobile excavating machine performs a V-Y curve (as shown in Fig. 1.2) between the loading site and the dumping site but in the case of a side dumping bucket, the motion of the machine is close to a straight line. The loading of some granular material on a nearby dumper in a short load cycle takes place in a small time frame of 25-30 seconds [6]. The challenge for the assisted remote-control operation is to at-least perform equal to an expert operator in manual operation.

Intensive research efforts are needed to close the gap from remote-control operation to an assisted remote control operation. In relation with Fig. 1.2, different procedural steps for implementing an assisted remote-control for a short loading cycle operation have been identified in Table 1.1. The control algorithm for loading the material is the most important and the most discussed step but it still remains as an open area of research [3]. A general control strategy for loading doesn't work because the properties of material (density, hardness, moisture and composition) being loaded varies a lot.

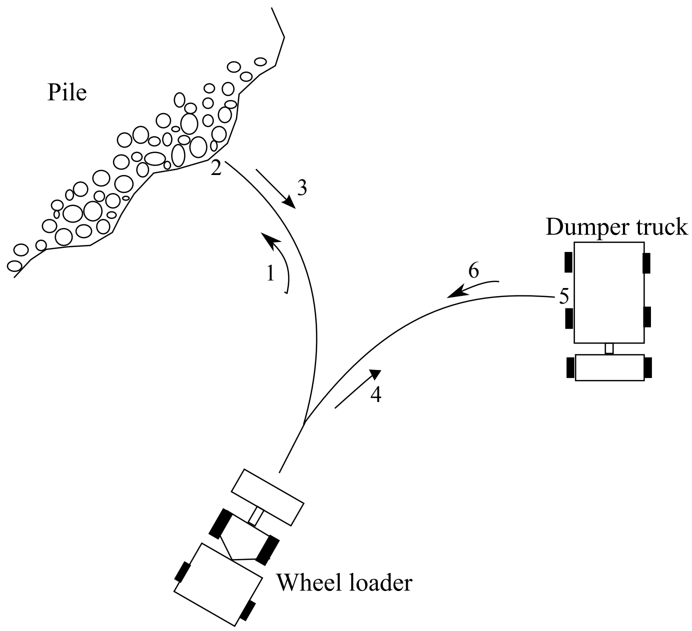

Figure 1.2: Short Loading Cycle
The steps performed by the wheel loader in one operation cycle are as follows: 1: Approach the pile, 2: Loading, 3: Retract from the pile 4: Approach the dumper, 5: Dumping, 6: Retract from the dumper

Approach to pile	1. Locate the best loading spot 2. Navigate to the loading spot safely and efficiently 3. Place the bucket in the right position for loading
Loading	1. Using the sensor input, run the control algorithm for loading the pile for the specific conditions 2. Adjust the load in the bucket to prevent spillage
Retract from pile	1. Locate the pose of the dumper 2. Identify a good target location for reversing 3. Reverse in a safe way avoiding any obstacles
Approach the dumper	1. Navigate to the dumper safely and efficiently 2. Prepare the boom and bucket for dumping
Dumping	1. Ensure that alignment is as desired 2. Activate the boom and bucket for dumping
Retract from the dumper	1. Locate a reversing point 2. Reverse in a safe way avoiding any obstacles 3. Lower the boom and bucket for next cycle.

Table 1.1: Steps in assisted remote-control operation for short loading cycle

1.2 Operator assistance functions

Operator assistance functions is a tool for striving towards full autonomy of the earth-moving process. In pure remote-control operation, operator assistance functions can for example warn the operator for collisions or alert them about inefficient and unsafe use. In assisted remote control operation, these functions can mostly take over the operator. Examples of operator assistance functions are:

- Path planning
- Collision detection, avoidance and navigation
- Prepare the boom and bucket for loading and dumping
- Alignment with the dumper
- Loading algorithm
- Dumping algorithm

A combination of manual operation with operator assistance functions for path planning and navigation is described in [7] as semi-automation. In [8] and [9], a semi-autonomous operation is developed with implements a collision detection, avoidance and navigation function to assist the operator. Assisted tele-remote operation is a combination of remote-operation and operator assistance functions. It can be seen as an extension of semi-automation which finds the right balance between remote control and automation.

1.3 Communication

The communication support for remote control operations is often overlooked by researchers. It has been observed that only a 2D video feedback to the remote operation results in a poor performance during remote control of the machine [10]. Since an operator in manual operation uses all his visual (3D), sonar, tactile and other sensory organs to operate the machine [11], the remote operator must also be provided with more feedback than just a plain video. It is identified in [2], [10] and [12] that the operators makes their decisions based on their vision, the sound from the surrounding and the vibration from the machine. Although it is undesirable to trouble the remote-operator with noisy sound feedback and uncomfortable vibrations, some reduced form of audio and vibration feedback will certainly help the remote operator. In total, there can be four streams of feedback data to the remote control station (Fig. 1.3), which are:

- Video stream
- Audio stream

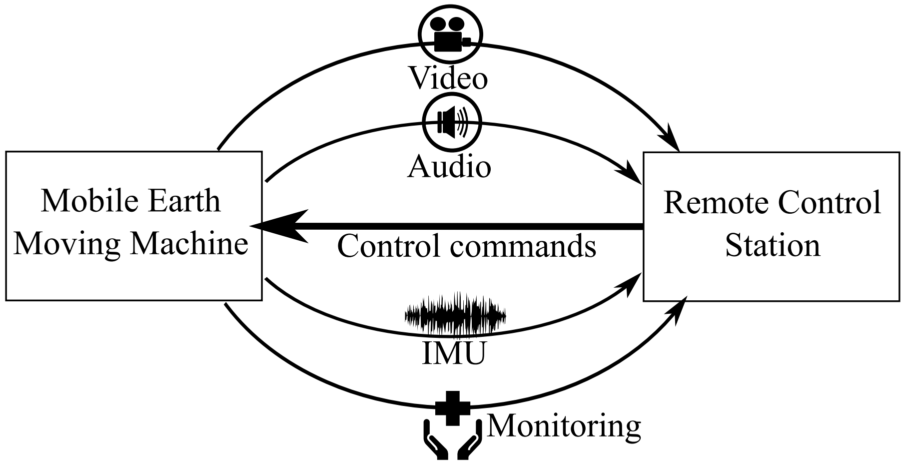

Figure 1.3: Data Streams between mobile machine and remote control station

- Vibration data from the IMU mounted in the machine
- Monitoring data

Since these machines communicates over wireless links, the adverse effects of wireless channels like multipath-propagation, varying signal strength and interference can plague the communication performance. Even a small glitch or delay in the feedback data can significantly destroy the experience of the remote operator effecting their ability to control the machine. Therefore, the design of a good communication setup should not be overlooked when designing a remote control system for mobile earth-moving machines.

The organization of this report is as follows. The next chapter highlights the requirements of the targeted unit operation of the research project. In chapter 3, a classification of relevant research areas in the broad field of automation of heavy construction machines is presented. This survey also highlights the state of art in all different research areas in this field. In chapter 4, some important research questions have been raised where the knowledge gaps are still very wide. These research questions motivate the need of research work in this field. Finally, chapter 5 concludes the report giving the direction for future work.

Chapter 2

Requirements of the Targeted Unit Operation

The targeted unit operation for this research project is the short loading cycle operation by a wheel loader for moving fragmented rock. The wheel loaders and the LHD machines are the most common heavy machines used in short loading cycle operation and thus from now on this discussion will focus primarily on wheel loaders as the mobile earth-moving machine. LHD machines are used only in certain underground mines and they are just a modification of wheel loaders. Since this operation cycle (short loading cycle) is repeated thousands of time, it is important to define stringent requirements for the operation. Two aspects in which these requirements can be classified are: Safe operation and Performance.

2.1 Safe operation

Safety is a priority for companies in developed countries [4], but reducing the maintenance cost in operation is of interest to all companies around the globe who are using the mobile earth-moving machines. Safety to human must be given the highest priority. Normally this is done by separating the zones of remote-operated (or automated) machines by the zones where humans could be freely walking. Safety to the machine comes second which is also very important because apart from the direct cost of repairing a broken machine, the maintenance cost also includes the cost of production loss during the down time of the machine. Given the importance of safe operation, below is a discussion of safety threats and their mitigation for the humans and the machines.

Safety for humans

As safety for humans must be the first priority for the industries using heaving machinery, more than one method should be implemented to ensure the absolute guarantee against accidents. The collision detection systems installed in machines can be used to detect humans in the proximity of the mobile machines. These systems use sensor technologies such as laser, radar, RFID and time of flight cameras. RFID tags is potentially the most economical solution where each personnel is wearing an RFID tag [13]. Each of these systems must issue a warning to the operator much before a human comes within a dangerous distance to the machine.

Wheel slip

Wheel slip is an undesirable phenomenon which results in loss of traction. It occurs when the applied torque to the wheels exceeds much more than the friction available from the surface. Naturally this can occur when the torque applied to the wheel is too high or when there is not enough friction on the surface (e.g. icy and wet surfaces). For the wheel loader operation, this can occur during loading phase when the resistance force on the tool is very high invoking the operator to apply even more throttle. This practice is common with novice drivers and wheel slip becomes a bigger risk with them [14].

Wheel slip can really damage the tires and according to [10], this contributes to 20-25% of the machine's total maintenance cost. Therefore, wheel slip is highly undesirable and should never occur [15]. This can be achieved by incorporating a traction control algorithm running during the loading step in the short loading cycle.

Collision with walls, boulders and other vehicles

Wear and tear to the machine due to collisions with the side walls are very common in tele-remote operation during hauling (also called tramming) even at low speeds. This results in an increased maintenance cost and hence collisions are considered as a big disadvantage of the tele-remote operation [9]. Driving backwards is one critical step in the short load cycle where the chances of collision are even more. Slamming the tool into an obstacle while driving backwards is not very uncommon during remote-operation [8]. There can also be collisions from boulders falling from loaded trucks working in the same area and therefore it is important to have the collision detection and collision avoidance mechanism as an integral part of the navigation system of these machines.

A lot of research on the topic of collision avoidance already exists in the field of mobile robotics and it must be used when developing navigation systems for automated or tele-remote operated mobile earth-moving machines. Most of the collision avoidance systems use laser range finders as in [5], [8], [9] and [10]. Laser based navigation systems are the preferred method of navigation currently but some researchers have also developed radar based collision avoidance systems [13]. It is important to mention that both laser and radar based systems can suffer from performance degradation due to dusty and foggy conditions.

Driving into ditches

In certain underground mines, there can be ditches along the corridor and the drivers are trained to drive close to the wall opposite to the ditch [8]. Since the mobile earth-moving machines will traverse the corridors once in a while, the algorithm to avoid driving into the ditches must also be a part of the navigation system. It is important to mention that once a machine ends in a ditch, it is needed to be towed resulting in a longer disruption to the production.

Security attack

According to [16], roughly 1 in 3 mining companies experienced a cyber attack in 2013. The threat posed by such attacks is increasing because the operations and maintenance systems which are less secure are increasingly being merged into the remote-control systems and IT. In [17], the realization of the threat of cyber attack is presented and the counteractions needed by companies are suggested. Although the criminal minds are more interested in the financial data, these attacks can also easily disrupt the operations. Therefore, the communication system must embrace itself for any security attack possible on the system.

2.2 Performance

With the increasing oil prices and growing demand of resources, the construction and mining industries are under consistent pressure. Their productivity is an importance driver for the development of new industries. As mentioned in [8], the remote-controlled machines are often less productive than manual mode operation. Therefore, it is important to dissect the short loading cycle in steps and study the scope of improvement in performance in each step. The performance of a short load cycle operation is a combination of fill factor, fuel efficiency and cycle time of the operation.

Fill factor

Fill factor or bucket fill factor is the amount of material loaded in the bucket in one scooping. Although the fill factor can be accurately measured by a mounting weighing scale system on the bucket, it can also be estimated by joint torques only. In [15], an operator assistance function for loading is presented with a conclusion that it is very difficult to fill the bucket completely even with soil. The low productivity of a remote operation is majorly due to a less fill factor compared to a manual operation. Keeping this information in mind, it is important to consider fill factor as an requirement while developing automatic loading function for mobile earth-moving machines.

Fuel efficiency

The fuel efficiency of the machine directly affects the operational cost. In [1], arguments are presented to support an operator assistance function for increasing the fuel efficiency. In some publications, productivity and fill factor are considered as analogous and the use of full engine power to load the material is suggested as in [18]. The use of full power is not a good proposal as not only can it result in reduced performance due to the increased fuel consumption but it can also result in increased wear and tear of the tool.

Operation cycle time

Operation cycle time is also important as the short load cycle is repeated over and over again. A small improvement in cycle time can result in many more extra cycles resulting in improved productivity. Navigation phase in the short load cycle has more scope of improvement in cycle time than loading and dumping. A small operation cycle time demands more fuel consumption due to higher acceleration and deceleration. Therefore there is a requirement of a trade-off between the cycle time and fuel efficiency. This particular trade-off problem has been looked upon in [19].

Short loading cycle performance index (SLCPI)

As mentioned before, all three factors (the fill factor, the fuel efficiency and the operation cycle time) are important for the performance of the wheel loader in the short loading cycle. An combination of these factors called as short loading cycle performance index (SLCPI) can be defined as

$$SLCPI = \frac{Fillfactor \cdot FuelEfficiency}{OperationCycleTime}$$

The SLCPI cannot be computed on the fly during the loading step but it can serve as an indicator of performance of the short loading cycle operation on a longer time scale. The goal of the operator assistance functions should be to maximize the SLCPI rather than having singular objectives.

Chapter 3

Relevant Research

This chapter is an attempt to categorize different research publications in the field of robotic excavation. The survey of publications is done with an aim to highlight the previous and ongoing research work in this field. Another goal of the survey is to identify the research areas where essential knowledge to automate the earth moving process is lagging behind. Below is the list of the categories of research areas in this field together with some relevant publications. An effort has been made to strike out a balance between recent and older publications.

(a) Modeling for control : Automatic control functions for all three steps (loading, navigation and dumping) require a model of the machine. But developing an automatic loading function also require modeling the tool-media interaction. As depicted in the control block diagram (Fig. 3.1), the tool-media interactions are highly complex and stochastic. Also the model of pile (G_p) is unknown and changing after every scoop. Modeling the machine (G_m) on the other hand is comparatively an easy task.

- Modeling the kinematics-dynamics of machine : Many literature exits that presents the model of excavators or wheel loaders. In [20], a dynamic model of a back-hoe excavator has been developed. In [21], the kinematic and dynamic models of a tracked earth-moving machine is presented. The robotic mechanism of the machine in this paper is similar to a typical wheel loader. In [10], models are developed for an LHD machine which are used for navigation purpose.

- Modeling of tool-media interactions : Several attempts to model tool-media interactions have been done from as early as 1960's. Early models were based on the interaction forces between the tool and the media and many of them converge to a five-force model, presented in [22], [23] and [24]. These models are often very complex and computationally so expensive that they remain unusable for real time automatic control.

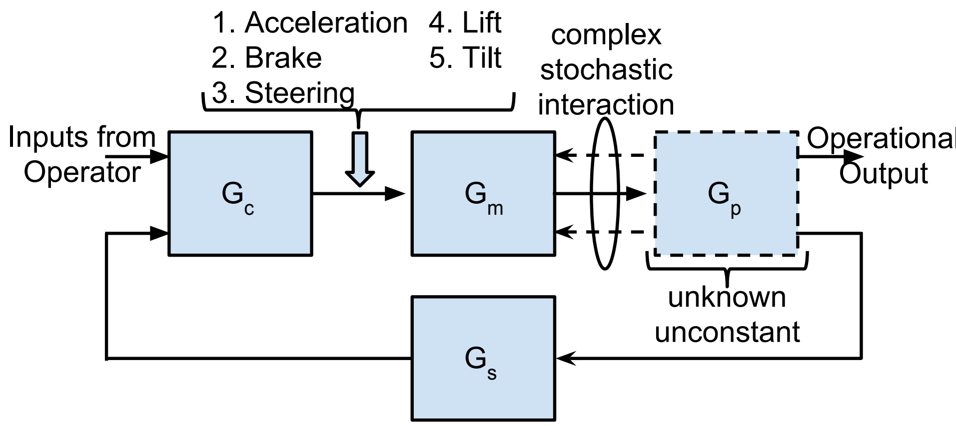

Figure 3.1: Control block diagram. G_i is the transfer function for i = c (controller), m (machine), p (process/pile) and s (sensors)

(b) Automatic loading : Due to the complex nature of the tool-media interaction, developing automatic loading functions which are better than manual operators is a difficult task. One of the biggest question for the automatic loading control problem is which signal should be controlled [2] and which signal should be used for the feedback. Due to the existing challenges in this control problem, very few control philosophies can be implemented. Some of them have been discussed below:

- Position (Trajectory) control : One idea to load the bucket is to follow a planned trajectory. This idea is based on the early work by [25] in which the aim is to maximize the volume between the trajectory cut and the profile of the pile. Many current researchers take the trajectory planning as a starting point for their work as in [15] and [26]. Although a trajectory may be approximately followed for low density sand or woodchips, it is impossible to follow a trajectory for harder media such as fragmented rock. This happens because of the immense amount of resistance force on the tool by the fragmented rock which drives the actuators into saturation and sometimes also results in wheel slip.

- Compliance control : A strict position control can only be realized in free air and not while traversing through a pile. One thought is to modify the trajectory of the tool on the fly in compliance with the resisting forces on the tool. This type of control philosophy is found by several names like compliance control, two-level (force, position/velocity) control, force-feedback control, inner-outer loop control, admittance, impedance control and more. The compliance control is also a fundamental area of research in robotics. In [27], the basic formulation of compliance control is discussed. In [24] and [28], compliance control is applied to excavators. In [29], it has been suggested to use the dump cylinder pressure as an input for admittance control for automatic loading of fragmented rock. A paper from mobile robotics that combines the ideas behind admittance and impedance control is [30]. Compliance control is also applied to wheel loaders in [31] and [32].

- Feed-forward control : Some researchers argue that the un-modeled dynamics of the pile (G_p in Fig. 3.1) can be modeled as an disturbance to the process. In [3], a disturbance observer for the resisting forces is proposed and an iterative learning algorithm has been used to model the repetitive part of the resisting forces. Also in [33], G_p is assumed as a disturbance and it is suggested that a robust controller could be sufficient to counteract the resisting forces.

- Artificial intelligence control : Modeling the tool-media interaction is impossible [34] and the traditional control techniques can be impractical or in-feasible especially for rock excavation [35]. This is often the motivation behind turning towards artificial intelligent techniques like neural-network and fuzzy logic. In [34] and [35], an small scale experiment with close resemblance to an excavation process is performed by breaking the tasks into behaviors and actuator actions. This work uses fuzzy logic and is continued in [36]. Other works that use rule based methods for robotic excavation are [12] and [37]. These data driven methods rely on the experiment rather than theory. A common idea behind these artificial intelligence based methods is to code the intelligence of an expert operator into a computer program.

(c) Full scale experiments : With the aim to develop an automatic loading function, most research works start by studying the actions of an expert operator during loading. Full scale experiments with instrumented wheel loaders and excavators are performed to interpret the operator's philosophy of loading. Researchers use these results to give direction to their research work. In [1] and [14], experiments with wheel loader are performed to load sand, gravel and fragmented rock by 80 different operators ranging from novice drivers to skilled operators. The aim of this experiment was to establish the ground for an automatic loading function. In [29], full scale experiments are performed with wheel loader on fragmented rock. In [38], an attempt is made to extract the skills required to use an excavator for excavating soil.

(d) Machine vision : An area of research in robotic excavation is to use machine vision to aid full autonomous and remote operation. In [39], stereo vision is used to identify the best location to load on the pile of material to be moved. In [40], a laser based task planner is developed for an excavator. This system has been capable to excavate ground as fast as a human operator. A similar method for determining the attack pose for wheel loaders is discussed in [41]. Apart from the attack pose, it is possible to use laser data to identify large boulders in the pile [42] and use stereo vision to estimate the fill factor of soil in the bucket [43].

(e) Communication : A good communication system is a must for the remote operation. It is also very important for the fully autonomous system to have a reliable communication system to monitor the safety of the operation. Although communication is critical for the remote operation, it is far less discussed in literature. A valuable discussion of communication solutions for underground mines is presented in [44]. The requirements of the remote control solution from the communication system are low latency, minimal loss and high throughput. In [33], a Simulink-Opnet simulation is shown to test a proposed communication system for a remote control solution. When it comes to software implementation of communication system, the two conventional transport layer protocols, UDP and TCP have some disadvantages for the real time communication required by the mobile earth-moving machines. For example, TCP may introduce undesired delays due to its mandatory in-order delivery feature since it buffers data awaiting successful re-transmission of lost packets [45]. UDP on the other hand does not implement congestion avoidance and control, and may hence overload wireless networks resulting in high loss rates and extensive delays as packets are buffered in the network.

(f) Localization and navigation : Localization and navigation are relatively more discussed topics especially in the field of mobile robotics. From this heritage, the navigation techniques for mobile earth-moving machines are already quite advanced. Many mine companies use automatic hauling in their mines [46]. Laser based techniques are dominant in localization and navigation in underground mines. Some good references who use laser scanners in their work are [5] and [8]. In the scope of short load cycle, a relative localization technique between the dumper truck and the wheel loader is also a viable solution. The main challenge during navigation in a short loading cycle is to avoid collisions with the walls, boulders and other vehicles. Recent advancements in the ultra-wide-bandwidth technologies [47] can also be exploited for the relative navigation between the wheel loader and the dumper truck.

(g) Path planning : In the short loading cycle with the regular bucket, the wheel loader moves on a slightly varying V-Y curve as shown in Fig. 1.2. The aim of path planning is to generate this V-Y curve given the starting pose of the machine, the pose of the dumper truck and other constraints (walls and obstacles). Different objectives for optimizing this V-Y curve as pointed out in [48] are fuel efficiency, travel distance, travel time and more. Another recent publication concerning path planning for short loading cycle is [49]. An important but often ignored fact is that the wheel loader's starting position in the short load cycle will be at a higher and uneven terrain with respect to the dumper truck . For this reason, a 3D relative localization should be used instead of a 2D methods.

(h) Powertrain and traction control : Although the research on powertrain is done during the design of new vehicles at automotive companies, the problem of wheel slip during loading heavy and dense media raises enough questions to open the scope of research in this area. Efficient transmissions aim to minimize the fuel consumption and wear and tear of tires. In [10], improvements in traction control of LHD machines are proposed. In [50], advanced control theory has been applied on the wheel loader transmission to improve fuel efficiency.

(i) Human machine interface (HMI) : Since the remote control demands real time interaction with the operator, the HMI should provide the feedback in the most effective way. An advanced HMI is proposed for excavators in [51] where a complete virtual environment of the excavation task has been visioned with heads-up-displays. A virtual reality may be suitable for minimally moving excavator but it is not so easy to apply for the short load cycle due to the mobility of the machine. Stereo vision displays have been proposed in [52] for presenting an augmented reality of industrial robots. In [53], hepatic feedback joysticks are proposed for excavators. Many of these techniques can be used to present the feedback to the remote-operator of the wheel loaders but they should only be included if they improve the operator's experience significantly.

(j) Task planning : Some researchers attempt the automation of the mobile earth-moving machines from the highest level and they aim at breakdown of the main objective into smaller tasks much like how an human operator will see the work. A task planner for an excavator using state chart flow diagrams has been developed in [54] and [55]. Task planning can be seen as a last piece in the puzzle of a fully autonomous operation. Another task planning algorithm for excavators working in a wide open area is proposed in [56].

(k) Computer simulation of environment : Detailed computer simulations are used to design the control system and to develop operator training simulators. Unfortunately, for wheel loaders and excavators, the environment is unpredictable and the forces exerted by the media (soil, sand, gravel, rock etc) are random and unpredictable. Nevertheless efforts to simulate the environment can be seen in some literature. In [26], a pile of consistent gravel is simulated to study different bucket trajectories for wheel loaders and in [57], a simulation of soil is developed to test automatic loading functions for excavators.

(l) Survey papers : There is a lot of evident interest in automation of mobile earth-moving machines which has generated quite a handful of survey papers. The two papers, [2] and [22], provides excellent background and knowledge for the automation of the loading step. A survey work specially targeting automatic loading of fragmented rock is [58]. An overview of navigation technologies for LHD machines is presented in [13]. Some more survey papers for automation of excavators are [4] and [59]. Some recent ongoing work towards automation of wheel loaders are presented in [60] and [61].

In this chapter we have reviewed some possible areas of research in the field of automation of mobile earth-moving machines. Some key and some recent publications for each research area has also been mentioned. It would be difficult to claim that this survey covers all possible research areas but it definitely provides a good start to the research project WROOMM which focuses on the short loading cycle operation of a wheel loader to move fragmented rock.

Chapter 4

Identified Knowledge Gaps and Research Questions

Despite the long going research in automation of earth moving machinery, there are some under explored areas. In this chapter, such knowledge gaps are discussed by bringing up important research questions that makes the base of this research project.

4.1 Knowledge gaps

The research areas such as navigation, dynamic modeling and optimal trajectory of bucket have received a lot of attention which has helped the research in these areas to move far forward. On the other hand, some area lack attention or are relatively new. Such research areas which represent the knowledge gap have been discussed below:

Fragmented rock

In [58], the need for specific research in loading of fragmented rock has been summoned highlighting the fact that bucket-rock interactions are much more complex than bucket-soil interactions.

While developing automatic loading functions for fragmented rock, it might be necessary to adapt the loading algorithm for different grades of blasted rock. In [62], a method to estimate the fragment size distribution after blasting has been discussed. Many papers develop methods for automatic loading of rock but very few actually do the experiments on fragmented rock. More experimental research is required when it comes to loading of fragmented rock also because the system can not be modeled easily.

Communication for remote operation

The latency in audio and video are important issues for remote-operation. Humans can tolerate audio delays upto 400ms [45] but beyond that it can hamper the control. The jitters in the real time video can cause many frames to be dropped resulting in a sluggish video. Although one argument says that these problems can be mitigated just by upgrading to higher bandwidth, a good throughput can never be guaranteed over wireless network due to signal degradation, multi-path propagation and interference. Therefore, it is important to use the network bandwidth efficiently by choosing the most efficient protocol for remote-operation. As discussed in the last chapter, security is also very important when implementing a communication solution.

Operator experience during remote operation

Operation experience makes a big difference in remote control performance. In manual operation, operators use their vision, hearing and balance detecting capacities to judge and make decisions in real time. It is possible to create a virtual reality for the remote-operator with motion simulator and head-mount display with surround sound. However, doing so dilutes the main reason of removing the operator from harsh environments. Also, any form of feedback to the remote-operator will be slightly delayed which should be minimized as far as possible. Force feedback enabled joysticks and pedal can be of interest for improving the operator's experience especially during loading.

Integration of operator assistance functions

Assisted remote control operation can use many operation assistance functions. Some of these functions mentioned in this report are specific to the short loading cycle operation such as prepare the boom for dumping and aligning the wheel loader with the dumper. How these functions interact with each other and with the remote operator is a question to be answered. Finally, several operator assistance functions are needed to be integrated making sure that they don't overlap and cancel out each other.

Hybrid and electric working machines

There is a trend in the automotive industry to move from diesel engine powered machines to hybrid and electric machines. This change requires a parallel effort from the academia to shift their ground of research. Models for mobile earth-moving machines are needed for the newer machines. With electric engines, it might also be possible to control each wheel separately, which can provide additional support to counter act on wheel slip.

4.2 Research questions

The research questions are a tool to give direction to the research work. From the survey and offline discussions, six research questions have been identified to start the course of this project work for improving remote control of short loading cycle for moving fragmented rock in a underground mining environment.

1. What is the best indicator of the short loading cycle performance index (sec 2.2) for one bucket loading of fragmented rock?

2. Which communication protocol is best to support safe and efficient remote control operation and monitoring?

3. What is the best selection of sensor inputs to assist remote operator of a mobile earth-moving machine to compensate for the absence of direct involvement of their human sensory receptors?

4. Should the automatic loading function for fragmented rock be based on artificial intelligent methods or can it be based on compliance control?

5. What should be the boundaries between remote operation and on-board operation assistance functions?

6. How to effectively use the power of individual-wheel drive to avoid wheel slip during loading of fragmented rock?

Chapter 5

Conclusions

There is an increasing interest in automation of mobile working machines. Automation of wheel loader operation has its own challenges because of high level of interaction with its environment during loading.

The first two chapters in this report defines the background of the problem and the next two chapters presents the literature survey with the identification of knowledge gaps for the remote operation of the targeted unit operation. Automation of mobile earth-moving machines involves many different research areas. Although the project aims to experiment with wheel loaders in short loading cycle moving fragmented rock, the results of such a study may potentially benefit the entire automation industry.

Fully autonomous systems which perform better than humans are still far fetched and the current requirement of the industry is to upscale productivity but still keeping the operators out from the hazardous working environments. Adding operator assistance functions to an established remote operation seems a good starting point to meet the current industrial needs.

The different areas of research related to automation of mobile working machines have been identified. Majority of the research papers listed in this report have done experiments with excavators which makes the automation of excavators far ahead of wheel loaders. However, excavators unlike wheel loaders are less mobile during operation which make this project work more challenging.

There is a split between researchers about which approach is more suitable for automatic loading. Two main strategies tried by researchers are the artificial intelligence based control (fuzzy logic) and the compliance control. But very few papers have reported results on fragmented rock which looks like a mountain not yet climbed. The experiments with fragmented rock which are planned during this project work aims to study the bucket-rock interactions in order to develop an operation assistance function for automated loading.

This report has identified few knowledge gaps which will be addressed during the course of this project. The communication solution for remote control is one of the critical area because the efficiency of the wireless communication system directly effects the productivity of remote-operation via the operator

Sensing	1. Instrument the wheel loader with speedometer 2. Read and log tilt, boom and articulation angles and, cylinder pressures in the two links
Manual experiment	1. Import fragmented rock at the experiment site 2. Perform loading experiment with expert operator 3. Log and analyze the data for developing automatic control algorithm
Evaluation of transport protocols	1. Setup a test environment for candidate transport protocols such as SCTP, DCCP and QUIC 2. Design and conduct experiments to evaluate features for mobility and multi-stream congestion control and avoidance
Multimedia solution	1. Evaluate and implement possible video and audio solutions 2. Design an experiment to measure the operator's experience
Automatic Loading	1. Develop an automatic control function for loading of fragmented rock 2. Perform experiments and compare with manual operation

Table 5.1: Goals and tasks for future work of the project

experience. Other identified knowledge gaps such as integration of operator assistance functions and the research on hybrid and electric machines could also be a part of future work.

Figure 5.1: Oryx Simulator for Volvo L110G

Future work

Luleå Technical University have a 20-22 tonne wheel loader provided by Volvo CE and a remote control station for the wheel loader has been provided by Oryx Simulations. The Oryx remote control station is shown in Fig. 5.1.

A remote control solution for the wheel loader is under development following the thesis work of [63] and [64]. The remote control station can so far control all main vehicle signals including boom, bucket, steering, brake and acceleration. The video and audio feedback is the next step in finishing a basic remote control setup. Thereafter, the plan is to explore the knowledge gaps by conducting a series of experiments with manual and remote control operation. The planned course of actions to perform the proposed research for the project is shown in Table 5.1.

Bibliography

[1] Bobbie Frank, Lennart Skogh, Reno Filla, Anders Fröberg, and Mats Alaküla. On Increasing Fuel Efficiency By Operator Assistant Systems in a Wheel Loader. In *International Conference on Advanced Vehicle Technologies and Integration*, 2012.

[2] Ahmad Hemami and Ferri Hassani. An overview of autonomous loading of bulk material. *26th International Symposium on Automation and Robotics in Construction and Mining*, pages 405–411, 2009.

[3] Guilherme Jorge Maeda. *Learning and Reacting with Inaccurate Prediction: Applications to Autonomous Excavation.* PhD thesis, The University of Sydney, 2013.

[4] Vivek Chacko, Hongnian Yu, Shuang Cang, Luige Vladareanu, United Kingdom, United Kingdom, and Romanian Academy. State of the Art in Excavators. In *Advanced Mechatronic Systems*, pages 481–488, 2014.

[5] Jonathan M. Roberts, Elliot S. Duff, and Peter I. Corke. Reactive navigation and opportunistic localization for autonomous underground mining vehicles. *Information Sciences*, 145:127–146, 2002.

[6] Reno Filla. *Quantifying Operability of Working Machines.* PhD thesis, Linköping University, 2011.

[7] Anna Gustafson. Dependability Assurance for Automatic Load Haul Dump Machines. Technical report, LuleåUniversity of Technology, 2011.

[8] Johan Larsson, Mathias Broxvall, and Alessandro Saffiotti. An evaluation of local autonomy applied to teleoperated vehicles in underground mines. *Proceedings - IEEE International Conference on Robotics and Automation*, pages 1745–1752, 2010.

[9] Johan Larsson. *Unmanned Operation of Load-Haul-Dump Vehicles in Mining Environments.* PhD thesis, Örebro University, 2011.

[10] Ulf Andersson. *Automation and Traction Control of Articulated Vehicles.* PhD thesis, LuleåUniversity of Technology, 2013.

[11] A. Hemami. Fundamental Analysis of Automatic Excavation. *Journal of Aerospace Engineering*, 8(4):175–179, 1995.

[12] Paul Lever. An automated digging control for a wheel loader. *Robotica*, 19(September 2001):497–511, 2001.

[13] B. J. Dragt, F. R. Camisani-Calzolari, and I. K. Craig. An overview of the automation of Load-Haul-Dump vehicles in an underground mining environment. *IFAC Proceedings*, 16:37–48, 2005.

[14] Bobbie Frank, Lennart Skogh, and Mats Alaküla. On wheel loader fuel efficiency difference due to operator behaviour distribution. *Commercial Vehicle Technology Symposium*, 2012.

[15] H Almqvist. Automatic bucket fill. Technical report, Linköping University, 2009.

[16] Symantec Corporation. Internet Security Threat Report. Technical Report April, 2014.

[17] Ernst & Young. Under cyber attack - Global Information Security Survey 2013. Technical Report October, 2013.

[18] Satish L. Kale, Richard G. Ingram, and Kevin J. Sergott. System for automated excavation control based on productivity, 2011.

[19] Vaheed Nezhadali and Lars Eriksson. Optimal control of wheel loader operation in the short loading cycle using two braking alternatives. *Vehicle Power and Propulsion Conference (VPPC)*, pages 447–452, 2013.

[20] P. K. Vaha and M. J. Skibniewski. Dynamic Model of Excavator. *Journal of Aerospace Engineering*, 6(2):148–158, 1993.

[21] Y H Zweiri, L D Seneviratne, and K Althoefer. Modelling and control of an unmanned excavator vehicle. *Proceedings of the I MECH E Part I Journal of Systems & Control Engineering*, 217:259–274, 2003.

[22] Sanjiv Singh. State of the Art in Automation of Earthmoving. *Journal of Aerospace Engineering*, 10:179–188, 1997.

[23] O. Luengo, S. Singh, and H. Cannon. Modeling and identification of soil-tool interaction in automated excavation. *International Conference on Intelligent Robots and Systems*, 3:1900–1906, 1998.

[24] W. Richardson-Little and C.J. Damaren. Position accommodation and compliance control for robotic excavation. *IEEE Conference on Control Applications*, pages 1194–1199, 2005.

[25] P. A. Mikhirev. Theory of the working cycle of automated rock-loading machines of periodic action. *Soviet Mining Science*, 19(6):515–522, 1983.

[26] Reno Filla, Martin Obermayr, and Bobbie Frank. A study to compare trajectory generation algorithms for automatic bucket filling in wheel loaders. *3rd Commercial Vehicle Technology Symposium*, 2014.

[27] Hong Zhang and R P Paul. Hybrid control of robot manipulators. Technical report, Hewlett Packard, 1985.

[28] P K Väha and M J Skibniewski. Cognitive Force Control of Excavators. *Journal of Aerospace Engineering*, 6(2):159–166, 1993.

[29] Joshua A. Marshall, Patrick F. Murphy, and Laeeque K. Daneshmend. Toward autonomous excavation of fragmented rock: Full-scale experiments. *IEEE Transactions on Automation Science and Engineering*, 5(3):562–566, July 2008.

[30] Christian Ott, Ranjan Mukherjee, and Yoshihiko Nakamura. Unified impedance and admittance control. *Proceedings - IEEE International Conference on Robotics and Automation*, pages 554–561, 2010.

[31] S. Sarata, H. Osumi, Y. Kawai, and F. Tomita. Trajectory arrangement based on resistance force and shape of pile at scooping motion. *IEEE International Conference on Robotics and Automation*, 4:3488–3493, 2004.

[32] Megan Clark, Chad Magstadt, Gregory Mettlach, Robert J. Price, and Bassam J. Alshaer. Velocity based control process for a machine digging cycle, 2011.

[33] Yang Liu, Mohammad Shahidul Hasan, and Hong Nian Yu. Modelling and Remote Control of an Excavator. *International Journal of Automation and Computing*, 7:349–358, 2010.

[34] Shi Xiaobo, Paul Lever, and Wang Fei-Yue. Fuzzy Behavior Integration and Action Fusion for Robotic Excavation. *IEEE Transactions on Industrial Electronics*, 43(3):395–402, 1996.

[35] Xiaobo Shi, Paul Lever, and Wang Fei-Yue. Experimental Robotic Excavation with Fuzzy Logic and Neural Network. In *International Conference on Robotics and Automation*, pages 957–962, 1996.

[36] Fei Yue Wang. Agent-based control for fuzzy behavior programming in robotic excavation. *IEEE Transactions on Fuzzy Systems*, 12(4):540–548, 2004.

[37] Long Wu. *A study on automatic control of wheel loaders in rock/soil loading*. PhD thesis, University of Arizona, 2003.

[38] Yuki Sakaida, Daisuke Chugo, Hiroshi Yamamoto, and Hajime Asama. The analysis of excavator operation by skillful operator - Extraction of common skills. *Proceedings of the SICE Annual Conference*, pages 538–542, 2008.

[39] Shigeru Sarata, Yossewee Weeramhaeng, and Takashi Tsubouchi. Approach path generation to scooping position for wheel loader. *Proceedings - IEEE International Conference on Robotics and Automation*, (April):1809–1814, 2005.

[40] Anthony Stentz, John Bares, Sanjiv Singh, and Patrick Rowe. Robotic excavator for autonomous truck loading. *Autonomous Robots*, 7:175–186, 1999.

[41] Martin Magnusson and Hakan Almqvist. Consistent pile-shape quantification for autonomous wheel loaders. *IEEE International Conference on Intelligent Robots and Systems*, pages 4078–4083, 2011.

[42] C McKinnon and J. A. Marshall. Automatic Identification of Large Fragments in a Pile of Broken Rock Using a Time-of-Flight Camera. *IEEE Transactions on Automation Science and Engineering*, 11(3):935–942, 2014.

[43] Hamza Anwar, Syed Muhammad Abbas, Abubakr Muhammad, and Karsten Berns. Volumetric Estimation of Contained Soil using 3D Sensors. In *Commercial Vehicle Technology Symposium*, pages 11–13, 2014.

[44] Arghavan Emami Forooshani, Shahzad Bashir, David G. Michelson, and Sima Noghanian. A survey of wireless communications and propagation modeling in underground mines. *IEEE Communications Surveys and Tutorials*, 15(4):1524–1545, 2013.

[45] James F. Kurose and Keith W. Ross. *Computer Networking: A Top-Down Approach*. 6 edition, 2013.

[46] Karen Mcnab and Magaly Garcia-vasquez. Autonomous and remote operation technologies in Australian mining Centre for Social Responsibility in Mining. Technical Report 2, Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland. Brisbane, 2011.

[47] Jeroen D. Hol, Fred Dijkstra, Henk Luinge, and Thomas B. Schöny. Tightly coupled UWB/IMU pose estimation. *IEEE International Conference on Ultra-Wideband*, pages 688–692, 2009.

[48] Reno Filla. Optimizing the trajectory of a wheel loader working in short loading cycles. *The 13th Scandinavian International Conference on Fluid Power*, pages 307–317, 2013.

[49] B. J. Alshaer, T. T. Darabseh, and M. A. Alhanouti. Path planning, modeling and simulation of an autonomous articulated heavy construction machine performing a loading cycle. *Applied Mathematical Modelling*, 37(7):5315–5325, 2013.

[50] Tomas Nilsson. *Optimal Predictive Control of Wheel Loader Transmissions*. PhD thesis, Linköpings University, 2015.

[51] Tao Ni, Hongyan Zhang, Changzhi Yu, Dingxuan Zhao, and Songyue Liu. Design of highly realistic virtual environment for excavator simulator. *Computers and Electrical Engineering*, 39(7):2112–2123, 2013.

[52] Markus Sauer, Florian Leutert, and Klaus Schilling. An augmented reality supported control system for remote operation and monitoring of an industrial work cell. In *2nd IFAC Symposium on Telematics Applications*, pages 83–88, 2010.

[53] K W Oh, D Kim, N H Kim, and D Hong. The Virtual Environment For Force-Feedback Experiment Of Excavator Using A Novel Designed Haptic Device. *Proceedings of the 28th ISARC*, pages 51–56, 2011.

[54] Quang Ha, Miguel Santos, Quang Nguyen, David Rye, and Hugh Durrant-Whyte. Robotic excavation in construction automation. *IEEE Robotics and Automation Magazine*, 9:20–28, 2002.

[55] Q. P. Ha and D. C. Rye. A control architecture for robotic excavation in construction. *Computer-Aided Civil and Infrastructure Engineering*, 19(2004):28–41, 2004.

[56] Jongwon Seo, Seungsoo Lee, Jeonghwan Kim, and Sung Keun Kim. Task planner design for an automated excavation system. *Automation in Construction*, 20(7):954–966, 2011.

[57] Daniel Schmidt. Soil Simulation and Behaviour-Based Control for Landscaping Tasks of an Autonomous Bucket Excavator. *IEEE International Conference on Robotics and Automation*, pages 5108–5113, 2010.

[58] J. A. Marshall and L.K. Daneshmend. Automated loading of fragmented rock in mining: A literature and technology survey. Technical report, Queen's University at Kingston, 2001.

[59] Hongnian Yu, Yang Liu, and Mohammad Shahidul Hasan. Review of modelling and remote control for excavators. *International Journal of Advanced Mechatronic Systems*, 2:68, 2010.

[60] N. Koyachi and S. Sarata. Unmanned loading operation by autonomous wheel loader. *ICCAS-SICE*, pages 2221–2225, 2009.

[61] Adrian Bonchis, Nicholas Hillier, Julian Ryde, Elliot Duff, and Cédric Pradalier. Experiments in autonomous earth moving. *18th IFAC World Congress*, 18, 2011.

[62] Sang Ho Cho, Masaaki Nishi, Masaaki Yamamoto, and Katsuhiko Kaneko. Fragment Size Distribution in Blasting. *Materials Transactions*, 44(5):951–956, 2003.

[63] Fredrik Häggström. Electronic Breakout Unit. Technical report, Lulea Technical University, 2012.

[64] Robin Bond and Theren Hakan. Transport layer protocols for remote control and monitoring of moving objects. Technical report, LuleåTechnical University, 2014.