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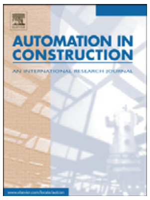

Key challenges in automation of earth-moving machines☆

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ABSTRACT

A wheel loader is an earth-moving machine used in construction sites, gravel pits and mining to move blasted rock, soil and gravel. In the presence of a nearby dump truck, the wheel loader is said to be operating in a short loading cycle. This paper concerns the moving of material (soil, gravel and fragmented rock) by a wheel loader in a short loading cycle with more emphasis on the loading step. Due to the complexity of bucket-environment interactions, even three decades of research efforts towards automation of the bucket loading operation have not yet resulted in any fully autonomous system. This paper highlights the key challenges in automation and tele-remote operation of earth-moving machines and provides a survey of different areas of research within the scope of the earth-moving operation. The survey of publications presented in this paper is conducted with an aim to highlight the previous and ongoing research work in this field with an effort to strike a balance between recent and older publications. Another goal of the survey is to identify the research areas in which knowledge essential to automate the earth moving process is lagging behind. The paper concludes by identifying the knowledge gaps to give direction to future research in this field.

1. Introduction

Earth-moving machines comprise a large set of industrial machines used in construction, mining, forestry, agriculture, cleaning and many other industries. Such machines generally include a vehicle (i.e., a main body) and a robotic mechanism mounted on the vehicle. Many types of earth-moving machines are available with different combinations of vehicle and robotic mechanisms. The robotic mechanism typically consists of a robotic arm (a combination of links and joints) powered by a hydraulic system and a tool designed for tasks such as loading or excavation of materials. It is often possible to change the tool to adapt to different tasks. Wheel loaders and excavators are two common examples of mobile earth-moving machines.

Wheel loaders are extremely versatile and often used as multi-purpose machines at production sites [1]. Applications for which wheel loaders are used everyday include the transportation of soil, ore, snow, wood-chips and construction material. Wheel loaders have extensive use in the mining industry, where they are used to transport ore in both open-pit mines and underground mines. In underground mines, special types of wheel loaders are used: LHD (Load-Haul-Dump) machines. Fundamentally, LHD machines are the same as wheel loaders except that they are adapted for the low ceilings of underground mines.

Automation of wheel loaders and excavators has been an active area of research over the past three decades [2]. As claimed by Maeda [3], despite much research in this field, a fully automated system for a mobile earth-moving machine has never been demonstrated. In Hemami and Hassani [2], the authors conclude that the subject demands more research, together with industrial support, to speed up the process towards successful autonomous loading of bulk material.

In this paper, the focus is on automation and remote control of earth-moving machines such as wheel loaders and LHD machines. The main contributions of the paper are the review and assessment of different approaches for automating the steps involved in short cycle loading and the survey of publications on automation of earth-moving machines. We also provide an in-depth review of different automatic bucket loading strategies and discussion on possible approaches (Section 4.2). In the paper, we highlight important knowledge gaps in the areas of automatic loading of fragmented bulk material, wireless communications, and operator experience and performance in tele-remote operation.

We find that automating the complete short loading cycle is not viable in the short to mid-term. Given the identified challenges in full automation of the earth-moving process, we consider semi-automation through assisted tele-remote operation to be an important step to collect experience for further research and development. Reliable wireless communication becomes essential when machines are tele-remotely

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☆ This review article is a result of an ongoing research project at Luleå University of Technology which aims at developing remote control solution for earth-moving machines.

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operated. This paper also gives a brief overview of communication-related challenges and possible solutions.

The difficulty in automating the entire 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 are central to the problem. Examples of different media are snow, soil, gravel, wood chips, fragmented rock, mud, etc. Autonomous excavation of soil is a well-studied problem, and yet fully automated excavators are rare [4].

Because full automation of the earth-moving process is difficult, researchers commonly aim for small steps in moving towards automation. In Roberts et al. [5], a five-step approach is suggested, from fully manual operation at step one to fully autonomous operation at step five. In Frank et al. [1], another nomenclature for these steps is proposed. Our review and assessment of different automation approaches relate to these steps from manual towards fully autonomous operation, as well as the procedural steps in the short cycle loading process. We define a versatile set of requirements on the semi-automated and fully autonomous short loading cycle, among which some relate to the complete process, while others apply to one or more of these procedural steps.

The survey of publications on the automation of earth-moving machines presented here is categorized into different areas: modeling for control, automatic loading, pile characterization, localization and navigation, and path planning. Our most important contributions are the survey of automatic bucket loading strategies and the assessment of the viability of different approaches. We provide arguments in support of reinforcement learning methods as a possible solution for the automatic bucket-loading problem.

The reminder of the paper has been organized as follows. Section 2 assesses the problem of automating earth-moving machines. It presents the automation steps and the procedural steps involved in the short loading cycle. This section also defines operator assistance functions and presents a previously reported case study on tele-remote operation and assisted loading. In Section 3, the fundamental requirements for autonomous and tele-remote earth-moving operation are discussed from the standpoint of safety and efficiency. Section 4 addresses the machine side of the problem, discussing the different aspects of autonomous operation that can be realized via operator assistance functions. In Section 5, communication requirements in tele-remote operation are discussed. Section 6 addresses the operator station for a remotely operated earth-moving machine. Section 7 presents various research areas and publications that could not be categorized in Sections 4, 5 or 6. Section 8 presents identified knowledge gaps and Section 9 summarizes and concludes the paper.

2. Problem assessment and breakdown

The challenges in automating earth-moving machines are multifaceted, motivating us to separately address the different parts of the problem. For breakdown and assessment of this problem, we need to envision the possible steps from fully manual to completely autonomous operation and understand the procedural steps that are performed in the short cycle loading process. Because the intermediate steps towards full automation most likely involve tele-remote operation, we also need to understand possible ways to assist a remote operator. After providing these tools to better understand and assess the problem, we present a case study on tele-remote and assisted loading from an iron-ore mine in Kiruna, Sweden. This case study illustrates how an intermediate step towards fully autonomous loading can be implemented and how operator assistance functions can improve the performance in terms of average bucket weights.

2.1. Steps towards full automation

A five step approach from manual operation at step one to fully autonomous operation at step five is discussed in Frank et al. [1] and Roberts et al. [5]. These five steps to full automation tailored for short cycle loading operation 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 data communicated over the network. The 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, 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 far away from the loading site but still performing all the tasks with the help of a remote and audio-video feedback from the machine (Fig. 1).
- Assisted tele-remote operation: The machine performs many tasks by itself via the use of operator assistance functions (Section 2.3). The operator intervenes in the tasks where human supervision is of importance.
- Fully autonomous: The machine performs all tasks by itself. The operator is only present to give high-level commands, take care of emergencies and handle failures.

2.2. Short loading cycle

Most commonly, the mobile earth-moving machines perform the following three tasks during one cycle of operation. Because this cycle is repeated thousands of time in many applications, it is important to ensure that efficiency is respected in each step.

1. Loading
2. Navigating
3. Dumping

The mobile earth-moving machines transport material (soil, fragmented rock, gravel, etc.) from one place to another, where 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 load and carry cycle and the short loading cycle. In the load and carry 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 to the loading machine, which may be in the form of a dump truck or conveyor belt. The focus of this work is on the short loading cycle which, puts stricter constraints on the cycle time of operation of the earth-moving machine.

Most commonly, the mobile excavating machine performs a V–Y curve (as shown in Fig. 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 s [6], and the challenge for the assisted remote-control operation is to perform at-least equal to an expert driver in manual operation.

Intensive research efforts are needed to close the gap from remote-control operation to assisted remote-control operation. In relation with Fig. 2, different procedural steps for implementing assisted remote-control for a short loading cycle operation have been identified in Table 1. The control algorithm for loading the material is the most important and the most discussed step, but it still remains an open area of research [3]. A general control strategy for loading does not work because the properties of the material (density, hardness, moisture and composition) being loaded varies significantly.

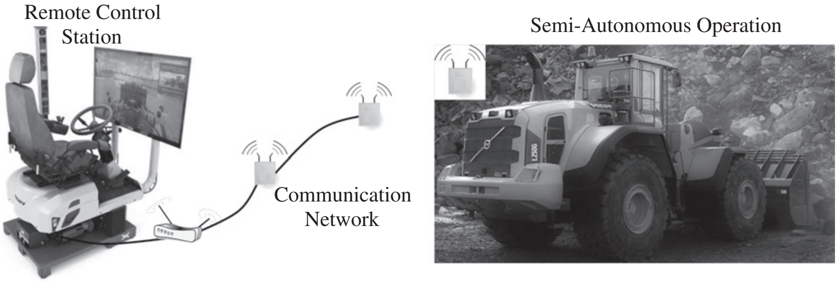

Fig. 1. Components of tele-remote operation of earth-moving machine.

2.3. Operator assistance functions

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

- Path planning
- Collision detection, avoidance and navigation
- Preparing the boom and bucket for loading and dumping
- Loading algorithm
- Dumping algorithm.

A combination of manual operation with operator assistance functions for path planning and navigation is described by Gustafson [7] as semi-automation. In Larsson et al. [8] and Larsson [9], a semi-autonomous operation is developed by implementing collision detection and avoidance, and navigation functions 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 that finds the right balance between remote control and automation.

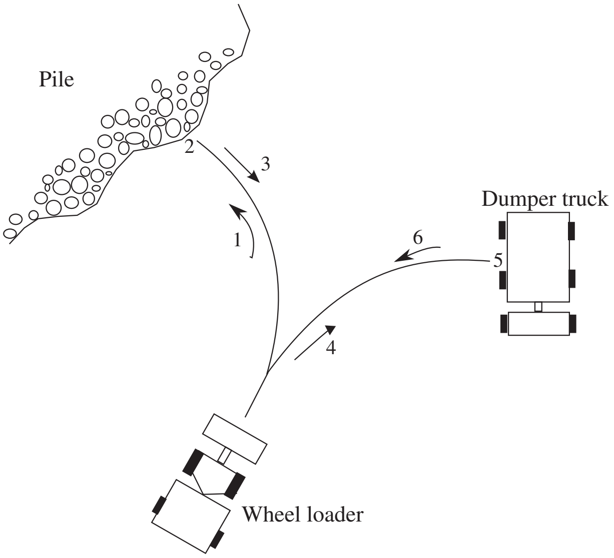

Fig. 2. Short loading cycle. The steps performed by a wheel loader in one operation cycle are as follows: 1: Approach to the pile, 2: Loading, 3: Retract from the pile 4: Approach the dumper, 5: Dumping, 6: Retract from the dumper.

2.4. Case study on tele-operation and assisted loading

During a 10-year period from 1999 to 2009 in the underground mine at Kiruna, Sweden, the iron ore was partly transported by semi-automatic tele-remote controlled LHDs [10]. It was discovered quite early that the average bucket weights of remotely operated LHDs were lower when compared to manual LHDs. To address the problem, an operating assistance function was introduced to the tele-remote LHDs that automatically controlled the robotic mechanism (the boom and the bucket) during the scooping. Tests with two machines indicated that the average bucket weight increased by nearly 5% when using the assistance function (semi-automated LHDs) compared to pure tele-remote controlled scooping [10]. The remote operators were able to use the operator assistance function at their own decision so there is no knowledge of how frequently the function was invoked. Table 2 summarizes one full year of production with five semi-automatic LHDs and eight manually operated LHDs.

As is clear from Table 2, the productivity of the semi-automatic LHDs was still far less than that of the manual LHDs when considering the average bucket weights. It should be noted, however, that the material transported was blasted rock, and in the case of a failed blasting, the blast contained a large number of boulders, which would mean that the volume of the load in the bucket contained more air than when the blasting produced well-fragmented rock. The figures in Table 2 should therefore be interpreted as indicators rather than absolute facts.

In underground mining, there are both pros and cons with semi-/automated machines. An advantage with semi-automated LHDs is that they can operate directly after a blast whereas manual LHDs need to wait several hours before gases and dust produced from the blast are ventilated. However, a drawback with semi-/automated LHDs is the need of isolating the area in which they operate, due to safety regulations, which heavily constraints other activities in those areas. The

Table 1
Steps in assisted remote-control operation for a short loading cycle.

Steps	Strategy
Approach to the 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 the 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 reversal point. 2. Reverse in a safe way, avoiding any obstacles. 3. Lower the boom and bucket for the next cycle.

Table 2
Comparison of manual operation and tele-remote operation in terms of loaded bucket weight averaged over one year (Data from LKAB Mine, Kiruna) [10].

	Average bucket weight (ton)
Manual LHDs	26.7
Semi-automatic LHDs	23.3

pros and cons pose an optimization requirement for the most efficient use of semi-/automated machines alongside manual machines.

3. Requirements of operation

Earth-moving operation requires heavy construction machinery, which necessitates the safe and efficient use of such machinery. Because any construction operation cycle, including the short loading cycle, is repeated thousands of times, it is important to define stringent requirements for the operation. Two aspects in which these requirements can be classified are safe operation and performance.

3.1. Safe operation

Safety is a priority for companies in developed countries [4], but reducing the maintenance cost of operation is of interest to all companies around the globe who are using mobile earth-moving machines. Human safety comes before any other priority. Normally, this is performed by separating the zones of remote-operated (or automated) machines by the zones where humans could be freely working. Safety to the machine 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 major safety threats during operation and their mitigation.

3.1.1. Wheel slip

Wheel slip is an undesirable phenomenon that results in the loss of traction. It occurs when the torque applied to the wheels greatly exceeds the friction available from the surface. Reasonably, 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 the loading phase when the resistance force on the tool is very high, leading the operator to apply more and more throttle. This practice is common with novice drivers, and wheel slip becomes a larger risk with such drivers [11].

According to Andersson [10], wheel slip can greatly damage the tires, and it contributes to 20–25% of the machine's total maintenance cost. Therefore, wheel slip is highly undesirable and should never occur [12]. To avoid wheel slip conditions, traction control algorithms can be incorporated during the loading step in the operation cycle.

3.1.2. Collision detection and avoidance

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

In certain underground mines, there are ditches along the tunnels that are part of the water drainage system in the mine. The drivers regularly driving in these tunnels are trained to drive close to the wall opposite to the ditch [8]. Because all mobile earth-moving machines working in an underground mine will traverse the tunnels once in a while, an algorithm to avoid driving into the ditches must also be part of the remote-control system.

Much research on the topic of collision avoidance already exists in the field of mobile robotics, and it must be exploited when developing control systems for automated or tele-remote-operated mobile earth-moving machines. Most of the collision avoidance systems use laser range finders, as in Roberts et al. [5], Larsson et al. [8], Larsson [9] and Andersson [10]. Some researchers have also experimented with 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.

3.2. Performance

Performance is an important aspect for companies to be able to remain in business against their competitors. The performance of a short loading cycle or a load and carry operation can be captured in terms of productivity and fuel efficiency. As mentioned in Larsson et al. [8], the remote-controlled machines are often less productive than manually controlled machines. Therefore, to realize the vision of full automation of these earth-moving machines, it is necessary to dissect the operation cycle in pieces and study the possibility of improvement in performance for each piece. The performance of a short load cycle operation and that of other operations can be captured by measuring the fill factor, fuel efficiency and cycle time of the operation.

3.2.1. Fill factor

Fill factor or bucket fill factor is the amount of material loaded in the bucket in one scoop. The fill factor can be measured by a weighing scale system in the machine when lifting the bucket. A weighing scale system uses the pressure in the cylinders to calculate the loaded weight. Therefore, in the absence of a weighing system, the loaded weight can be computed by the measurements from the pressure sensors of the boom and bucket cylinders in a wheel loader, for instance. In Almqvist [12], one theory for developing an automatic scooping function is presented, wherein a zigzag motion strategy is proposed for the bucket. In this report, the conclusion is that it is very difficult to fill the bucket via an automatic function as good as a manual driver can, even with soil.

The lower productivity of remote operation is primarily due to the lesser fill factor compared to manual operation [10]. Keeping this information in mind, it is important to consider fill factor as a requirement while developing an automatic loading function for mobile earth-moving machines.

3.2.2. Fuel efficiency

The fuel efficiency of the machine directly affects the operational cost. In Frank et al. [1], arguments are presented to support an operator assistance function for increasing the fuel efficiency. They claim that fuel consumption roughly contributes 30–60% of the operations cost measured per unit of the loaded material. Moreover, pollutant emissions increase with decrease in operational efficiency [14]. Therefore, it is important to ensure that the fuel efficiency of an automated solution is at least close to the most fuel efficient drivers.

In some publications, productivity and fill factor are considered to be the same, and the use of full engine power to load the material is suggested, as in Kale et al. [15] for instance. The use of full power may not be a good solution, 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.

3.2.3. Operation cycle time

Operation cycle time is also important, as the short loading cycle is repeated over and over again. A small improvement in cycle time can result in many more extra loading cycles, resulting in improved productivity. The loading step in the short loading cycle has greater potential for improvement with regard to the cycle time than navigation and dumping. A shorter operation cycle time demands increased fuel consumption due to the higher acceleration and deceleration. Therefore, a trade-off is necessary between the cycle time and fuel efficiency. This particular trade-off problem has been considered in Nezhadali and Eriksson [16].

3.2.4. Unified performance indication

It can be useful to capture the two aspects of performance, i.e., productivity and fuel efficiency, in one figure and to access the performance at a lower time resolution for each individual operation cycle. This can serve as a tool to compare and critique different operator styles and also different automatic bucket loading algorithms. The productivity is defined as the ratio of the fill factor and operation cycle time and thus is measured in weight of loaded material per unit time. In Filla [6], it is argued that the operator's mental and physical workload should also be captured in the performance of the operation.

4. Towards autonomous operation

Although research towards automation of earth-moving machinery has long been active, in practice, only a handful of construction and mining companies use remote controlled or semi-autonomous machines. In this section, several challenging problems involved in the automation of heavy earth-moving machines are highlighted. In the next two sections after this section, the focus is moved to aspects related to remote control of earth-moving machines due to their significantly growing presence in industry.

The majority of the reviewed papers aimed towards automation of earth-moving machines can be categorized in one of the following areas.

4.1. Modeling for control

A machine model is required for developing automatic control functions for all three steps of a short loading cycle i.e., loading, navigation and dumping. An automatic control function for loading also requires a model for the bucket-media interaction. In Fig. 3, a block diagram depiction of this approach is presented in the form of a closed-loop control framework. There are some issues with this representation of the system. First, as highlighted in the diagram, the bucket-media interactions are too highly complex and stochastic to be accurately captured by any practical measurement system. Second, the model of the pile (G_p in Fig. 3) is also unknown and changing during each loading cycle. Modeling the machine (G_m in Fig. 3), alternatively, is an easy task comparatively.

4.1.1. Modeling the kinematics-dynamics of the machine

Modeling the machine boils down to representing the robotic mechanisms (links, joints and the tool), the hydraulics and the power train of the machine in terms of kinematic or dynamical equations. Several pieces of literature exist that present the model of excavators or wheel loaders. In Vaha and Skibniewski [17], a dynamic model of a back-hoe excavator has been developed. In Zweiri et al. [18], the kinematic and dynamic model of a tracked earth-moving machine is presented. The robotic mechanism of the machine in this paper is similar to that of a typical wheel loader. In Andersson [10], models are developed for an LHD machine to be used for autonomous navigation.

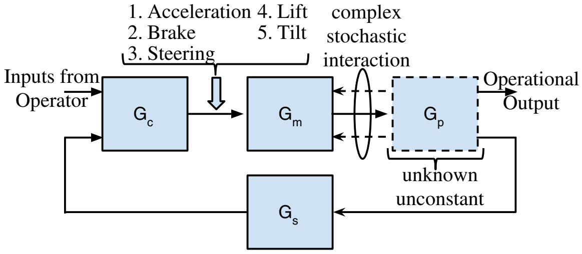

Fig. 3. Control block diagram of a loading process. G_i is the transfer function for i = c (controller), m (machine), p (process/pile) and s (sensors).

4.1.2. Modeling of bucket-media interactions

Many efforts, from as early as 1960's, have been conducted to create models that represent the bucket-media interactions. These 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 Singh [19] and Luengo et al. [20]. A good review of many investigations into determining bucket media interaction is presented in Hemami and Lipsett [21]. These models are often very complex and so computationally expensive that they remain unusable for real-time automatic control. However, in Richardson-Little and Damaren [22], an over-simplified model based on the 5-force bucket-soil interaction model is used in a closed-loop compliance control scheme. Despite a considerable amount of discussion on such models, a reliable bucket-media interaction model has not yet been achieved.

4.2. Automatic loading

Due to the complex nature of the bucket-media interaction, developing automatic loading functions that are better than or equal to expert manual drivers with regard to performance is a highly difficult task. One of the main questions 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 problem, only a few control philosophies can be implemented. In this subsection, the possible candidates for solving the automatic loading problem are discussed.

With the aim to develop an automatic loading function, most research works start by studying the actions of expert drivers during loading. Full-scale experiments with instrumented wheel loaders and excavators are performed to interpret the driver's philosophy of loading. Researchers use these results to give direction to their research work. In Frank et al. [1] and Frank et al. [11], experiments with a wheel loader are performed, with the loading of sand, gravel and fragmented rock by 80 different drivers ranging from novice to skilled. The aim of this experiment was to establish the basis for an automatic loading function. In Marshall et al. [23], full-scale experiments are performed with an LHD machine loading fragmented rock. Sakaida et al. [24] presents another study on the actions of drivers while excavating soil with an excavator.

4.2.1. Position (trajectory) control

One idea for loading the bucket is to follow a planned trajectory. This idea is based on the early work by Mikhirev [25] in which the aim is to maximize the volume between the trajectory cut and the profile of the pile. A limiting factor for this approach is that, with the available technology for pile characterization (laser scanners or vision-based systems), only the surface of the pile is illuminated, which is not enough information to define an optimal trajectory. Although the idea of trajectory control is comprehensible, it fails to capture the fact that following the desired trajectory may be impossible in a real-world situation of non-homogeneous media.

Many current researchers take trajectory planning as a starting point for their work, as in Almqvist [12] and Filla et al. [26]. Although a trajectory may be approximately followed for low-density sand or wood chips, it is impossible to follow a trajectory for high-density media, such as fragmented rock. This is because of the immense amount of resistive forces on the tool by the media, which drives the actuators into saturation and sometimes also results in wheel slip. In Marshall et al. [23] and Hemani [27], it is noted that, since the aim of the control system is to fill the bucket and not to follow a predefined path, trajectory control should not have priority.

4.2.2. Compliance control

It is not surprising that strict position (trajectory) control can only be realized in extremely low-density media and not while moving through a pile. To address this fact, several opinions have converged on the idea of modifying the trajectory of the tool on the fly in compliance with the resisting forces on the tool. This type of control philosophy named here as compliance control, is also found under several other names, such as two-level (force, position/velocity) control, force-feedback control, inner-outer loop control, admittance, impedance control and more. Compliance control is a fundamental area of research in robotics [28].

A clear and basic formulation of compliance control with an improvement in its formulation is presented in Zhang and Paul [29]. In Maeda [3], Richardson-Little and Damaren [22], and Väha and Skibniewski [30], compliance control is applied to excavators. In Marshall et al. [23], it has been suggested to use the bucket cylinder pressure as an input for admittance control for automatic loading of fragmented rock. Research in the mobile robotics field that combines the ideas behind admittance and impedance control is presented in Ott et al. [31]. A small-scale laboratory experiment designed around wheel loader operation to advocate a compliance control strategy to modify tool trajectory is presented in Sarata et al. [32]. Recent industrial interest towards automation of earth-moving machines can be seen in a patent based on velocity control of the digging work cycle of an excavator in Clark et al. [33].

4.2.3. Feed-forward control

In a feed-forward control scheme, the focus is on measuring the effect of disturbances to the system and pre-compensating their effect by modifying the controller actions. In the setting of an excavation process, the disturbances would be the tool-media interaction forces for a trajectory control problem. Some researchers argue that the unmodeled dynamics of the pile (G_p in Fig. 3) can be modeled as a disturbance to the process. For example, in Liu et al. [34], the interaction forces from the pile are assumed as a disturbance, and it is suggested that a robust controller could be sufficient to counteract the resisting forces. However, this study is only backed up by a simulation study. In Maeda [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. In this work, experiments are performed by a 1.5-ton excavator but only on near homogeneous soil, which does not resemble, for instance, a fragmented rock scenario. In summary, it is hard to conclude that modeling the pile only as a disturbance to the excavation process can be used as a general approach for the autonomous excavation problem.

4.2.4. Artificial intelligence methods

The automatic bucket loading problem has also received attention from the artificial intelligence research community. Modeling the tool-media interaction is impossible [35], and the traditional control techniques can be impractical or infeasible, especially for rock excavation [36]. This is often the motivation behind exploration of artificial intelligent techniques, such as neural networks and fuzzy logic, to address this problem. In Xiabo et al. [35] and Shi et al. [36], a small-scale experiment is designed to investigate the excavation process and involves digging out two rocks of varying sizes from a pile of muck. Their approach for handling the excavation goal is to break the goal down into different tasks, which are further broken down into excavation behaviors and actuator actions. In their work, the excavator behaviors and actuator actions are coded using fuzzy logic and a neural network based on finite state machine methods. Wang [37] further continues the work on fuzzy logic control for robotic excavation presented in Xiabo et al. [35] and Shi et al. [36].

Other works that also use rule-based methods for robotic excavation are Lever [38] and Wu [39]. These data driven methods rely more on the experiment than theory, and a common idea behind these artificial intelligence-based methods is to code the intelligence of an expert operator into a computer program. A rational criticism against the proposal of being inspired by an expert operator comes from Hemani [27], which states that the way an operator has learned to use the earth-moving machine might not be the most efficient method to control the machine.

4.2.5. Reinforcement learning methods

Reinforcement learning is a field in machine learning that finds some of its applications in the field of automatic control. In reinforcement learning, an autonomous agent (controller) interacts with the environment (via sensor and actuators) in real-time and learns to choose optimal actions to achieve its goal [40]. Because several reinforcement learning algorithms are model-free, it is attaining the interest of many research groups. A good survey of several algorithms and challenges for applying reinforcement learning in robotics is presented in Kober et al. [41].

Although reinforcement learning has never been applied to robotic excavation to our knowledge, it is a promising potential candidate to address the automatic loading problem. Because excavation tasks take place in an episodic setting with a significant interval between two bucket loadings, the real-time constraints on reinforcement learning are not so harsh. Furthermore, if excavation data from an expert driver is available, it can be included in the framework of imitation learning to create a baseline controller for learning experiments [41].

Reinforcement learning is applied in robotics to control humanoid robotic arms in Khan et al. [42]. They use a Q-learning algorithm where the Q-value function is learned by neural networks. In Khan et al. [43], a review of reinforcement learning is presented from the view point of adaptive control. Despite reinforcement learning and optimal control being somewhat related fields, reinforcement learning cannot guarantee optimal performance for autonomous loading, mainly because of the absence of a complete model of the earth-moving process.

4.3. Pile characterization

Pile characterization is an area of interest in robotic excavation that uses machine vision techniques to aid autonomous and remote operation. Some applications of pile characterization via vision-based systems are identifying a good excavation location for short-term (e.g., next scoop) and long-term action (e.g., task planner), and computing the most suitable pose of the machine to scoop the next bucket. Other applications include identification of the quality of blasted rock and estimation of the volume of the loaded material in one scooped bucket.

In Sarata et al. [44], stereo vision is used to identify the best loading location on the pile of material to be moved. In Stentz et al. [45], a laser-based task planner is developed for an excavator and has been shown to be capable of excavating the ground as fast as a human driver. A similar method for determining the attack pose for wheel loaders is discussed in Magnusson and Almqvist [46].

Apart from the attack pose, laser scanner data has also been used to identify large boulders in the pile [47]. In Anwar et al. [48], a stereo vision system has been demonstrated to estimate the fill factor of soil in the bucket.

4.4. 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. Several companies, including Caterpillar, Atlas Copco and Sandvik, offer navigation products for the mining industry, and many sites already use automatic hauling in their mines McNab et al. [49]. Laser-based techniques are dominant in localization and navigation in underground mines. Some good references that use laser scanners in their work are Roberts et al. [5] and Larsson et al. [8]. In the scope of a short loading cycle, a relative localization technique between the dump 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 ultra-wide-bandwidth technologies [50] can also be exploited for the relative navigation between the wheel loader and the dump truck.

4.5. Path planning

In the short loading cycle, the wheel loader moves on a slightly varying V-Y curve, as shown in Fig. 2. The aim of path planning is to generate this V-Y curve given the starting pose of the machine, the pose of the dump truck and other constraints (walls and obstacles). Different objectives for optimizing this V-Y curve as noted in Filla [51] are fuel efficiency, travel distance, travel time and more. Another recent publication concerning path planning for a short loading cycle is Alshaer et al. [52]. The surfaces at earth-moving operation sites can be bumpy and uneven due to pebbles and small rocks, and for this reason, a 3D relative localization could be a better alternative than 2D localization methods.

5. Communication for remote operations

It is identified in Hemani and Hassani [2], Andersson [10] and Lever [38] that operators make their decisions based on their vision, the sound from the surroundings and the vibrations from the machine. Because an operator in manual operation uses all his visual (3D), auditory, tactile and other sensory organs to operate the machine [27], the tele-remote operator should also be provided with more feedback than just plain video streams for different views around the machine. Although it is undesirable to trouble the tele-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 types of streams of feedback data to the remote control station along with the upstream of control commands as shown in Fig. 4.

5.1. Wireless network properties

Because mobile machines usually need to communicate over wireless links, the adverse effects of wireless channels, such as multi-path 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, affecting their ability to control the machine. Therefore, the design of a good communication setup should not be overlooked when designing a tele-remote control system for mobile earth-moving machines.

Although specialized wireless networks could potentially offer highly predictable performance, the benefits of using multi-purpose wireless networks that cannot only be used for tele-remote operations but also for other applications motivate the choice of network technologies that can carry Internet Protocol (IP) traffic. Choosing a technology such as wireless local area networks (WLANs) is also attractive for reasons of cost savings since WLAN equipment is widely popular and therefore less expensive.

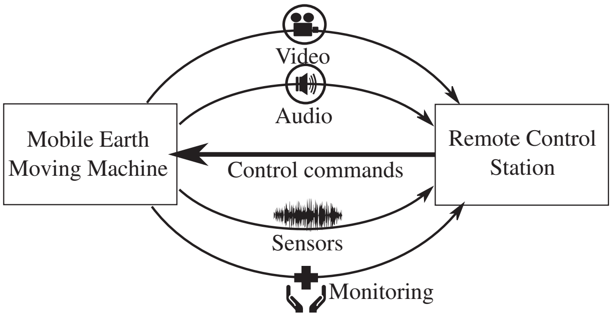

Fig. 4. Data Streams between mobile machine and remote control station.

A reliable wireless communication system is also very important to a fully autonomous system to monitor the safety of the operation, e.g., by overseeing the operation and acknowledging safety-critical tasks and actions. Although communication is critical for the remote earth-moving operations, it is far less discussed in the literature. A valuable discussion of communication solutions for underground mines is presented in Forooshani et al. [53]. The requirements of the tele-remote control solution from the communication system are low latency, minimal loss and high throughput. In Liu et al. [34], a Simulink–Opnet simulation is implemented to test a proposed communication system for a tele-remote control solution.

Wireless communications at construction sites and in industrial and mining environments may be provided with a combination of different network technologies. For example, IEEE 802.11ac [54] or IEEE 802.11n [55] WLANs can be deployed and controlled specifically for a construction site, industry or mine. To extend the wireless network coverage, such WLAN deployments may be complemented with 4G cellular infrastructures based on ETSI 3GPP LTE-Advanced [56]. These wireless networks technologies are capable of several hundreds of Mbps to Gigabit speeds, but as with most wireless communications, the actual speed varies with radio conditions. When disturbances such as undesired reflections causing multi-path propagation and interference appear, receiving devices experience errors in the received data, which makes the system adapt to stronger coding and consequently lower transmission rates.

In datagram-based networks, queuing delays, jitters (i.e., delay variations) and eventually loss of data appear when the communication speed falls short of the data consumption rate of the application. The amount of buffers allocated for queuing in WLAN devices is decided based on a trade-off between delay and throughput. For example, a maximum of 1600 datagrams may need to be buffered at outgoing IEEE 802.11n interfaces to ensure that the network can operate at its full capacity [57]. With such an allocation of buffer space, delays of more than 300 ms can appear when the network is saturated. In addition to the latencies that occur when data is queued for transmission, link-layer retransmission of data can also cause delay and jitters.

For tele-remote operation of earth-moving machines, the risk of being exposed to throughput degradation and excessive delay and jitters can be reduced by designing a system in which the demand for capacity stays well below the available network capacity. However, this approach alone can prove fatal when the wireless network suffers from unpredictable variations in radio channel quality. Recent IEEE 802.11 standards offer schemes and mechanisms that provide Quality-of-Service (QoS) satisfaction for real-time multimedia flows over WLANs, allowing the prioritization of mission-critical streams for tele-remote operations [58]. Still, available wireless capacity can vary greatly and cause severe problems for the operation.

5.2. End-to-end transport services

Varying wireless capacity can be handled by adapting the sending rates of the different data streams for tele-remote control. In Internet Protocol (IP)-based networks, such adaptation is typically performed at the endpoints of the communication system. The widely used Transmission Control Protocol (TCP), originally published as an Internet standard in 1981, provided congestion control and avoidance for applications on IP-based networks [59]. TCP, however, has some disadvantages for the real-time communication required for tele-remote operations. That is, TCP may introduce undesired delays due to its mandatory in-order delivery feature since it buffers data awaiting successful re-transmission of lost packets [60]. This problem is referred to as head-of-line blocking. Alternatively, the User Datagram Protocol (UDP), the other most commonly used transport layer protocol on IP networks, does not implement congestion avoidance and control, and applications using this protocol may hence overload wireless networks, resulting in high loss rate, jitters and extensive delays.

The end-to-end communications for tele-remote operations over IP networks share many requirements for telephony signaling transport. The need of telephony signaling transport over IP motivated the design of a new protocol for signaling transport. As a result, the Stream Control Transmission Protocol (SCTP) was published by the IETF (Internet Engineering Task Force) as a standard track document in 2007 [61]. SCTP provides similar congestion control and avoidance as TCP along with additional features, such as avoidance of head-of-line blocking of messages and multi-homing for endpoint devices.

Head-of-line blocking can be avoided with SCTP by using the unordered delivery service offered by this protocol. The multi-homing feature allows an endpoint device to be connected to its peer endpoint via more than one network interface. This feature is highly desirable for tele-remote operation as it allows for the possibility of switching to a backup wireless network if the primary one becomes unavailable, e.g., from a WLAN to a 4G network. Extensions to SCTP for partial reliability (PR-SCTP) further allow for the early discard of stale data, such as delayed video frames or control messages [62]. In Sanson et al. [63], it is shown that limiting the maximum number of retransmissions with the H.264/AVC video standard can provide reliable delivery similar to TCP along with lower delay. In general, the scalable video coding extension of the H.264/AVC standard offers temporal, spatial, and quality scalability to video streams, which allows the use of rate-adaptive transport protocols, such as TCP and SCTP [64].

Given the several advantages of SCTP over TCP and UDP, it appears as a valid alternative for the end-to-end transport of streams for tele-remote control of earth-moving machines. Another alternative for video transport is the TCP Friendly Rate Control (TFRC), which offers a much lower variation of throughput over time compared with TCP or SCTP. This makes TFRC more suitable for applications where a relatively smooth sending rate is of importance [65], such as streaming media. TFRC can be used with the Datagram Congestion Control Protocol (DCCP), which is a transport protocol that provides bidirectional unicast connections of congestion-controlled unreliable datagrams [66]. Multi-homing support for DCCP is currently being considered by the IETF for possible standardization [67].

5.3. Key communication aspects

As discussed above, the importance of good wireless communication for tele-remote operation of earth-moving machines should not be underestimated. Modern wireless technologies, such as IEEE 802.11ac, IEEE 802.11n and 3GPP LTE-Advanced, are likely to provide the desired communication quality, but the network load and varying radio condition need to be carefully considered and properly handled through careful design and planning. Available schemes and mechanisms for QoS should be used to prioritize mission-critical messages. Additionally, transport layer protocols offering features such as congestion control and avoidance without head-of-line blocking and support for multi-homing can prove valuable for tele-remote operations.

6. Remote control station

The tele-remote operation of earth-moving machines is gaining popularity in some industries. Remote-controlled equipment does provide a present-day solution while autonomous solutions evolve. In this section, a remote control station is discussed in brief.

6.1. Human–machine interaction

Because remote control demands real-time interaction with the operator, the Human Machine Interface (HMI) should provide only the necessary information for efficient remote operation. Irrelevant information should be suppressed to lessen the stress on the remote operator. An advanced HMI is proposed for excavators in Ni et al. [68], where a complete virtual environment of the excavation task has been envisioned with heads-up displays. Virtual reality may be suitable for a minimally moving excavator, but it may not be so useful to apply to a short loading cycle due to the mobility of the machine. Stereo vision displays have been proposed in Sauer et al. [69] for presenting augmented reality of industrial robots. In Oh et al. [70], haptic feedback joysticks are proposed for excavators. Many of these techniques can be used to present feedback from the wheel loaders to the remote-operator, but they should only be included if they improve the conditions for efficient remote operation.

6.2. Task planning

Some researchers strive for automation of the mobile earth-moving machines from the highest level, and they aim to break the main objective down into smaller tasks much like how a human operator will see the work. A task planner software implements such an architecture to help the operator or the autonomous agent in making high-level decisions (e.g., discretization of the working area into a grid for planning the excavation). A task planner for an excavator using state chart flow diagrams has been developed in Ha et al. [71] and ha and Rye [72]. Another task planning algorithm for excavators working in a wide-open area is proposed in Seo et al. [73].

7. Other related works

In this section, research areas that do not fall into the previous categories but which are still quite interesting with regard to automation of earth-moving machines are discussed in brief.

7.1. Power-train and traction control

The research in traction control and power-train technologies also addresses autonomous earth-moving aspects by posing certain requirements. The problem of wheel slip during loading of heavy and dense media already raises enough questions to open the scope. Efficient transmissions aim to minimize the fuel consumption and wear and tear of tires. In Andersson [10], improvements in the traction control of LHD machines are proposed. In Nilsson [74], advanced control theory has been applied on the wheel loader transmission to improve fuel efficiency.

7.2. Simulation of the environment for development and training

Detailed computer simulations are used to design control systems 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 of the literature. In Filla et al. [26], a pile of consistent gravel is simulated to study different bucket trajectories for wheel loaders, and in Schmidt [75], a simulation of soil is developed to test automatic loading functions for excavators.

7.3. Connected things at mobile machines

Earth-moving machines are for different reasons equipped with various types of ad-on sensors. For example, construction equipment for autonomous and remote operation requires video cameras and laser sensors [5,8,32,45,47,48] and autonomous loading could further require speed and pressure sensors [10,23]. Additionally, construction equipment industry strives towards remote health monitoring of key components in machines to facilitate proactive and predictive maintenance [76]. Remote monitoring includes logging, pre-processing, and wireless transmission of controller area network (CAN) signals, and data from ad-on sensors [77]. For example, accelerometers may be mounted at a strategic location on machines to detect wear and fatigue of critical components such as a wet clutch of a wheel loader [78].

The increasing need for connecting sensors to construction machines turns them into mobile cyber-physical systems (CPS) and a part of the Internet of Things (IoT). The communication techniques discussed previously not only facilitate remote operation, but also the transport of sensor data to an Industry Control System (ICS) and to advanced machine analysis systems [78].

7.4. Survey work

There is much evident interest in automation of mobile earth-moving machines, which has generated quite a selection of survey papers. Two papers, Hassani [2] and Singh [19], provide excellent background and knowledge for automation of the loading step. An overview of navigation technologies for LHD machines is presented in Dragt et al. [13]. A couple of good survey papers in the field of the automation of excavators are Chacko et al. [4] and Yu et al. [79]. Some recent work towards automation of wheel loaders is presented in Koyachi and Sarata [80] and Bonchis et al. [81].

8. Knowledge gaps

Despite the long on-going research for automation of earth moving machinery, there are some under-explored areas. In this section, such knowledge gaps are discussed to motivate further work in this field. Some areas, such as navigation, dynamic modeling and optimal trajectory for the bucket, have received much attention, which has helped the research in these areas to move forward significantly. Alternatively, some areas lack attention or are relatively new.

8.1. Fragmented rock

In Marshall et al. [23], the need for specific research on the loading of fragmented rock has been noted, 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 Cho et al. [82], 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 perform experiments on fragmented rock. More experimental research is required in regard to the loading of fragmented rock mainly because the pile cannot be modeled in this case. Additionally, the potential use of artificial intelligence or machine learning methods, or a combination of these methods, needs to be further explored.

8.2. Communication performance for remote operation

The latency in audio and video are important issues for tele-remote operation. Humans can tolerate audio delays up to 400 ms [60], but beyond that, it can hamper the control. Wireless network jitters can cause many frames to be dropped, resulting in sluggish video. Although one argument says that these problems can be mitigated just by upgrading to higher bandwidth or by using available schemes and mechanisms for QoS, 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 suitable protocol suite for tele-remote operation, especially at the end-to-end transport layer.

Candidate transport layer protocols for tele-remote operation include SCTP [61], DCCP [66] and TFRC [65]. TFRC can prove beneficial for the scalable video coding extension of the H.264/AVC standard, which offers temporal, spatial, and quality scalability to video streams [64]. The use of these transport protocols (or others) for tele-remote operation remains to be explored and tested together with wireless network technologies to gain more knowledge on how a dependable communication solution should be designed.

8.3. Operator experience during remote operation

Operator experience makes a big difference in remote control performance. In manual operation, drivers 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 a motion simulator and head-mount display with surround sound. However, doing so dilutes the main reason for removing the operator from the harsh environment. Additionally, any form of feedback to the remote operator will be slightly delayed, which should be minimized as much as possible. Force feedback-enabled joysticks and pedals can be of interest for improving the operator's experience, especially during loading. Hence, suitable means of feedback to tele-remote operators of earth-moving machines require more attention.

9. Summary and future work

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

This paper provides background for the problem of autonomous excavation, presents a wide literature survey covering several research topics and concludes with the identification of knowledge gaps for autonomous/tele-remote operation of earth-moving machines. Automation of mobile earth-moving machines involves many different research areas. Although the article is slightly inclined towards operation of wheel loaders in a short loading cycle, this setting covers several aspects of autonomous earth-moving, which is seen as the future by several industries, including mining, construction, and forestry.

The research relating to excavators has advanced ahead of the research relating to wheel loaders, which can be noted from the fact that the majority of citations listed in this article have performed experiments with excavators. However, excavators, unlike wheel loaders, are much less mobile during operation, which makes wheel loader automation more challenging. The more extensive movements of the wheel loader challenge the wireless communication needed for tele-remote operations. This motivates the need for careful consideration and planning to balance the communication load and wireless network capacity as well as the proper use of available schemes, mechanisms and protocols to obtain the desired quality of the communication services.

There is a split between researchers regarding which approach is more suitable for the automatic bucket loading problem. Two main strategies attempted by research communities are artificial intelligence-based methods and compliance control. However, very few papers have reported results on fragmented rock, which appears to be a mountain not yet climbed.

10. Future work

Fully autonomous systems that can perform equally well as manual operation are still far-fetched. Future work towards fully autonomous operation needs to address different areas encompassing the following topics.

Autonomous loading algorithms that can adapt to different materials and machines, and can still perform better than or equal to human drivers are important for autonomous operation. Rather than programming based methods, we advocate for learning based methods like reinforcement learning. Model free deep reinforcement learning [83] is an interesting approach which can be build to support variations in machine and material, and could potentially optimize over multiple performance metrics.

Machine to machine communication technology enables task coordination between machines. For example, an autonomous loader and an autonomous dumper working together at a draw point in a narrow corridor in an underground mine need to communicate with each other and use coordinated path planning and navigation.

Pile shape and geometry characterization enable cognitive decision making by the machine for the loading process. Existing technologies such as laser based lidar system can address this requirement. Autonomous navigation and path planning in a constantly changing environment such as a blasting site should be done with an accurate map of the environment. Simultaneous localization and mapping (SLAM) technology can be used to create the latest and accurate map of the site to be distributed to other machines and to the site management software. The site management technology also requires further research and development to incorporate autonomous machines for their operation, monitoring and maintenance.

The requirements of the construction and mining industries to be more efficient can be met by automation of earth-moving machines, and doing so, also relieve humans from harsh working environments. Adding operator assistance functions over tele-remote operation is a good enabler for companies to increase automation in their operation.

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