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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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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.

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