Automated loading and dumping for enhanced efficiency (ALDEE)

Public report

Project within	Electronics, software and communication – FFI | Vinnova
Author	Ulf Bodin, Luleå University of Technology
Date	19 August 2022

FFI Fordonsstrategisk Forskning och Innovation

Content

1. Summary

The *purpose* of the project was to enhance the efficiency of the loading and unloading processes in construction projects with the help of machine learning (ML) methods. The research *method* used was divided into two complementary phases, where the first phase focused on refining the problem description and identifying related knowledge gaps and the second phase was an iterative process devoted to closing those gaps. The general *approach* used in the project has been to apply ML to automate these complex processes by learning to imitate operators, as well as further improving the solution based on data collected during autonomous operation.

ML is likely to play an important role in the development of semiautomatic and fully autonomous construction equipment such as wheel-loaders, excavators, and dump trucks. Such machines are typically used for diverse operations in complex environments. ML-based solutions are attractive in this context since they are known to have the capacity to model complex processes by learning and imitating them efficiently as well as further improving the solution based on data collected during operation. For example, imitation learning methods are shown useful to train neural networks for them to perform task like automated loading of material from a pile, while re-enforced learning can be used to improve the performance when loading materials not included in the training data for imitation learning [1].

This project aimed to address the following problems:

- How to use ML approaches to develop functions that automate the loading process starting before the bucket is engaged with the pile, when the bucket is in the air before it contacts the pile and stops after the bucket is filled.
- How to use ML approaches to develop functions that automate the dumping process, including identifying and approaching different loading trucks as well as dumping material on such load receivers in a proper way.

Given the *limitations* imposed by the Covid-19 situation that hindered live meetings and prevented full-scale experiments, the originally planned demonstrations of solutions based on ML and computer vision for automated loading and dumping with a full-scale wheel-loader could not be performed. Instead, the use of scale-models and simulations have been investigated regarding the development of such solutions with focus on camera input to identify and approach a load receiver and accomplish the dumping process in a proper way. Furthermore, the use of camera input to identify the attack point when scooping material from a pile and initiate the scooping from the pile has been studied in the project.

The *results* of the project include demonstrating the use of transfer learning, scale-models, and automatic annotation to train ML-models to detect objects on full-sized dump trucks [2][3]. The results also include a survey of state-of-the art on deep-learning-based vision for earth-moving automation [4]. This literature study identified the importance of computer vision and data-driven approaches (i.e., ML) for the automation

of wheel-loaders. These results, together with those on the use of scale-models, are collected and described in the context of automated navigation of when-loaders during the short-loading cycle using machine vision [5]. The main result of the project is the increased knowledge on applied machine learning (ML) for the automation of wheel-loaders.

The *deliveries* made by the project include two conference papers [2][3], one journal paper [4], as well as publications and online presentations and a webinar by LTU for Volvo. Moreover, a licentiate thesis on solutions for automated loading and dumping based on machine learning has been delivered [5]. Finally, demonstrations of the use of scale-models and simulations have been made by LTU and Volvo as part of the joint work to develop ML-based solutions for automated loading and dumping with wheel-loaders used in short-loading cycle operations. In particular, the project has prepared a simulation environment (aka AI gym) with a model of a Volvo wheel-loader in which camera-based navigation based on ML can be examined.

Experiments with full-scale wheel-loaders were originally planned for in ALDEE, but the Covid-19 situation has made it impossible to perform such activities. This means that neither further development of the automated loading solution demonstrated in the SALM project [6] nor dumping have been possible since such work requires full-scale experiments. However, the project has re-focused and provided other results on computer vision, approaches for navigation and simulations for training ML-models, which together with knowledge transfer to Volvo have paved the way for the next steps towards the ML and camera-based automation of wheel-loaders. These next steps are planned for the VALD project, which starts in May 2022 [7].

2. Sammanfattning på svenska

ALDEE har undersökt användningen av maskininlärningsmetoder (ML metoder) för att automatisera lastnings- och lossningsprocesser med hjullastare i byggprojekt i allmänhet, och specifikt för kortcykellastning. Projektets fokus har legat på kameraseende baserad på ML, och användningen av sådan input för att upptäcka föremål på lastmottagare såsom dumprar för att underlätta navigering och dumpning av material på dessa. De undersökta metoderna för kameraseende förväntas vara användbara även för att initiera en automatiserad lastningsprocess för att lasta material från en hög, även om den applikationen inte explicit har studerats i projektet.

Tung anläggningsutrustning såsom hjullastare utvecklas mot full automation av flera skäl [8]. Till exempel är byggarbetsplatser ofta avlägset belägna och operatörer upplever tuffa arbetsförhållanden och farliga miljöer, där trötthet hos förarna är en vanlig orsak till olyckor. Således är utrustningen alltmer beroende av funktioner för autonom drift. För hjullastare är effektiv lastning och lossning av olika typer av material viktiga uppgifter i byggprojekt. Att utföra sådana uppgifter snabbt och effektivt har stor effekt på produktivitet och kostnader och är därför av stor betydelse för byggföretag.

Tillvägagångssätt för ML är kända för att ha förmågan att modellera komplexa processer genom att lära och imitera dem effektivt samt ytterligare förbättra lösningen baserat på data som samlas in under drift. Dadhich har framgångsrikt demonstrerat användningen av både imitation och förstärkt maskininlärning för att lasta grus med en hjullastare [9]. I den korta lastningscykeln måste hjullastare också automatiskt initiera lastningsprocessen samt närma sig en lastmottagare och utföra dumpningsprocessen på ett korrekt sätt. Alla dessa steg kräver återkoppling till det neurala nätverket om avstånd och angreppsvinkel till lastbilen, till exempel genom att använda 2D- och/eller 3D-kameror för datorseende.

Kameror är mycket bra på att upptäcka och känna igen objekt och det data de producerar kan matas till algoritmer baserade på ML för objektklassificering. Precis som för autonoma bilar motiverar detta användningen av kameror även för entreprenadutrustning såsom hjullastare som behöver navigera och utföra uppgifter autonomt, inklusive att initiera en lastningsprocess, navigera från hög till lastmottagare och dumpa material på en lastmottagare.

Syftet med projektet var att effektivisera lastnings- och lossningsprocesserna i byggprojekt med hjälp av ML-metoder. Den använda forskningsmetoden var uppdelad i två kompletterande faser, där den första fasen fokuserade på att förfina problembeskrivningen och identifiera relaterade kunskapsluckor. Den andra fasen var en iterativ process ägnad åt att täppa till dessa luckor. Det allmänna tillvägagångssättet som använts i projektet har varit att tillämpa ML för att automatisera dessa komplexa processer genom att lära sig att imitera operatörer, samt att ytterligare förbättra lösningen baserad på data som samlats in under autonom drift.

Detta projekt syftade till att lösa följande problem:

- Hur man använder ML tillvägagångssätt för att utveckla funktioner som automatiserar lastningsprocessen med början innan skopan är i ingrepp med pålen, när skopan är i luften innan den kommer i kontakt med högen och stannar efter att skopan är fylld.
- Hur man använder ML-metoder för att utveckla funktioner som automatiserar tömningsprocessen, inklusive att identifiera och närma sig olika lastbilar samt dumpa material på sådana lastmottagare på ett korrekt sätt.

Resultaten från projektet inkluderar demonstration av användningen av överföringsinlärning, skalmodeller och automatisk anteckning för att träna ML-modeller för att upptäcka objekt på fullstora dumprar [2][3]. Resultaten inkluderar också en kartläggning av det senaste inom djupinlärningsbaserat seende för automation av markarbeten [4]. Denna litteraturstudie identifierade betydelsen av datorseende och datadrivna tillvägagångssätt (dvs ML) för automatisering av hjullastare. Dessa resultat, tillsammans med de om användningen av skalmodeller, samlas in och beskrivs i samband med automatiserad navigering av när-lastare under den korta laddningscykeln med hjälp av maskinseende [5]. Huvudresultatet av projektet är den ökade kunskapen om tillämpad ML för automatisering av hjullastare.

Projektets leveranser inkluderar två konferensbidrag [2][3], en tidskriftsartikel [4], samt publikationer och online-presentationer och ett webbseminarium av LTU för Volvo. Dessutom har en licentiatuppsats om lösningar för automatiserad lastning och dumpning baserad på maskininlärning levererats [5]. Slutligen har demonstrationer av användningen av skalmodeller och simuleringar gjorts av LTU och Volvo som en del av det gemensamma arbetet med att utveckla ML-baserade lösningar för automatiserad lastning och dumpning med hjullastare som används vid kortlastningscykeloperationer. I synnerhet har projektet utarbetat en simuleringsmiljö (alias AI gym) med en modell av en Volvo hjullastare där kamerabaserad navigering baserad på ML kan undersökas.

Experiment med fullskaliga hjullastare planerades ursprungligen i ALDEE, men Covid-19 har gjort det omöjligt att utföra sådana aktiviteter. Detta innebär att varken vidareutveckling av den automatiserade lastningslösning som demonstrerats i SALM-projektet [6] eller dumpning har varit möjlig eftersom sådant arbete kräver fullskaliga experiment. Projektet har dock fokuserat om och tagit fram andra resultat om datorseende, tillvägagångssätt för navigering och simuleringar för träning av ML-modeller, vilket tillsammans med kunskapsöverföring till Volvo har banat väg för nästa steg mot ML och kamerabaserad automatisering av hjullastare. Dessa kommande steg är planerade för det VALD projektet, som startar i maj 2022 [7].

3. Background

Heavy construction equipment such as wheel-loaders are developed towards full automation for several reasons [8]. For example, construction sites are often remotely located, and operators experience harsh working conditions and dangerous environments, where fatigue with the drivers is a common cause of accidents. Thus, the equipment is increasingly dependent on the functions for autonomous operation. For wheel-loaders efficient loading and unloading of different types of material are important tasks in construction projects. Performing such tasks fast and efficiently have a major effect on productivity and cost and are hence of great significance for construction companies.

Machine learning (ML) approaches are known to have the capacity to model complex processes by learning and imitating them efficiently as well as further improving the solution based on data collected during operation. Dadhich has successfully demonstrated the use of both imitation and re-enforced machine learning for scooping of gravel with a wheel-loader [9]. This work included the development of an automated loading function for which the trained neural network was initiated after the bucket was engaged with the gravel pile and sensors read a clear pressure increase on lift hydraulics. While this function successfully has demonstrated the capacity of ML for automated digging, having it initiated as such prevents the function from enhancing the efficiency of the complete digging process starting from when the machine is approaching the pile.

In addition to an extended function for automated loading, an automated dumping function is needed to enhance the efficiency of the loading and unloading process in construction projects. For such function, the machine needs to approach a load receiver and accomplish the dumping process in a proper way. This requires feedback to the neural network on distance, and approach angle to the loading truck, e.g., using 2D and/or 3D cameras for computer vision. Moreover, information is required on what type of loading truck that is approached, i.e., identifying various trucks, haulers and TARA systems of different sizes.

Cameras are very good at detecting and recognizing objects, and the image data they produce can be fed to algorithms based on machine learning for object classification. Like for autonomous cars, this motivates the use of cameras also for construction equipment such as wheel-loaders that need to navigate and perform tasks autonomously, including initiating a loading process, navigating from pile to load receiver, and dumping material on the load receiver.

4. Purpose, research questions and method

The *purpose* of the project was to enhance the efficiency of the loading and unloading processes in construction projects with the help of machine learning (ML) methods. This includes to use ML for the automation these complex processes by learning to imitate operators, as well as further improving the solution based on data collected during autonomous operation. The work in this project builds upon and make use of results from the WROOMM [10] and SALM [6] projects. These projects have successfully demonstrated the use of both imitation and re-enforced machine learning for scooping of gravel with a wheel-loader [9].

The problems addressed in this project are the following:

- How to use machine learning approaches to develop functions that automate the loading process starting before the bucket is engaged with the pile, when the bucket is in the air before it contacts the pile and stops after the bucket is filled.
- How to use machine learning approaches to develop functions that automate the dumping process, including identifying and approaching different loading trucks as well as dumping material on such load receivers in a proper way.

The research *method* used was divided into two complementary phases, where the first phase focused on refining the problem description and identifying related knowledge gaps. The second phase was an iterative process, where a hypothesis was formulated of how the refined problems can be solved using existing knowledge. Guided by the hypothesis, a literature study and development were used to facilitate exploration of said hypothesis. Development entailed both the development of prerequisite knowledge, from the literature study, and the development of the tools needed to use said knowledge. Examples of such tools included a simulation environment and the use of scale-model vehicles to perform experiments.

The general *approach* used in the project has been to apply ML to automate these complex processes by learning to imitate operators, as well as further improving the solution based on data collected during autonomous operation. This approach together with the research method, the following *research questions* were used to guide the work and address the problems addressed by the project:

R1. What are the challenges and knowledge gaps preventing automation of the short-loading cycle?

R2. How can computer vision aid in the automation of the short-loading cycle and address the challenges identified in Question 1?

The answer to R1 found in the project is that the main knowledge gaps relate to loading of heterogeneous material and navigation during loading and unloading. The answer to R2 is that computer vision sensors and techniques, especially cameras, can be used to extract high level information about the world around the vehicle without requiring some type of interaction. Complete descriptions of these findings are available in [5].

5. Objectives

5.1 Overreaching FFI objectives

ALDEE will help increasing the Swedish capacity for research and innovation, thereby ensuring competitiveness and jobs in the field of vehicle industry, by strengthening the competence in the area of applied computer vision for use in environments where heavy construction equipment typically operates. The project will include cooperation between industry and a university, which will provide a connection to higher education of people needed to facilitate the automation of heavy equipment and development of heavy construction equipment in Sweden.

5.2 Sub-programme objectives

ALDEE contributes to the *architecture sub-programme* of the FFI Electronics, software, and communication programme. The project focuses primarily on the *machine learning objective*, regarding the automation of the individual steps of loading and dumping material with a wheel-loader on a load receiver, and regarding the use of computer vision based on machine learning for these steps and for wider use in automating heavy construction equipment like wheel-loaders. ALDEE aims at reaching the goal of demonstrating two or more applications for wheel-loaders based on machine learning (i.e., automated loading and dumping).

In addition, the project indirectly addresses the *computational power objective* as well as the *internal communication objective* in that the project results are expected to provide valuable input to further work on these objectives after the project finishes. Such further work is likely to be based on results achieved by other projects that Volvo is involved in to efficiently use on-board hardware and software platforms and guarantee the predictability of the system functionality, i.e., the DPAC [11] project and the DESTINE project [12].

6. Results and deliverables

6.1 Results

The results of the project include demonstrating the use of transfer learning, scale-models, and automatic annotation to train ML-models to detect objects on full-sized dump trucks [2][3]. The results also include a survey of state-of-the art on deep-learning-based vision for earth-moving automation [4]. This literature study indicated that computer vision, in combination with on-board sensors, is more critical than coordinate-based positioning for the automation of wheel-loaders, and data-driven approaches (i.e., ML), in general, have high potential in terms of productivity, adaptability, versatility and wear and tear with respect to automation system solutions. The main knowledge gaps identified in the study relate to loading non-fine heterogeneous material and navigation during loading and unloading. These results, together with those on the use of scale-models, are collected and described in the context of automated navigation of when-loaders during the short-loading cycle using machine vision [5]. The main result of the project is the increased knowledge on applied machine learning (ML) for the automation of wheel-loaders.

6.2 Deliverables

The deliveries made by the project include two conference papers [2][3], one journal paper [4], as well as publications and online presentations and a webinar by LTU for Volvo. These presentations and the webinar covered background as well as new knowledge on the use of ML-methods and camera vision for the autonomous operation of heavy construction equipment in the complex and dynamic environment at a construction or production site. Moreover, a licentiate thesis on solutions for automated loading and dumping based on machine learning has been delivered [5]. Finally, demonstrations of the use of scale-models and simulations have been made by LTU and Volvo as part of the joint work to develop ML-based solutions for automated loading and dumping with wheel-loaders used in short-loading cycle operations. In particular, the project has prepared a simulation environment (aka AI gym) with a model of a Volvo wheel-loader in which camera-based navigation based on ML can be examined.

6.3 Contribution to FFI objectives

The results and deliverables of the project has contributed to the objectives of the FFI-program discussed in Section 5 (Objectives). For the overreaching FFI objectives identified in Section 5.1, the project has *helped strengthening the competence* on *applied ML-based computer vision* for use in environments where heavy construction equipment typically operates. This objective has been reached through collaboration between LTU senor researchers and one Ph.D. student, and experts on heavy construction equipment at

Volvo CE. The competence has been strengthened also beyond these experts through a webinar at which Volvo CE employees attended to learn about results and findings from the Ph.D. student that led this webinar. The competence has further been strengthened by involving undergraduate students in the work at LTU. Five M.Sc. students in Computer Science has been involved in a project course (15 ECTS in their third year) and one M.Sc. student in Computer Science for the thesis work (30 ECTS).

For the sub-programme objectives in the *architecture sub-programme* as identified in Section 5.2, results and deliverables of the project are focused on the *machine learning objective*, and on developing solutions directly related to the topics mentioned. These topics are the automation of the individual steps of loading and dumping material with a wheel-loader on a load receiver, and the use of computer vision based on machine learning for these steps and for wider use in automating heavy construction equipment like wheel-loaders.

The project has also contributed to the *computational power objective* by giving input from LTU to Volvo CE on computational complexity and need for CPU and GPU capacities to train the ML-models investigated in the project. The ML-models investigated are used for real-time camera vision and navigation. The project has however not addressed the *internal communication objective*.

The project has reached the goal of demonstrating two or more applications for wheel-loaders based on machine learning (i.e., automated loading and dumping). The demonstrations covered the following topics:

- The use of ML for camera vision to detect objects on dump trucks, to identify target load receivers in short-cycle loading. Demonstrated with scale-models of a dump truck for the training and validation of ML-models, and verification with full-scale dump trucks at Volvo CE test area in Eskilstuna [2].
- The automatic annotation of data for training and validation with scale-models of a dump truck to identify target load receivers in short-cycle loading. Demonstrated with scale-models of a dump truck for the automatic annotation, training and validation of ML-models, and verification with full-scale dump trucks at Volvo CE test area in Eskilstuna [3].
- The simulation of a wheel-loader navigating using ML. Demonstrated using PyBullet [13]. The demonstration showed navigation with a modelled Volvo L150 wheel-loader towards a load receiver represented by its tipping body. The Volvo L150 was modelled with most of its physical properties to facilitate realistic navigation based on actuations made by the ML-models.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	New knowledge developed by LTU and Volvo CE. Disseminated at Volvo and through publications.
Be passed on to other advanced technological development projects	X	Mainly to a follow-up project, i.e., VALD [7]. Input on computational complexity and need for CPU and GPU capacities to train the ML-models investigated in the project passed on to DPAC and DESTINE [11][12].
Be passed on to product development projects		Results not yet mature enough for product development.
Introduced on the market		N/A
Used in investigations / regulatory / licensing / political decisions		N/A

7.2 Publications

The following papers have been published in the project:

[1] S. Dadhich, F. Sandin, U. Bodin, U. Andersson and T. Martinsson, "Adaptation of a wheel loader automatic bucket filling neural network using reinforcement learning," 2020 International Joint Conference on Neural Networks (IJCNN), 2020, pp. 1-9, doi: 10.1109/IJCNN48605.2020.9206849.

[2] C. Borngrund, U. Bodin and F. Sandin, "Machine Vision for Construction Equipment by Transfer Learning with Scale Models," 2020 International Joint Conference on Neural Networks (IJCNN), 2020, pp. 1-8, doi: 10.1109/IJCNN48605.2020.9207577.

[3] C. Borngrund, T. Hammarkvist, U. Bodin and F. Sandin, "Semi-Automatic Video Frame Annotation for Construction Equipment Automation Using Scale-Models," IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society, 2021, pp. 1-6, doi: 10.1109/IECON48115.2021.9589255.

[4] C. Borngrund, F. Sandin, and U. Bodin, 'Deep-learning-based vision for earth-moving automation', Automation in Construction, vol. 133. Elsevier, 2022. doi: 10.1016/j.autcon.2021.104013

[5] C. Borngrund, 'Automation of Navigation During the Short-loading Cycle Using Machine Vision', Licentiate dissertation, Luleå University of Technology, January 2022. urn:nbn:se:ltu:diva-88009.

The following papers relevant to the work presented in this report:

[6] U. Bodin, "System Architecture for Learning Machines (SALM)", public report, 2019-09-20, URL (accessed 2021-12-03): https://www.vinnova.se/globalassets/mikrosajter/ffi/dokument/slutrapporter-ffi/elektronik-mjukvara-och-kommunikation-rapporter/2017-01958eng.pdf

[7] Vision-based Automated Loading and Dumping (VALD), project funded by Vinnova FFI ESC Ref. 2021-05035, URL (accessed 2022-08-17): https://www.vinnova.se/en/p/vision-based-automated-loading-and-dumping-vald/

[8] S. Dadhich, U. Bodin, U. Andersson, Key challenges in automation of earth-moving machines, Automation in Construction, Volume 68, 2016, Pages 212-222, ISSN 0926-5805, doi: 10.1016/j.autcon.2016.05.009.

[9] Dadhich, Automation of wheel-loaders, Doctoral thesis, Luleå University of Technology, December 2018, urn:nbn:se:ltu:diva-71460.

[10] Wireless and remote operation of mobile machines (WROOMM), project funded by Vinnova, Ref. 2014-01882, URL (accessed 2022-08-17): https://www.vinnova.se/p/wireless-and-remote--operation-of-mobile-machines-wroomm/

[11] DPAC - Dependable Platforms for Autonomous systems and Control, project funded by KK-stiftelsen, started Sep 2015 – finishes Aug 2023, URL: http://www.es.mdh.se/dpac/

[12] DESTINE: Utveckling av förutsägbar mjukvara för fordonssystem genom att använda Time Sensitive Networking, project funded by Vinnova, Ref. 2018-02728, started Januari 2019 – finishes December 2021, URL: https://www.vinnova.se/p/destine-utveckling-av-forutsagbar-mjukvara-for-fordonssystem-genom-att-anvanda-time-sensitive-networking/

[13] PyBullet (home page), URL (accessed 2022-08-18): https://pybullet.org/

8. Conclusions and future research

ALDEE has investigated the use of machine learning (ML) methods to automate the loading and unloading processes with wheel-loaders in construction projects in general, and specifically for the short-cycle loading. The focus of the project has been on camera vision based on ML, and the use of such input to detect objects on load receivers such as dump trucks to facilitate the navigation and dumping of material on those. The investigated camera vision methods are expected to come useful also to initiate an automated scooping process to load material from a pile although that application has not been explicitly studied in the project.

The results of the project include demonstrating the use of transfer learning, scale-models, and automatic annotation to train ML-models to detect objects on full-sized dump trucks [2][3] as well as a survey of state-of-the art on deep-learning-based vision for earth-moving automation [4]. This literature study identified the importance of computer vision and data-driven approaches (i.e., ML) for the automation of wheel-loaders. In addition, a licentiate thesis is provided that describes and discusses the results in the context of automated navigation of when-loaders during the short-loading cycle using machine vision [5].

The project results have paved the way for upcoming g work aiming at automating the entire short-cycle loading process using ML and complementary methods known from previous experience on automating wheel-loaders. Such upcoming work will be done in the VALD project that starts in May 2022 [7].

9. Participating parties and contact persons

The participating parties in the project were Volvo CE AB and Luleå University of Technology (LTU). The contact person at Volvo CE is Andreas Hjertström (andreas.hjertstrom@volvo.com) and the contact person at LTU is Ulf Bodin (ulf.bodin@ltu.se).

VOLVO Construction Equipment

LULEÅ UNIVERSITY OF TECHNOLOGY