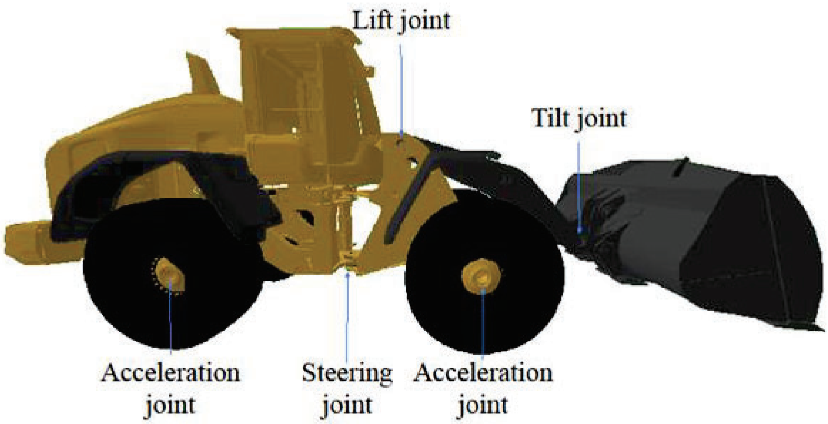
Vision-based Automated Loading and Dumping (VALD)

Public report



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FFI Fordonsstrategisk Forskning och Innovation
VINNOVA Energimyndigheten TRAFIKVERKET FKG VOLVO SCANIA VOLVO

Innehållsförteckning

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation, and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which about €40 is governmental funding.

For more information www.vinnova.se/ffi.

1 Executive summary

The purpose of the project was to automate the loading, navigation, and dumping operations of load carriers for improved driver support in products offered at the market today, as well as autonomous operation of next-generation unmanned machines such as the Volvo ZEUX LX03 prototype battery-electric wheel-loader [6][7]. The project aimed at using neural network models and machine learning (ML) with frame-based camera vision as the main sensory input for capturing environmental aspects and properties. Previously to this project, camera vision for the dumping of material on a load receiver has been investigated [5]. As part of that work, a simulation environment (gym) was created to train ML models for the automatic navigation of such machines. This project targeted the development of the entire control and navigation path of the short loading cycle. The main results of the project are captured in a doctoral thesis [1] and three of the included papers [2][3][4]. The project covered the last part of the thesis, while the earlier parts were addressed in two previous projects, ALDEE [5] and SALM [8]. Aiming at developing the entire control and navigation path of the short loading cycle for products offered at the market today and future unmanned load carriers like Volvo ZEUX LX03 that cannot easily be used with supervised and imitation learning, we decided to focus on deep-learning-based actuation and reinforced learning for the control and navigation between the place where material is to be scooped and the load receiver.

We first made simulation-based experiments to assess the feasibility of using camera vision as the main direct sensory input to an autoencoder neural network with reward functions for reinforcement learning for an agent to perform the given navigation tasks. These tasks include controlling the boom and bucket while driving from the pile of material to the load receiver, or the other way around. The experiments indicated that it is very difficult to configure such an agent for it to successfully perform the control and navigation tasks, and no working solution could be identified. Therefore, we decided to divide the problem into two main parts; (1) the use of camera vision to position the load carrier relative to a load receiver, and (2) the use of reinforced learning to perform the control and navigation task based on position information. This allowed us to focus on performing the control and navigation task based on position information provided by a differential GPS deployed on a Volvo CE wheel-loader for this project.

The work on performing the control and navigation task based on GPS positioning also involved simulation-based experiments to tune reward functions for an agent to perform the intended navigation tasks. The experiments showed that although the neural network is relaxed from performing positioning based on camera vision, the control and navigation tasks are still difficult to make work and that the training requires a very large number of time steps. The results indicate that training the agent in simulation is desired as the agent obtains the maximum reward after timesteps in the order of millions before being capable of performing the task. These results were verified by deploying the agent for the navigation of a Volvo L180H wheel-loader equipped with differential GPS and prepared for control by the agent. This suggests that the trained agent can bridge the gap between simulation and reality to complete a simplified version of the navigation task during the short-loading cycle. The experiments provide proof of concept that indicates deep learning techniques can aid in the realization of an autonomous solution. Moreover, the results show that simulations that allow for experiments providing large numbers of timesteps can facilitate the practical use of such techniques.

2 Sammanfattning på svenska

Projektet har syftat till att automatisera hela kortcykellastningscykeln med hjullastare genom att utveckla maskinlärningsbaserade lösningar för navigering mellan materialhög och lastmottagare, inklusive dumpning av material på lastmottagare. Tidigare projekt har utvecklat maskinlärningsbaserade lösningar för lastning av material från materialhögar. Både produktionsmaskiner och framtida autonoma maskiner utan styrhytt för manuell körning has övervägts i arbetet. Produktivitet och kostnad i form av energieffektivitet har använts för att bedöma prestanda. Arbetet har fokuserat på att använda simuleringar med modeller av hjullastare för att träna maskinlärningsbaserade agenter som utför navigering och kontroll av maskinen.

Den initiala ansatsen i projektet för att utveckla navigeringslösningarna var att använda kameror som den huvudsakliga sensorn för indata till maskinlärningsmodeller med förstärkt inlärning for agenten som ska styra maskinen. Simulationsbaserade experiment indikerade att det är mycket svårt att konfigurera en sådan agent för att framgångsrikt kunna utföra kontroll- och navigeringsuppgifterna, och ingen fungerande lösning kunde identifieras. Problemet delades därför upp i två huvuddelar; (1) användningen av kameraseende för att placera hjullastaren i förhållande till en lastmottagare, och (2) användningen av förstärkt inlärning för att utföra kontroll- och navigeringsuppgiften baserat på positionsinformation. Det möjliggjorde att fokusera på att utföra kontroll- och navigeringsuppgiften baserat på positionsinformation som tillhandahålls av en differentiell GPS som installerades på en Volvo CE-hjullastare för detta projekt.

Arbetet med att utföra kontroll- och navigeringsuppgiften baserad på GPS-positionering involverade också simuleringsbaserade experiment för att ställa in belöningsfunktioner för en agent att utföra de avsedda navigeringsuppgifterna. Experimenten visade att även om det neurala nätverket inte behöver utföra positionering baserad på kameraseende, så är kontroll- och navigeringsuppgifterna fortfarande svåra att få till att fungera och att träningen kräver ett mycket stort antal tidssteg. Resultaten indikerar att träning av agenten i simulering är önskvärd eftersom agenten får maximal belöning efter tidssteg i storleksordningen miljoner innan han kan utföra uppgiften. Dessa resultat verifierades genom att sätta in agenten för navigering av en Volvo L180H hjullastare utrustad med differentiell GPS och förberedd för kontroll av agenten. Resultaten tyder på att den tränade agenten kan överbrygga gapet mellan simulering och verklighet för att slutföra en förenklad version av navigeringsuppgiften under den korta laddningscykeln. De visar också att utvecklingsvägar som tillåter experiment som medger ett stort antal tidssteg kan underlätta den praktiska användningen av sådana tekniker.

Den rekommenderade fortsatta forskningen inkluderar att utforska strategin att (a) använda regelbaserad kontroll och sensorfusion för att öka abstraktionsnivån så mycket som möjligt för ML-agenterna som används för automatisering av hela kortladdningscykeln, och att (b) använda sådana agenter för uppgifter som inte kan innebära någon typ av osäkerhet och därför inte kan modelleras och lösas korrekt med hjälp av regelbaserade tillvägagångssätt. Materialet som ska lastas är känt för att vara svårt att modellera på grund av okänd sammansättning och fuktighet, och de interaktioner mellan däck och underlag som kan få maskinen att glida i sidled vid svängning är exempel på sådana osäkerheter. Slutligen, även om förstärkt lärande har potential att tillföra stort värde i automatisering av kortladdningscykeln, som att ingen manuell operatör behövs för att samla in träningsdata, och fortsatt anpassning till nya förhållanden som förändringar i miljön, leder svårigheterna med att utveckla fungerande lösningar till att (c) imitation och övervakat lärande bör väljas som huvudmetod. Resultaten av detta projekt tyder på att förstärkt lärande främst bör användas för att ytterligare förbättra fungerande ML-baserade lösningar baserade på dessa tillvägagångssätt.

3 Background

Similar to several industrial sectors, large construction and earth-moving equipment, e.g., 20+ tons, is moving fast towards automation for reasons such as safety and productivity. Mainly, harsh working conditions in the construction environment can lead to operator fatigue which is a common source of accidents and one of the major contributors to degrading safety. One approach to address this issue is to equip machines with an appropriate level of intelligence to be able to automatically move and act safely in the environment. The short loading cycle is one good candidate from the category of the loading and unloading process to be automated since it has a simple repetitive cycle. The efficient loading and unloading process is one important process in the mining and construction industry. Efficient processes with high uptime have a significant impact on site productivity and costs and are of great significance for construction companies. In this project, we aimed to use AI and learning-based techniques to automate these complex processes maintain or even improve the efficiency of the processes.

Previously to the project, an automated loading functionality has been developed for wheel-loaders where the trained neural network was initiated after the bucket was engaged with the gravel pile and sensors to read a clear pressure increase on lift hydraulics [8]. The neural network was initially trained using imitation learning, and thereafter further trained using reinforcement learning for better performance and to learn the loading of new materials. Moreover, camera vision for the dumping of material onto a load receiver with a wheel-loader has been investigated and methods have been developed [5]. As part of that work, a simulation environment has been created to train a neural network for the automatic navigation of such machines. This simulation environment has been further developed and used in this project. Other types of vision sensors such as LiDAR and RADAR have been explored in collaborations and several ongoing research projects involving Volvo CE and Örebro University (ÖRU), TAMMP [9], and TeamRob [10]. This experience has been used in the project to assess alternative sensory input in addition to camera vision.

4 Purpose, research questions, and method

Previously developed automated loading functionality for wheel-loaders constitutes an important step towards fully automated and autonomous machines, via tele-operation and semi-automation. The next task to automate is the navigation process that starts when the machine approaches the pile before loading. This process continues after loading by reversing from the pile to thereafter approach a load receiver to dump the load. Finally, for fully autonomous short-cycle loading the dumping of material on such machines needs to be automated. The autonomous operation of wheel-loaders is an essential capacity making it possible to remove human operators from the harsh working conditions in the construction environment. Thereby, avoiding operator fatigue that may lead to accidents and degraded safety, reducing cost, and addressing the lack of skilled operators.

The following research questions were used to guide the work:

- How can computer vision be used to facilitate the automation of the navigation during the short-loading cycle, and how can this be done in a cost-efficient manner?
- How can Machine Learning (ML) and deep-learning-based actuation in the form of reinforcement learning, be leveraged to facilitate the automation of the navigation steps during the short-loading cycle, and how can these be developed in a cost-efficient manner?

The research methodology used in the project was the Design Science Research Process (DSRP) [11]. DSRP is a high-level research methodology where the main goal is to create artifacts that can be shown to solve an observable problem through demonstration and evaluation. The following steps were used to guide the overall research:

1 Problem identification and motivation.
2 Define the objectives for a solution.
3 Design and development.
4 Demonstration.
5 Evaluation.
6 Communication.

5 Objectives

The overarching objective of the project was to automate the loading, navigation, and dumping functionality for unmanned machines such as Volvo ZEUX LX03 prototype battery-electric wheel-loader and provide operator support for tele-operating or manually operated machines through the development of such functionalities. The project aimed to develop the whole control and navigation path of the short loading cycle, which involves a loading, navigation, and unloading process that starts when the machine approaches the pile, loads the bucket, reverses until it approaches a load receiver, and dumps the load.

The specific objectives of the project:

- Demonstrate with a full-scale load carrier the autonomous short cycle loading based on camera vision and ML, including the data-driven methods used to develop, and tune the solution for increased productivity and fuel efficiency, and to adapt ML models for unmanned machines.
- Increase the knowledge and skills at Volvo CE on applying ML models for the automation of heavy equipment, specifically including load carriers such as wheel-loaders.
- Establish a collaboration between Luleå University of Technology and Örebro University on researching the automation of such equipment based on computer vision and ML.

Although the project could not reach the first specific objective, it was not changed. We aimed to reach this objective throughout the project. The results are in line with the first objective and include a demonstration of a full-scale load carrier performing simplified navigation based on GPS data instead of camera vision as a first step toward reaching the objective. Neither the two other specific objectives were changed.

6 Results and deliverables

The target system concerns load carriers such as wheel-loaders offered at the market today as well as next-generation hybrid and electrical machines with different geometry and capacities, like the unmanned Volvo ZEUX LX03 prototype battery-electric wheel-loader. In this project, we aimed to develop methods and supporting software that enables automated loading, navigation, and dumping functionality that can be utilized for operator support with load carriers offered at the market today as well as autonomous operation of next-generation unmanned machines. We will focus on the short cycle loading for this work, and how camera vision techniques should be used with machine learning (ML) to achieve the targeted automation.

Deliveries:

- A prototype simulation environment for the training of ML models for autonomous short-cycle loading, capturing the properties and dynamics of Volvo production wheel-loaders and extendable to capture future load carriers like the Volvo ZEUX LX03 prototype [7]. This simulation environment, including source code and documentation, is uploaded to a code repository at Volvo CE.
- Prototype methods and supporting software for the automatic control of loading, navigation, and dumping with load carriers such as production machines of today and next-generation hybrid and electrical machines. The delivered methods and software support basic navigation only, i.e., reversing and driving straight toward a load receiver while lifting the bucket to a target position. Additional work is needed to perform the complete automatic control of loading, navigation, and dumping with load carriers using ML agents. The prototype software, including documentation and instructions, is uploaded to a code repository at Volvo CE.
- Several combined demonstrations and experiments of those methods with a full-scale Volvo production wheel-loader equipped for tele-remote and autonomous operation controlled with the prototype software. The demonstrations and experiments were done in Eskilstuna at the test site of Volvo CE to validate simulation results on the developed agent for navigation based on GPS data.
- One workshop internal to Volvo CE AB for skills development and knowledge transfer from academic partners (i.e., LTU and ÖRU) and employees at Volvo actively participating in the project to other personnel at Volvo. The workshop was done in Eskilstuna at Volvo CE to transfer knowledge and to present and hand over the software developed in the project.
- One Doctoral thesis on solutions for automated short-cycle loading based on machine learning and camera vision as the main sensory input. The Doctoral thesis was defended and approved in February 2024.

In addition to the above-listed deliveries, connected to the overarching FFI objectives, the project has helped increase the Swedish capacity for research and innovation, thereby ensuring competitiveness and jobs in the vehicle industry by strengthening the competence in applied computer vision for use in environments where construction heavy equipment typically operates. The project included cooperation between industry and two universities, which has provided a connection to the higher education of people needed to facilitate the automation of heavy equipment and the development of heavy construction equipment in Sweden.

The project has further contributed to the architecture sub-program of the FFI Electronics, software, and communication program (ESC). The project has focused primarily on the ***machine learning*** (ML) objective, regarding the automation of the individual steps of loading, navigating, and dumping material with a load carrier on a load receiver, regarding the use of computer vision based on ML for these steps and for the wider use in automating heavy construction equipment like load carriers.

Moreover, the project has indirectly addressed the ***computational power*** objective as well as the ***internal communication*** objective in that the project results provide valuable input to further work on these objectives. The project has also contributed to the ***intelligent and reliable systems*** sub-program of FFI ESC, focusing on the ***complex vehicle functions and system of systems*** objectives. This is regarding the research and development of complex on-board control functions based on ML and thus logged usage, vehicle, and environmental data, with optimization in real-time through off-board reinforcement learning.

7 Dissemination and publications

7.1 Dissemination of knowledge and results

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	The project results will be used by Volvo CE to strengthen capabilities to develop and test new functions based on machine learning (ML) and camera vision. Knowledge of difficulties in using reinforced learning will be taken into account.
Be passed on to other advanced technological development projects	X	The project results have been presented internally to Volvo CE and/or AB Volvo for possible use in other projects related to advanced functions in present product lines as well as for future products.
Be passed on to product development projects	(X)	The project results will not be passed on directly to product development projects, but rather to continued research activities.
Introduced to the market		The project results will not be directly used to introduce new products or new product features to the market.
Used in investigations, regulations, permit matters/political decisions	(X)	The project results may be used to influence rules and regulations on the use of semi-autonomous and/or fully autonomous heavy equipment.

7.2 Publications

One journal paper [2], one peer-reviewed conference paper [3], and one paper published on arXiv [4] have been produced in the project. In addition, the project has resulted in one doctoral thesis [1].

8 Conclusions and continued research

The project has investigated the use of neural network models and machine learning (ML) to automate the short-loading cycle, aiming at demonstrating the entire control and navigation path of this cycle. The work was done using a simulation environment in which models of wheel-loaders were developed. The approach selected for the project was to use frame-based camera vision as the main sensory input for capturing environmental aspects and properties. This approach proved to be very difficult to make work for the navigation and driving from a pile of material to a load receiver, or the other way around. The simulation-based experiments indicated that it is very difficult to configure an ML agent for it to successfully perform such a task, and no working solution could be identified. Therefore, the problem was divided into two main parts; (1) the use of camera vision to position the load carrier relative to a load receiver, and (2) the use of reinforced learning to perform the control and navigation task based on position information. This allowed us to focus on performing the control and navigation task based on position information provided by a differential GPS deployed on a Volvo CE wheel-loader for this project.

The simulation-based experiments assuming such GPS data showed that although the neural network is relaxed from performing positioning based on camera vision, the control and navigation tasks are still difficult to make work and that the training requires a very large number of time steps. The results indicate that training the agent in simulation is desired as the agent obtains the maximum reward after timesteps in the order of millions before being capable of performing the task. These results were verified by deploying the agent for the navigation of a Volvo L180H wheel-loader equipped with differential GPS and prepared for control by the agent. This suggests that the trained agent can bridge the gap between simulation and reality to complete a simplified version of the navigation task during the short-loading cycle. The experiments provide proof of concept that indicates deep learning techniques can aid in the realization of an autonomous solution. Moreover, the results show that development paths allowing for experiments providing large numbers of timesteps can facilitate the practical use of such techniques.

The recommended continued research includes exploring the strategy of (a) using rule-based control and sensor fusion to increase the abstraction level as much as possible for the ML agents used for the automation of the entire short-loading cycle, and (b) using such agents for tasks that cannot involve some type of uncertainty and therefore cannot be properly modeled and solved using rule-based approaches. The material to be scooped is known to be hard to accurately model due to unknown composition and humidity, and the tire-to-surface interactions that can cause the machine to slide sideways when turning are examples of such uncertainties. Finally, although reinforced learning brings great promises for the automation of the short-loading cycle such as that no manual operator is needed to collect training data, and continued adaptation to new conditions like changes in the environment, the difficulties in developing working solutions lead to that (c) imitation and supervised learning should be selected as the main approach. The results of this project suggest that reinforced learning should be used primarily to further improve working ML-based solutions based on these approaches.

9 Participating parties and contact persons

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

VOLVO Construction Equipment

LULEÅ UNIVERSITY OF TECHNOLOGY

ÖREBRO UNIVERSITY

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