System Arkitekture for Learning Machines (SALM)

Public report

Project within Electronics, software and communication – FFI | Vinnova

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Content

1. Summary

The purpose of the project was to make it easier to develop and test control engineering solutions based on machine learning used for manually or tele-remote operated, semi-automatic and fully automatic work machines. Wheel loaders and excavators with different geometries and capacities are addressed in this goal. In order to handle such a wide range of machines the project has worked on applying machine learning for automated loading.

Machine learning are likely to play an important role in the development of semi-automatic and fully autonomous working machines. Also, tele-remote control is likely to prove essential in automating the operation of such machines for them to perform tasks that cannot be handled autonomously and to give input to learning algorithms that are designed to imitate advanced tasks from human input. Hence, learning algorithms, sensor systems and human-machine interaction (HMI) for tele-remote control and the interaction with autonomous machines should be jointly addressed.

The development and testing of tele-remote and automated control solutions for working machines is today hindered by available implementations of on-board systems supporting such work which are not well suited for field trials. The project aimed at (1) developing the embedded system for on-board sensors and actuation, (2) investigating communication technologies for tele-operation and autonomy, and (3) developing off-board solutions for tele-remote control and site management.

The project has addressed the above-mentioned purpose by developing, demonstrating and evaluating tele-remote short-cycle loading with a Volvo L180H wheel-loader (i.e. a general-purpose machine with the capacity of lifting 18 tons in the bucket) as well as the automated loading with the same machine. The evaluation of short-cycle loading has revealed differences in efficiency between tele-remote and on-board operation, indicating needs for automation and further developed HMI for remote drivers, which the project has helped develop for the off-board control station used for tele-remote operation. The project has also evaluated wireless communication solutions (i.e. Wifi), which has contributed to Volvo's ongoing effort to establish a test site in Eskilstuna for the use of 5G for tele-remote control and monitoring of construction equipment.

The demonstrated solutions for automated loading are based on imitation and reinforced (feedback) machine learning. The demonstrations have shown that a neural network can be trained to imitate an expert loading of material, and that this network can be automatically adapted to other materials. The adjustment has been made by having the machine automatically load the new material and update the neural network based on the load results. This adjustment can be made in a relatively short time, during one hour of automated loading, as has also been demonstrated with full-scale experiments. The demonstrated solutions for automatic loading can be regarded as a world leader in the

field of machine learning-based automatic loading with wheel loaders designed for wider applications.

The project has contributed to make it easier to develop and test control-engineering solutions based on machine learning for the automation of work machines. The contribution made lays mainly in the improved knowledge and methodology for how to perform such development and testing on a full-scale wheel-loader. The platform used is still experimental (i.e. Matlab and Speedgoat) but complemented with Python scripts, e.g. for the data management needed for applying machine learning on targeted automations.

Finally, the project has pre-studied object identification based on machine learning applied to the task of identifying load carriers for dumping material on with wheel loaders. This work together with above-mentioned results have been used as the base for a new application to Electronics, software and communication – FFI | Vinnova for continued research and development on the automation of work machines with support of machine learning methods.

2. Sammanfattning på svenska

Projektet har syftat till att utveckla och demonstrera lösningar som gör det lättare att utveckla och testa reglertekniska lösningar för tele-fjärrstyrda, semiautonoma och helt autonoma arbetsmaskiner. Det omfattar hjullastare och grävmaskiner med olika geometrier och kapaciteter. För att hantera ett sådant brett spektrum av maskiner som därtill var för sig ska klara av olika typer av lastning har projektet arbetat med att tillämpa maskinlärning för automatiserad lastning.

Projektet har framgångsrikt demonstrerat lösningar för automatiserad lastning som bygger på imiterande respektive förstärkt (återkopplad) maskinlärning. Demonstrationerna har visat att ett neuronnät kan tränas till att imitera en expertoperator för lastning av material, och att detta nät kan automatiskt anpassas till andra material. Anpassningen har gjorts genom att låta maskinen automatlasta det nya materialet och uppdatera neuronnätet baserat på lastresultaten. Denna anpassning kan göras på relativt kort tid, under en timmes automatiserad lastning, vilket också visats med fullskaliga experiment.

Projektet har även utvärderat trådlösa kommunikationslösningar vilket bidragit till Volvos pågående satsning på att etablera en testplats i Eskilstuna för användning av 5G till fjärrstyrning och övervakning av entreprenadmaskiner. Därtill har projektet bidragit till att vidareutveckla användargränssnitt för kontrollstationer som används vid fjärrstyrning. SALM har också bidragit till att göra det enklare att utveckla och testa styrtekniska lösningar baserade på maskininlärning för automatisering av arbetsmaskiner. Bidraget ligger främst i den förbättrade kunskapen och metodiken för hur man utför en sådan utveckling och testning på en fullskalig hjullastare. Den använda plattformen är fortfarande experimentell (dvs. Matlab och Speedgoat) men kompletterad med Pythonskript, t.ex. för datahantering som behövs för att tillämpa maskininlärning för att automatisera arbetsmaskiner.

SALM har producerat följande resultat:

- Tre journalartiklar [2], [3] och [4] och en konferensartikel [1]. Därtill har projektet producerat en doktorsavhandling [5] och ett examenarbete för civilingenjörsexamen [6].
- Ett sensorsystem, programvara och kommunikationsarkitektur för utveckling och testning av funktioner baserade på lärande algoritmer och/eller artificiell intelligens som används för halvautomatiska och helautomatiska arbetsmaskiner. Denna leverans stöder emellertid inte kommersialisering av resultaten som ursprungligen avsett. I efterhand var ett sådant mål alldeles för ambitiöst för att vara realistiskt inom projektets tidsram och med resurserna tillgängliga inom projektbudgeten.
- Ökad kunskap om hur man använder maskininlärning för att automatisera svåra uppgifter som utförs med arbetsmaskiner. Lastning av heterogent material har användas som det främsta exemplet på sådana uppgifter. Projektet har visat på hur sådan lastning kan göras med hjälp av maskininlärning.
- Projektet har bidragit tillsammans med andra relaterade aktiviteter på Volvo CE till ökad kunskap om hur människa-maskin interaktion bör utformas för säker och effektiv tele-fjärrkontroll och för interaktion med semi-autonoma funktioner.
- Demonstrationer inför olika grupperingar och individer på Volvo CE. Dessa demonstrationer har visat kortcykelbelastning via tele-fjärrstyrning, två automatiska laddningsfunktioner (dvs en baserad på imiteringsinlärning och en annan baserad på förstärkt inlärning) samt systemet ombord på en hjullastare som möjliggjort dessa demonstrationer (dvs. design och kod granskning, samt uppstarten och användningen av systemet).

Utöver det har projektet genomfört in inledande studie av objektidentifiering baserat på maskininlärning för identifiering av lastbärare på vilka material ska dumpas med hjullastare. Detta arbete tillsammans med ovan nämnda resultat har använts som bas för en ny applikation för elektronik, programvara och kommunikation - FFI | Vinnova för fortsatt forskning och utveckling om automatisering av arbetsmaskiner med stöd av maskininlärningsmetoder.

3. Background

Learning algorithms (a.k.a. machine learning) are likely to play an important role in the development of semi-automatic and fully autonomous working machines. Also, tele-remote control is likely to prove essential in automating the operation of such machines for them to perform tasks that cannot be handled autonomously. Learning algorithms that are designed to imitate advanced tasks from sensor information alone also need human input to properly replicate well-performed operations. Such input can be provided by on-board drivers or by tele-remote operators that use video and sensor feedback to train the algorithm with remote actuations.

An advantage in using tele-remote operators is that they can handle several machines and give input only when needed. Hence, learning algorithms, sensor systems and human-machine interaction (HMI) for tele-remote control and interaction with autonomous machines should be jointly addressed. The tele-remote operation and automation of working machines is discussed in *[20*].

The development and testing of tele-remote and automated control solutions for working machines is today hindered by available implementations of control systems and methodologies supporting such work which are well suited for experimentation but not for field trials. For example, the experiments and demonstrations targeted in a previous project named WROOMM (Wireless remote operation of mobile machines) *[13*] are performed using Matlab and Speedgoat, which is not directly suitable for field. Hence, a problem as identified for this project was the absence of methodology and platforms that are mature enough to facilitate the introduction in products of more intelligent and advanced control functions based on learning algorithms.

The challenge in automating working machines increases with the difficulty and required skills to perform the same tasks at on-board and manual operation. Experienced and skilled drivers typically use many of their senses to perform such tasks efficiently in terms of performance, energy consumption and without causing unnecessary wear and tear on the machine. The senses involved include visual and sound as well as balance to detect tilt and acceleration. Vibration is another type of feedback commonly used by the experienced driver. The experienced driver uses these inputs for efficiently control of the machine in a way known difficult to reproduce using traditional automatic control approaches *[7*].

The loading of heterogeneous material such as ore and blasted rock in quarries and mines clearly require highly skilled driver that can use the senses to perform well in such a task. Other examples include tasks in road construction where accurate ground preparation is needed to achieve high performance while limiting energy consumption. This motivates alternative approaches for how to automate certain tasks performed by working machines in general and especially wheel loaders and excavators since such machines commonly are used to perform tasks difficult to automate. In particular, methods based on learning algorithms are considered promising to facilitate the autonomous functions needed for efficient automation of such machines *[8*]. Similar methods based on fuzzy logic have also been tried before to address difficulties in different loading exercises *[9*]*[10*]*[11*]*[12*]. The state-of-art relevant at the start of this project was surveyed in *[7*].

4. Purpose, research questions and method

The purpose of the project was to make it easier to develop and test control engineering solutions based on machine learning used for manually or tele-remote operated, semi-automatic and fully automatic working machines. This involves (1) developing the embedded system for on-board sensors and actuation, (2) investigating communication technologies for tele-operation and autonomy, and (3) developing off-board solutions for tele-remote control and site management. Through these activities, maturing the solutions were assumed to take shorter time and be at lower risk for unexpected behaviours. Also, these activities aimed at contributing to develop the needed knowledge and supporting electric, software and communication functionality in working machines to reach the long-term goal of having completely autonomous working machines at industrial sites and on roads.

An example of the development of embedded system for on-board sensors and actuation is the sensor fusion for calculating proper feedback to learning algorithms. Such feedback can consist of lift and tilt angles, tube pressures translated into forces and accurate first and second order speed combined into trigger signals for learning algorithms to imitate the behaviour of skilled operators when they combine different senses to determine when and how to actuate the machine.

The designed sensor and software system was be used to develop automatic scooping of various materials including gravel, blasted rock and ore of heterogeneous size distributions, which is known to be challenging both to load manually with on-board drivers. The targeted solutions for improved scooping performance can be used as driver support for operators working on board the machine, for remote controlled and semi-autonomous machines, and ultimately for completely autonomous machines.

The intended users of the system include development teams at Volvo CE and possibly partners to Volvo that develops or adapts automation solutions for specific use cases. Moreover, users of project results are companies in Sweden and worldwide that benefit from operating working machines on tele-remote and autonomously in combination. In general, tele-remote and semi-autonomous working machines are likely to prove important in the automation of road constructions and maintenance, civil engineering projects and industries.

The project has considered wheel loaders and excavators that are offered at the market today as well as next generation hybrid and electrical machines with different geometry and capacities. The scope included a further developed sensor and software system that can be used to automate functions and operations carried out with machines that today requires an expert driver and is difficult to automate with traditional control engineering approaches, e.g. the loading and excavation of gravel as well as heterogeneous materials, such as blasted rock and ore. The scope also included communication technologies for tele-operation and autonomy, as well as further developed off-board solution for tele-remote control and site management.

Use cases addressed included short-cycle loading with wheel loaders, including specific tasks such as loading gravel, blasted rock and ore in mining or quarries as well as general performance-enhancing driver assistance functions. The solutions targets both operators working on board the machine and operator to remotely control one or more machines. The approach of the project was to address such specific and challenging use cases to elevate the technology maturity levels related to the automation of general purpose and versatile wheel loaders and possible also excavators for other applications on roads and in other use cases.

Learning algorithms generally needs functions based on sensor fusion (interpretation of multiple inputs), feedback to learning algorithms (combination of sensor measurements data and human feedback), and monitoring for safe use of the solutions (related to watchdog functionality). The design of the system for the development, testing and commercialization of loading algorithms have been based on such basic and reusable supporting functions.

The research issues that the project initially intended to address where the following:

- How to implement the basic working framework for machine learning based loading functions?
- How to make such functions based on supervised learning or imitation learning more adaptive using ideas from reinforcement learning like rewards functions?
- How to guarantee safe operation with a combination of remote operation and machine learning based local autonomous function?
- How to efficiently use communication technologies such as WLAN and 4/5G for tele-operation, autonomy and site management?

In contrast, the refined and added research questions that have been addressed and answered by a doctoral thesis finished in the project are the following [5]:

- What are the major difficulties in tele-operation of mobile earth moving machines and how to overcome them?
- Which combination of techniques are suitable to automate the bucket-filling task of a wheel-loader?
- How to develop an efficient data-driven automatic bucket-filling algorithm?
- How to adapt and improve the performance of the automatic bucket-filling function when operating conditions change?

In addition, the following research questions have been addressed and possible approaches have been partly validated by a master thesis finished in the project [6]:

- How can existing deep learning models be leveraged to perform object detection and classification from real time videos with the aim of autonomous earth-moving machines?

- How much training data is needed to reach good performance when using transfer learning?
- What type of environmental variation can make object detection and classification difficult for the deep learning model?
- How reliable is a deep learning model trained using transfer learning for the task of real time object detection?
- Can such a deep learning model be created using SoA principles?

The results of the master thesis are used for an application to Electronics, software and communication – FFI | Vinnova for a next step project aiming at developing further support for automated work machines.

5. Objective

The project aimed at developing a system and solutions for working machines that enables the development and testing of control engineering solutions based on learning algorithms (a.k.a. machine learning). It has focuseed on promoting cooperation between the industry (i.e. Volvo AB), universities and higher education institutions (i.e. Luleå University of Technology including the established international network that the university has in the area of machine learning). The collaboration between Volvo and LTU further aimed at contributing to the FFI objectives by increasing the Swedish capacity for research and innovation by that challenges that can be approached using machine learning become better known by Swedish academia and thus can be addressed in undergrad and graduate educations. The project have been staffed by a Ph.D. student that was already working in the specific field of research as part of the previous WROOMM project.

SALM further aimed at contributing to the specific sub-programme by further developing the sensor systems, software and communication solutions for Volvo CE's product lines to better support solutions that involve tele-remote operations and machine learning to solve challenging automation problems. Machine learning can be seen as a technology shift from traditional control only to solutions that adapts over time for better performance. By this, the project aimed at contributing to build needed knowledge within the Swedish vehicle industry in this area.

The approach of using machine learning for assisted and automated loading can result in innovative value-add services offered with working machines. Such services have the potential of providing an important competitive edge for Volvo and thus contribute to the sub-program objective related to breakthrough results.

The most relevant research field for this project proposal was the "Electrical architecture for embedded and connected systems". The project related to a general aim of having a coherent architecture for systems development allowing improved vehicle features and shortened development time. SALM further related to the potential from the increasing computational power on-board and communication possibilities external to the vehicle that facilitates the advanced computations that are needed to apply machine learning.

Within SALM, the industrial partner aimed at investigating suitable communication technologies, including protocols for communication with remote controlled and/or autonomous vehicles. Understanding the trade-off between for instance bandwidth and radio coverage is essential, including the need for redundancy of systems. Furthermore HMI development was targeted to simplify remote control, and potentially also research how operators of manual machines can interact with autonomous ditto. Development of complete site management systems, with governance of autonomous and remote controlled vehicles, were also to be carried out to make possible demonstrations of end-to-end data transfer and machine usage in relevant applications.

The measurable objectives initially defined for the project were the following:

- Software changes in ECUs and CAN communication with on-board computer for tele-remote and semi-autonomous function based on machine learning have been tested in a complete working machine (i.e. wheel loader and/or excavator)
- On-board safety functions related to communication for tele-remote operation and semi-autonomous functions have been tested in a complete working machine (i.e. wheel loader and/or excavator)
- Off-board HMI for tele-remote control and for interaction with semi-autonomous functions have been tested in a complete working machine (i.e. wheel loader and/or excavator)

The second objective was changed to focus more on the performance of an automated loading function based on machine learning rather than testing specifically safety functions as originally was stated. This objective was thus rephrased to the following:

- On-board loading functions connected with communication for tele-remote operation and semi-autonomous functions have been tested in a complete working machine (i.e. wheel loader and/or excavator)
    - Where the tests were done with a full scale and complete wheel loader only
    - Safety function were indirectly considered in how the automated loading function need to be initiated and stopped to meet requirements on safety

The reason for why the objective was changed is that the automated loading function was deemed considerably more important from the perspective of making progress towards the long-term goal of fully autonomous work machines. In addition, initial results in the early phases of the project shown a clear potation in developing the machine learning based scooping algorithms. These algorithms were successfully demonstrated in the project, which shown that revising the second objective in this direction was a good decision.

6. Results and deliverables

The system that was targeted by the project consider wheel loaders and excavators that are offered at the market today as well as next generation hybrid and electrical machines with different geometry and capacities. The goal was to research and develop methods and supporting functions that can be used to automate functions and operations carried out with machines that today requires an expert driver and is difficult to automate with traditional control engineering approaches, e.g. the loading and excavation of heterogeneous materials, such as blasted rock and ore.

Use cases that were addressed included short-cycle loading with wheel loaders, including specific tasks such as loading gravel, ore and blasted rock in mining or quarrying as well as general performance-enhancing driver assistance functions. Use cases also considered included challenging loading of heterogeneous material with excavators. The solutions will be targeted at both operators working on board the machine and operator to remotely controlling one or more machines.

Learning algorithms in testing and production generally needs functions based on sensor fusion (interpretation of multiple inputs), feedback to learning algorithms (combination of sensor measurements data and human feedback), and monitoring for safe use of the solutions (related to watchdog functionality). The design of the system for the development, testing and commercialization of loading algorithms aimed at being based on such basic functions.

Deliveries:

1. The development of sensor systems, software and communication architecture for the development, testing and commercialization of functions based on learning algorithms and/or artificial intelligence used for semi-automatic and fully automatic working machines. This involves ECUs, CAN bus, sensors, additional on-board computer used for tele-remote control and automated functions based on machine learning, components for wireless communications and off-board HMI systems for the tele-remote control and site management.
2. The increased knowledge on how to use machine learning to automate difficult tasks performed with working machines. The loading of heterogeneous material will be used as the prime example of such tasks.
3. The increased knowledge on how to use off-board HMI for tele-remote control and for interaction with semi-autonomous functions. This involves the operation of the working machines in performing specific tasks as the short-cycle loading as well as for general site management.
4. One Ph.D. thesis on the methods, reusable supporting functions and their application on automated loading based on machine learning.
5. Demonstrations of automated loading based on machine learning using a full size wheel loader and/or excavator. This will involve the complete short-cycle loading sequence where material is loaded, moved and dumped on a truck or dumper.

Outcome:

1. The project has successfully delivered sensor systems, software and communication architecture for the development and testing of functions based on learning algorithms and/or artificial intelligence used for semi-automatic and fully automatic working machines. This delivery does not however support commercialization of the results as originally intended. In retrospect, such goal was far too ambitious to be realistic in the timeframe of the project and with the resources made available within the project budget.
2. The second deliverable is successfully completed in all its parts and has contributed to improved capacities and knowledge for Volvo CE as well as Luleå University of Technology. This knowledge is captured in a PhD. thesis [5] and in a M.Sc. thesis [6] completed in the project.
3. The project has contributed together with other related activities at Volvo CE on HMI for tele-remote control and for interaction with semi-autonomous functions.
4. One Ph.D. thesis on the methods, reusable supporting functions and their application on automated loading based on machine learning was completed and successfully defended in January 2019 [5].
5. Several demonstrations has been done throughout the project, which have been seen by people at Volvo CE interested in the results. These demonstrations has shown short-cycle loading at tele-remote, the two automatic loading functions (i.e. one based on imitation learning and another based on reinforced learning) as well as the on-board system that facilitated these demonstrations (i.e. from design and code review to the practical start-up and use of the system).

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	This constitutes maybe the most important contributions made by the project, i.e. the increased knowledge on machine learning and how it can be used for the automation of work machines.
Be passed on to other advanced technological development projects	X	Results are used for other related activities within Volvos CE on HMI. Also, an applications for a next step project is submitted to Vinnova FFI EMK.
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

Three journal papers *[2*], *[3*] and *[4*] and one peer-reviewed conference paper *[1*] have been produced in the project. In addition, the project has resulted in one doctoral thesis *[5*] and one master thesis *[6*].

8. Conclusions and future research

The project has developed, demonstrated and evaluated tele-remote short-cycle loading with a Volvo L180H wheel-loader as well as the automated loading with the same machine. The evaluation of short-cycle loading has revealed differences in efficiency between tele-remote and on-board operation, indicating needs for automation and further developed HMI for remote drivers. The project has also evaluated Wifi for the tele-remote operations of wheel-loaders and by this revealed shortcomings with the examined wireless communication technique as well as means to alleviate problems that comes with varying communication capacities over wireless networks.

The demonstrated solutions for automated loading are based on imitation and reinforced (feedback) machine learning. The demonstrations have shown that a neural network can be trained to imitate an expert loading of material, and that this network can be automatically adapted to other materials.

The project has contributed to make it easier to develop and test control-engineering solutions based on machine learning for the automation of work machines. The contribution made lays mainly in the improved knowledge and methodology for how to perform such development and testing on a full-scale wheel-loader.

Finally, the project has pre-studied object identification based on machine learning applied to the task of identifying load carriers for dumping material on with wheel loaders. This work together with above-mentioned results have been used as the base for a new application to Vinnova FFI EMK for continued research and development on the automation of work machines with support of machine learning methods.

With the loading solutions demonstrated by the project, the trained neural network is initiated after the bucket is engaged with the gravel pile and sensors register a pre-defined pressure increase on the lift hydraulics. While this function successfully has demonstrated the capacity of machine learning for automated digging, the pre-defined initiation algorithm prevents the function from enhancing the efficiency of the complete digging process starting from when the machine is approaching the pile.

The new project applied for aims to model also the 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, and by that improve the automated digging function for it to enhance the efficiency of the loading process. Furthermore, to enhance the efficiency of the complete loading and unloading process, an automated dumping function is desired.

For an automated dumping 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 in combination with RADAR, LIDAR, GPS, IMUs etc. Moreover, information is required on what type of loading truck that is approached, i.e. identifying various trucks, haulers and HXs of different sizes. The project aims at develop automated functions for identifying and approaching loading trucks as well as dumping material on such load receivers. The approach identified for this part is based on the pre-study on object identification with transfer learning done in the project.

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

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