iQDeep: Machine Learning for Autonomous Driving

Public report

Project within Autonomous Driving
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Content

1. Summary

During the past decade, machine learning (ML), particularly the utilization of deep neural networks (DNNs), has demonstrated its substantial potency across various fields, driving significant advancements in many areas of technology. This has proven especially true in domains where conventional rule-based solutions fall short. One prominent application is autonomous driving, although integrating ML into safety-critical functions like self-driving vehicles presents significant challenges. Scania, in particular, faces several technical hurdles in employing ML for autonomous driving:

1. Balancing Strengths: One challenge is how to effectively blend the performance benefits of ML-based functions with the reliability and consistency of rule-based functions.

2. Data Challenges: Overcoming issues related to data, encompassing everything from data acquisition and preprocessing to addressing legal concerns like GDPR.

3. Black Box Nature: Dealing with the output predictions from DNNs, which have a black box nature, and integrating them effectively into the driving system.

4. Vehicle-Specific Considerations: Addressing the lack of attention in existing literature towards sensor placements and scenarios specific to heavy vehicles.

The advent of autonomous driving is poised to disrupt the transportation and mobility sector significantly. Scania recognizes that how they manage this disruption could dictate their success or failure. With this in mind, Scania launched iQDeep with three primary objectives:

1. Enhancing Self-Driving Pipeline: Develop ML-driven environment perception algorithms based on cutting-edge research and integrate them into the existing modular self-driving pipeline at Scania. This not only improves

the pipeline's performance but also facilitates continuous development of methods, tools, partnerships, and hardware platforms for ML algorithms.

2. Functional Performance Boost: Research and implement advanced methods using ML to enhance the functional performance of the autonomous driving pipeline while maintaining safety through the utilization of information derived from rule-based functions.

3. Quality Enhancement: Innovate techniques to enhance the quality information provided by neural network prediction outputs.

The lead for this 4-year project was Scania CV AB, collaborating with two research units at Linköping University (LiU), namely Division Computer Vision Laboratory (avdelning för datorseende) abbreviated as CVL, and Division for Automatic Control (avdelning för reglerteknik) abbreviated as RT.

The project, which began in Q1 2019, was allocated a total budget of 42.7 MSEK, with a funding of 12.8 MSEK (30%) from FFI. The project was initially expected to terminate at the end of 2022, but due to Covid19 outbreak and other unforeseen issues, the project was extended for seven months and officially terminated on July 31, 2023.

2. Sammanfattning på svenska

Under det senaste decenniet har maskininlärning (ML), särskilt användningen av djupa neurala nätverk (DNN), visat på stora potentialer och drivit betydande framsteg inom många och olika teknikområden. Detta gäller i synnerhet funktionaliteter/områden där konventionella regelbaserade lösningar kommer till korta. Autonom körning är välkänd exempel på ett sådant område. Dock finns ett flertal tekniska utmaningar med att introducera ML i säkerhetskritiska funktioner som självkörande fordon.

Scania, i synnerhet, står inför flera tekniska utmaningar så som:

1. Balansera av styrkor: En utmaning är hur man effektivt sammanför prestandafördelarna med ML-baserade funktioner med tillförlitligheten och repeterbarhet hos regelbaserade funktioner.
2. Utmaningar med data: Hantera problem kopplat till inlärningsdata, här inkluderas allt från datainsamling till preprocessing av data i syfte att exempelvis hantera rättsliga krav såsom GDPR.
3. Black Box karaktär: Hantera prediktioner från DNN, prediktioner som är av Black Box karaktär, och integrera dem effektivt i fordonsystemet.
4. Fordonsspecifika överväganden: Adressera bristen på arbeten och publikationer kopplat till sensorns placeringar och scenarier unika för tunga fordon.

Introduktionen av autonom körning förutspås få en stor påverkan på transport sektorn. För fordonstillverkare så som Scania CV AB, kommer hanteringen av introduktionen av autonom körning ha en stor påverkan på dess framtid. Med detta i åtanke så definierades tre huvudmål för iQDeep;

1. Förbättring av funktions pipelinen för autonoma körning: Utveckla ML-drivna perceptions algoritmer baserat på de senaste forskningsrönen och integrera dem i Scania CV AB befintliga modulära funktions pipelinen för autonom körning. Detta i syfte att förbättra systemets funktionalitet och kapacitet, tillika att underlättar kontinuerlig utveckling av metoder, verktyg, partnerskap och hårdvaruplattformar för ML-algoritmer.
2. Ökning av funktionell prestanda: Forska på och implementera avancerade metoder baserade på ML. Metoder som möjliggör ökad funktionell prestanda på autonom körnings systemet, samtidigt som säkerheten bibehålls genom att utnyttja information genererad från regel baserade funktioner.
3. Kvalitets förbättringar: Skapa tekniker för att förbättra kvalitets informationen som ges av de neurala nätverkets prediktioner.

Projektpartners för detta 4-åriga projekt var Scania CV AB samt två forskningsenheter vid Linköpings universitet (LiU), Avdelningen för datorseende (CVL) och Avdelningen för reglerteknik (RT). Scania CV AB vare den projektledande partner. Projektet, som började under första kvartalet 2019, hade en total budget på 42,7 MSEK, med finansiering på 12,8 MSEK (30%) från FFI. Projektet förväntades ursprungligen avslutas vid slutet av 2022, men på grund av Covid19-utbrottet och andra oförutsedda problem förlängdes projektet med sju månader och avslutades officiellt den 31 juli 2023.

3. Background

The advancement of machine learning (ML), particularly supervised learning and deep neural networks (DNNs), has sparked a significant evolution across various fields, such as natural language processing and computer vision. Deep learning (DL), characterized by DNNs with multiple layers, has emerged as a powerful tool. In the realm of automated driving, computer vision breakthroughs, including object detection, pixel-level segmentation, etc., have been instrumental. These developments underscore the crucial role of machine learning in autonomous driving, given the intricate nature of the task. However, this integration poses challenges both in the development and deployment stages, especially concerning safety considerations. Scania, like many industries, has faced a learning curve in this technical domain.

For Scania, the paradigm of autonomous driving marks a transformative imperative. Central to this transformation is machine learning, driving the need for Scania to master its development and incorporation into products.

Common functional pipelines and machine learning approaches in autonomous driving face many challenges. The pivotal obstacle lies in accurately perceiving and comprehending the vehicle's surroundings. This concern has prompted exploration into machine learning solutions.

Importantly, deep learning methods often remain opaque, lacking mechanisms to verify individual outputs despite their statistical performance across multiple samples. Current deep networks yield predictions without explicit uncertainty or reliability metrics, at least not at the same level of classical methods.

Notably, minimal focus exists on deep learning for heavy commercial vehicles in both academic research and commercial applications, as most efforts center around passenger cars. Heavy vehicles present distinct sensor perspectives and business-driven scenarios, necessitating specific development methods. The scarcity of commercial alternatives prompts in-house development and state-of-the-art efficient strategies.

This combination of challenges, advancements, and limited focus highlights the intricate interplay between machine learning and autonomous driving, with Scania navigating this complex landscape to shape its future endeavors.

4. Purpose, research questions and method

The main objective of the project is to advance the state-of-the-art in autonomous driving through the integration of machine learning, focusing on heavy commercial vehicles. This involves developing modular ML-based algorithms for environment perception, enhancing functional performance while maintaining safety, and addressing uncertainty quantification. The aim is to create adaptable, reliable, and transparent autonomous driving systems by leveraging the strengths of both rule-based and ML-based approaches, ultimately ensuring the safe, efficient, and context-aware navigation of heavy commercial vehicles. This project seeks to bridge the gap in research and commercial application for this domain, aligning Scania's technological evolution with the demands of a rapidly transforming transportation landscape.

To this end, the main research questions that we wanted to be answered by iQDeep are as follows:

1. **Balancing Modularity and Performance:**
    - How can the benefits of modularity in autonomous driving systems be effectively combined with the performance gains offered by machine learning approaches?
    - What strategies can be devised to adapt machine learning modules to new vehicle configurations or scenarios while minimizing development efforts?

2. **Ensuring Functional Safety:**

    - What methods can be employed to achieve functional safety while incorporating machine learning-based functions such as collision avoidance and path planning?
    - How can rule-based and machine learning-based functions be synergistically integrated to ensure reliability and safety in autonomous driving systems?

3. **Black Box Nature of Deep Learning:**

    - What techniques can be developed to enhance transparency and interpretability in deep learning-based systems, particularly when there are no known methods to validate individual output correctness?
    - How can the limitations posed by the black box nature of deep neural networks be overcome to ensure trust and reliability in the context of safety-critical applications?

4. **Adapting Machine Learning for Commercial Vehicles:**

    - In what ways can deep learning methodologies be tailored to the specific needs of heavy commercial vehicles, considering unique sensor field views and business-oriented autonomous driving scenarios?
    - How can existing research in passenger car-oriented deep learning be adapted and extended to address the challenges posed by commercial vehicles?

5. **Assessing Uncertainty and Trustworthiness:**

    - What novel approaches can be developed to determine whether a deep neural network's output is based on interpolation or extrapolation, and how can this uncertainty assessment be incorporated into the decision-making process?

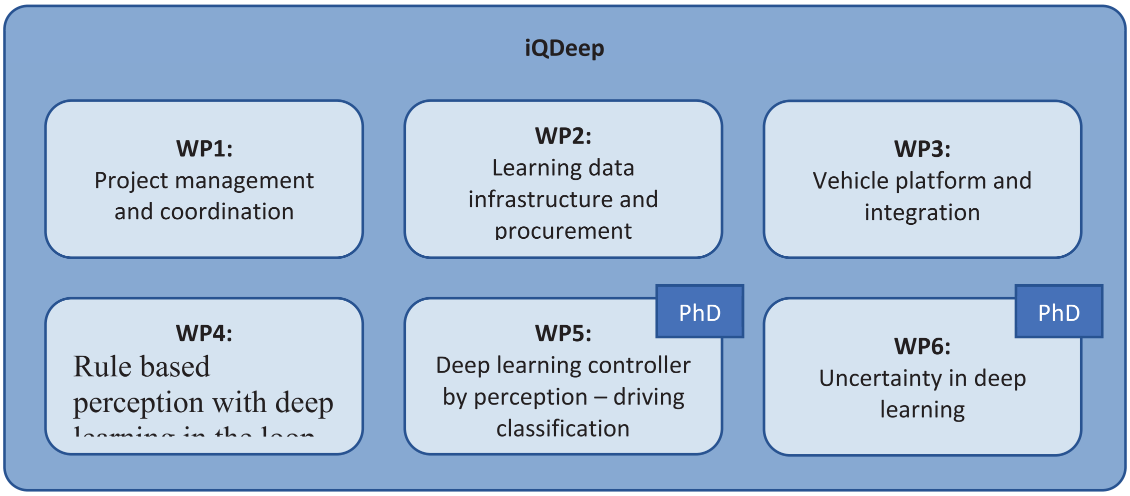
- How can techniques to quantify uncertainty in deep learning systems be advanced, especially in the context of safety-critical applications like autonomous driving?

These research questions encapsulate the challenges, innovations, and advancements discussed, offering avenues for further investigation and exploration within the field of machine learning and autonomous driving.

To be able to achieve the above-mentioned objectives and answer the above research questions, the project was partitioned into six Work Packages (WPs). The list of WPs with expected activities and outputs from each in the beginning of project was as follows:

- WP1; A final project report, in addition to a smooth running, efficient and successful project.
  - Leader: Scania
  - Other participants: N/A
- WP2; Infrastructure for procuring, storing and processing learning data as well as methods and tools to support the process. Furthermore datasets to be used for future work are expected as a result of this work package.
  - Leader: Scania
  - Other participants: N/A
- WP3; A hardware and software platform to support this project for data collection, development and evaluation.
  - Leader: Scania
  - Other participants: N/A
- WP4; An environment perception state estimate output to be used by the rule-based motion planner as well in the modular existing layer based autonomous driving pipeline at Scania.
  - Leader: Scania

    - Other participants: CVL
- WP5; Publications on the derived methods on a learning-based, dynamic two-stage process for selecting reference paths from visual input and the DL models that have been trained. An industrial PhD student was hired to carry out this research at CVL.
    - Leader: CVL
    - Other participants: Scania
- WP6: Publications on new theory and selected applications of how to assess uncertainty in DL in terms of accuracy and reliability. An academic PhD student was hired to carry out this research at RT.
    - Leader: RT
    - Other participants: Scania



5. Objective

The goals set for the project as stated in the submitted proposal were 3 fold:

1. Develop ML based environment perception algorithms based on state-of-the-art available research and integrate them into the current modular and layer based self-driving pipeline. By doing this we could both explicitly increase the performance and capacity of the existing

self- driving function pipeline as well as implicitly learn, develop and procure methods, infrastructure, tools, partnerships and hardware platforms for continuous work with ML based algorithms.

2. Research and develop state-of-the-art methods for increasing the functional performance of the autonomous driving (AD) functional pipeline by using ML methods and with maintained safety by utilizing also the information derived by rule-based functions.

3. Research and develop state-of-the-art methods for adding quality and uncertainty information to the prediction output from a neural network.

6. Results and deliverables

The project officially terminated on July 31st 2023. For Scania this project was a great success which built the infrastructure needed for Data-Driven Autonomous Driving at Scania and paved the way for integrating AI-based solutions to Scania's autonomous stack.

Below, we highlight activities, results and deliverables of each WP of the project mentioned in Section 4:

WP1: Project Management and Coordination

Project management and coordination were overseen by Scania, with Senior Development Engineer, Alireza Razavi, PhD, serving as the project manager.

Here is a compilation of tasks accomplished pertaining to Project Management and Coordination:

- Organizing semiannual steering committee meetings: Altogether we had 10 steering committee meeting to coordinate the activities in two sides, both scientific and financial parts. The first two meetings of this kind were physical, including one in Autumn 2019 held at Scania Autonomous Transport Department, which was extended as a workshop with invited speakers from KTH and Linköping University to promote the collaboration between academia and Scania in the field of Autonomous Driving.

- Submitting semiannual progress reports to Vinnova
- Preparing the collaboration agreement with Linköping University
- Monitoring and reporting the financial status of the project and coordinating between the controllers in two sides: LiU and Scania
- Presenting the progress and results of the project in FFI results conference in Gothenburg in September 2019, and Scania's Innovation days.

WP2: Learning Data Infrastructure and Procurement

Data preparation stands as an essential, and arguably the paramount, component of AI and any data-centric strategy (thus its name). Consequently, the initial internal undertakings within iQDeep were concentrated on this work package, encompassing the preparation of data. Several of these tasks include:

- Data annotation: Annotation is required for any supervised Machine Learning approach. We worked on the annotations specifications for our Semantic Segmentation and Object Detection networks and iterated them with the data annotation companies to make sure that the quality as well as the quantity of the annotations are in a level to enable safe and stable perception tasks.
- Data Selection tools: data annotation costs a lot as it is a labor-intensive task. Therefore, it is very important to select and send those data to the annotation companies which improve the performance of our networks. Under iQDeep, we developed and implemented a Data Selection Tool (DST) for the first time at Scania ATS department. DST helps us to find the data which is

most important and suitable for training of our networks and helps us to save a lot of money and energy.

- Cloud-based pipeline: To ease interaction with the third-party annotators and use the cloud utilities to automate our data pipeline, we implemented a cloud-based data storage and annotation pipeline.
- Anomaly Detection: In applications where safety is the highest priority, like Autonomous Driving, it is important to detect anomalies in the data. To this end one of the projects carried out in our group and integrated to DST was an Anomaly Detection algorithm.
- Uncertainty Measurement: To quantify the novelty in a new data taken, measuring the uncertainty in the new data point compared to existing data in database is a solution. Another method implemented in our DST is uncertainty measurement.

WP3: Vehicle Platform and Integration

Irrespective of the richness of the collected data and the perceptiveness of our trained networks, their commercial value remains unrealized unless integration and deployment into our vehicles can be achieved. To achieve this objective, we pursued the subsequent measures to ensure the eventual incorporation of our implemented models into the final product:

- Creating a deployment pipeline from trained neural networks to on-board vehicle deployment.
- GPU instalments in vehicle, with incremental updates to the hardware each year, enabling the possibility to test and use better GPU cards in vehicle.
- Development of a software application onboard our vehicles, acting as a neural network inference engine. The software enabled processing of several camera streams simuntainiously into DNNs, and in turn distributed the output to corresponding applications.

WP4: Rule-based Perception with Deep Learning in the Loop

This work package serves as the heart of AI-driven autonomous driving, focusing on harnessing Deep Learning algorithms for various tasks, particularly those involving perception, localization, and intention prediction. With this goal in mind, the following projects were undertaken throughout the duration of iQDeep:

- Semantic, Instance, and Panoptic Segmentation: to pixel-level classify the traffic environment and participants. This is one of the main building blocks for perception pipeline of Autonomous Driving as different types of objects need to be treated differently by the vehicle.
- Bounding Box Detection: The goal is to detect, classify, and estimate the bounding box around traffic participants such as vehicles, pedestrians, traffic signs, etc. This is also a vital part of the Deep Learning-based perception pipeline. The output of Bounding Box network is then used for Tracking other vehicles as well as pedestrians and other moving objects.
- Neural Network-Based Map Matching: Map Matching is the problem of estimating the current place of the ego-vehicle based on the perception of the surrounding environment.

WP5: Deep Learning Controller by Perception – Driving Classification

This work package was carried out in collaboration with Linköping Computer Vision Lab (CVL). An Industrial PhD student, Oliver Stromann, was hired by Scania to work on this WP, under academic supervision at CVL. Oliver started in February 2019. He successfully defended his Licentiate titled “Data-Driven Classification in Road Networks” in April 2022.

Below is a list of outcomes of the work Oliver carried out:

- **Publications**

- Visual Feature Encoding for GNNs on Road Networks
  O Stromann, A Razavi, M Felsberg (2022)
  arXiv preprint arXiv:2203.01187
- Learning to integrate vision data into road network data
  O Stromann, A Razavi, M Felsberg (2022)
  IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 4548-4552
- Graph representation learning for road type classification
  Z Gharaee, S Kowshik, O Stromann, M Felsberg (2021)
  Pattern Recognition 120, 108174
- A Bayesian Approach to Reinforcement Learning of Vision-Based Vehicular Control
  Z Gharaee, K Holmquist, L He, M Felsberg (2020)
  25th International Conference on Pattern Recognition (ICPR), 3947-3954

- **Licentiate thesis**: Defended VT 2022
  - Data-Driven Classification in Road Networks

- **Courses**: Oliver passed 57.5 credits:
  - Reading Group in Computer and Robot Vision, VT 2019, 1,0 hp
  - GPU Programming, VT 2019, 3,0 hp
  - Reading Group in Computer and Robot Vision, HT 2019, 2,0 hp
  - Research Ethics, HT 2019, 2,0 hp
  - Neural Networks and Deep Learning, HT 2019, 6,0 hp
  - Hardware for Machine Learning, VT 2020, 6,0 hp
  - Reading Group in Computer and Robot Vision, VT 2020, 1,0 hp
  - Methodology of Science and Technology, VT 2020, 4,0 hp
  - Autonomous Vehicles - Planning, Control, and Learning Systems, VT 2020, 6,0 hp

    - Reading Group in Computer and Robot Vision, VT 2021, 1,0 hp
    - WASP AS-Software Engineering and Cloud Computing, VT 2021, 6,0 hp
    - WASP Summer School 2021: Hybrid Racing - Using Virtual Engineering for Real Miniature
    - Cars, HT 2021, 1,5 hp
    - WASP Project Course, VT 2022, 6,0 hp
- **Master thesis supervision**: Oliver supervised the following Master students.
    - Rickard Eriksson, VT 2021
    - Eric Ekström, VT 2022
    - Marcus Nolkrantz, VT 2022

Oliver decided to leave the project in August 2022 to explore other opportunities.

WP6: Uncertainty in Deep Learning

This work package was carried out in collaboration with Linköping Automatic Control (RT). An academic PhD student, Magnus Malmström, was hired to work on this WP. Magnus started his PhD studies in Autumn 2018. He successfully defended his Licentiate titled "Uncertainties in Neural Networks – A System Identification Approach" in March 2021. He will defend his PhD thesis, provisionally titled "Approximative Uncertainty in Neural Network Predictions" in Autumn 2023 with the provisional date November 17, 2023. The opponent will be Kalle Åström (Lund University) and grading committee are Håkan Hjalmarsson (KTH), Maarten Schoukens (TU/e, Netherlands), and Hossein Azizpour (KTH).

Below is a list of outcomes of the work Magnus carried out at this position:

- **Publications**
  - 5G Positioning - A Machine Learning Approach, Magnus Malmström, Isaac Skog, Sara Modarres Razavi, Yuxin Zhao, and Fredrik Gunnarsson (2019), In Proc. of IEEE 16th Workshop on Positioning Navigation Communication, (WPNC), Bremen, Germany
  - Asymptotic Prediction Error Variance for Feedforward Neural Networks. Magnus Malmström, Isaac Skog, Daniel Axehill, and Fredrik Gustafsson (2020), In Proc. of 21st IFAC World Congress, (IFAC), Online (Berlin, Germany)
  - Modeling of the tire-road friction using neural networks including quantification of the prediction uncertainty, Magnus Malmström, Isaac Skog, Daniel Axehill, and Fredrik Gustafsson (2021), In Proc. of IEEE 24th Int. Conf. on Inf. Fusion (FUSION)
  - Detection of outliers in classification by using quantified uncertainty in neural networks, Magnus Malmström, Isaac Skog, Daniel Axehill, and Fredrik Gustafsson (2022), In Proc. of IEEE 25th Int. Conf. on Inf. Fusion (FUSION)
  - On the validity of using the delta method for calculating the uncertainty of the predictions from an overparameterized model, Magnus Malmström, Isaac Skog, Daniel Axehill, and Fredrik Gustafsson (2023), In Proc. of 22nd IFAC World Congress, (IFAC), Yokohama, Japan
  - Uncertainty quantification in neural network classifiers–a local linear approach, Magnus Malmström, Isaac Skog, Daniel Axehill, and Fredrik Gustafsson (2023), arXiv preprint arXiv:2303.07114, submitted for possible publication in Automatica
  - Fusion of predictions from neural networks – multimodal ensemble laplacian approximation and classification of a sequence of images, Magnus Malmström, Isaac Skog, Daniel Axehill, and Fredrik Gustafsson (2023), Ongoing work

- Extended target tracking utilizing machine learning software, with application to animal classification, Magnus Malmström, Anton Kullberg, Isaac Skog, Daniel Axehill, and Fredrik Gustafsson, submitted for possible publication in IEEE Signal Processing Letters.
- Uncertainties in Neural Networks – A System Identification Approach, Magnus Malmström, Licentiatavhandling, Linköpings universitet, Institutionen för systemteknik, Reglerteknik (2021)

- **Courses:**
    - Reinforcement Learning - 6FISY09 3.0 ect HT 2022
    - Nonlinear Control Systems 9.0 ect HT 2021
    - Sequential Monte Carlo Methods - 6FIDA13 6.0 ect HT 2021
    - System Identification 12.0 ect HT 2020
    - Neural Networks and Deep Learning - 6FIDA02 6.0 ect HT 2019
    - Applied Statistical Methods, Part I - MAI0137 5.0 ect Ht 2019
    - Machine Learning Reading Group: From Attention to Normalizing Flows 3.0 ect VT 2020
    - Optimal Linear Filtering 6.0 ect VT 2020
    - Methodology of Science and Technology - TFK005D 4.0 ect HT 2020
    - Becoming a Teacher in Higher Education - 7FDID01 6.0 ect VT 2019
    - Control Theory 6.0 ect VT 2019
    - Nonlinear Optimization, Equations and Least Squares - 6FMAI07 9.0 ect Vt 2019
    - Sensor Fusion 6.0 ect VT 2019
    - Research Ethics - TFK004D 2.0 ect HT 2018
    - Linear Systems 7.0 ect HT 2018

- **Teaching duties**
    - Teaching assistant
        - Digital signal processing, HT18, HT19, HT20
        - Engineering Project in automatic control, HT18, HT19, HT20, HT21
        - Automatic control, HT18, VT19, HT19, VT20, HT20, HT21
    - Lab supervisor
        - Automatic Control, HT18, VT19, HT19, VT20, HT20, HT21
        - Digital signal processing, HT18, HT19, HT20
        - Industrial Control Systems, VT19, VT20, VT21
        - Modelling and Simulation/ Modelling and Learning for Dynamical Systems, HT19, HT20, HT2, HT22
- **Master thesis supervision**
    - Lisa Eriksson, Temporal and Spatial Models for Temperature Estimation Using Vehicle Data 2019.
    - Tommy Karlsson Indirect Tire Pressure Monitoring Using Higher-Order Spectral Models, 2019.
    - Anton Kullberg Tire-Road Friction Estimation in AWD Vehicles, 2019.
    - Tomas Busk Blind Channel Equalization for Shortwave Digital Radio Communications, 2020.
    - Amanda Tydén and Sara Olsson Edge Machine Learning for Animal Detection, Classification, and Tracking, 2020.
    - Pontus Arnesson and Johan Forslund Edge Machine Learning for Wildlife Conservation: Detection of Poachers Using Camera Traps, 2021.
    - Jacob Eek Reconstruction of Hyperspectral Images Using Generative Adversarial Networks, 2021.
    - Andreas Lidstrom and Martin Andersson Indoor 5G Positioning using Multipath Measurements, 2022.

- Johan Linder and Oscar Olsson A Smart Surveillance System Using Edge-Devices for Wildlife Preservation in Animal Sanctuaries, 2022.
- Richard Gotthard and Marcus Broström, Edge Machine Learning for Wildlife Conservation – A part of the Ngulia Project, 2023
- Adam Gardell and William Hepp, Visualizing animal activity using intelligent tags, 2023
- Tilda Hylander and Miranda Alvenkrona Semi-Automatic Image Annotation Tool, 2023
- Afra Farkhooy and Victoria Stråberg, Interactive wide-angle view camera for a virtual watch tower – A part of the Ngulia Project, 2023

- **Other activities**
  - Demo work with a reversing truck and trailer system.
  - Participation/ help with organising two reading groups.
  - Participation and poster presentation at the Swedish control meeting 2022 (reglermöte).
  - Participation and poster presentation at European Research Network System Identification (ERNSI) 2022.
  - Participation at oral presentation at the ISY workshop.

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	
Be passed on to other advanced technological development projects	X	
Be passed on to product development projects	X	
Introduced on the market	X	
Used in investigations / regulatory / licensing / political decisions		

Are there links to other internal / external projects that can accelerate the introduction or give greater impact?

7.2 Publications

The following publications and innovations derived from the activities in this project:

- Publications:
  - Visual Feature Encoding for GNNs on Road Networks
    O Stromann, A Razavi, M Felsberg (2022)
    arXiv preprint arXiv:2203.01187
  - Learning to integrate vision data into road network data
    O Stromann, A Razavi, M Felsberg (2022)
    IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 4548-4552
  - Graph representation learning for road type classification
    Z Gharaee, S Kowshik, O Stromann, M Felsberg (2021)
    Pattern Recognition 120, 108174
  - A Bayesian Approach to Reinforcement Learning of Vision-Based Vehicular Control
    Z Gharaee, K Holmquist, L He, M Felsberg (2020)
    25th International Conference on Pattern Recognition (ICPR), 3947-3954

- 5G Positioning - A Machine Learning Approach, Magnus Malmström, Isaac Skog, Sara Modarres Razavi, Yuxin Zhao, and Fredrik Gunnarsson (2019), In Proc. of IEEE 16th Workshop on Positioning Navigation Communication, (WPNC), Bremen, Germany
- Asymptotic Prediction Error Variance for Feedforward Neural Networks. Magnus Malmström, Isaac Skog, Daniel Axehill, and Fredrik Gustafsson (2020), In Proc. of 21st IFAC World Congress, (IFAC), Online (Berlin, Germany)
- Modeling of the tire-road friction using neural networks including quantification of the prediction uncertainty, Magnus Malmström, Isaac Skog, Daniel Axehill, and Fredrik Gustafsson (2021), In Proc. of IEEE 24th Int. Conf. on Inf. Fusion (FUSION)
- Detection of outliers in classification by using quantified uncertainty in neural networks, Magnus Malmström, Isaac Skog, Daniel Axehill, and Fredrik Gustafsson (2022), In Proc. of IEEE 25th Int. Conf. on Inf. Fusion (FUSION)
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submitted for possible publication in IEEE Signal Processing Letters.
  - Uncertainties in Neural Networks – A System Identification Approach, Magnus Malmström, Licentiatavhandling, Linköpings universitet, Institutionen för systemteknik, Reglerteknik (2021)

- Patents:
  - Alireza Razavi, “2019-0238: Landmark2Vec: A Neural Network-based Method for Unsupervised Landmark Localization”
  - Alireza Razavi, Navid Mahabadi “2019-0440: Vehicle Position Finder in GPS-denied Environments”
- Trade Secrets:
  - Alireza Razavi, “2021-0025” – This trade secret was selected as an extra valuable trade secret by Scania CV AB which has saved money and time for Scania

8. Conclusions and future research

iQDeep brought the capabilities of carrying out research and development in the field of Data-Driven Autonomous Driving to Scania Autonomous Transport Solutions for the first time. This provides us with the infrastructure and tools needed to research and develop more data-driven solutions for the perception pipeline as well as the other modules of our Autonomous Driving stack at Scania.

9. Participating parties and contact persons

Scania:

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