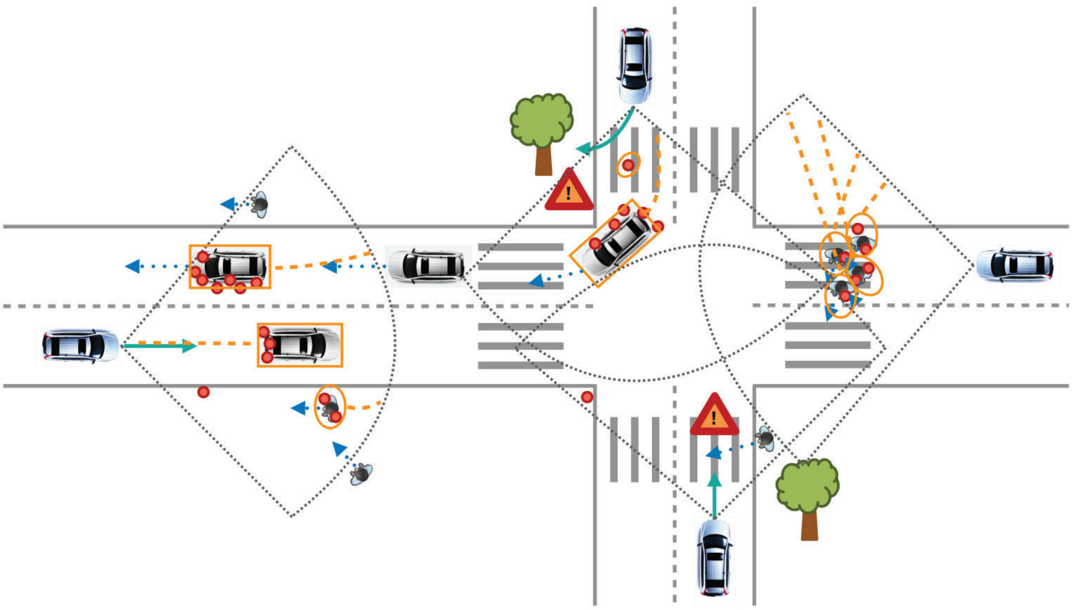
Deep multi-object tracking for ground truth trajectory estimation

Public report



Project within Traffic safety and automated vehicles
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Content

1. Summary

The development of automated vehicles and active safety systems are of great importance for the Swedish vehicle industry, and may also lead to substantial gains for society. Accurate environment perception is essential to automated vehicles, since it enables vehicles to sense nearby objects, and estimate their positions as well as other relevant properties. The perception systems in modern vehicles make use of data from cameras, LIDAR sensors, etc., in order to obtain a detailed understanding of the current situation. However, more development is needed before these systems can robustly provide the accuracy required for a vehicle to drive autonomously in all situations.
In this project, we addressed certain aspects of the environment perception problem, pertaining to the tracking of multiple dynamic objects. More specifically, we developed algorithms that can provide high-precision estimates of the trajectories of all dynamic objects in the vicinity of the host vehicle. Since the results of the project were aimed at producing ground truth for perception systems, we focused on offline techniques that would enable the extraction of as much information as possible from the available sensor data.

The research in this project was mainly carried out by a PhD student at Chalmers university who successfully defended his PhD and made important contributions along his journey. I addition, several master theses were run under this project both at Chalmers university and Zenuity/Zenseact.

2. Sammanfattning på svenska

Utvecklingen av självkörande fordon och aktiva trafiksäkerhetssystem är av stort värde för den svenska fordonsindustrin och kan också leda till stora förbättringar för samhället i stort. Ett väl fungerande perceptionssystem är centralt för självkörande fordon eftersom det möjliggör för fordon att kunna upptäcka närliggande fordon och skatta både deras position och egenskaper. Perceptionssystem i moderna fordon använder sig ofta av kameror, lidarsensorer och andra sensorer för att få fram en detaljerad förståelse för trafiksituationen. Samtidigt krävs betydligt mer forskning och utveckling innan dessa system kan tillhandahålla robusta skattningar i alla trafikmiljöer. I det här projektet har vi arbetat med att förbättra vissa delar av perceptionssystemen kopplade till följningen av multipla dynamiska fordon. Mer specifikt har vi utvecklat algoritmer för noggrann skattning av trajektorier av samtliga dynamiska objekt nära vårt eget fordon. Vår ambition har varit att ta fram mycket precisa skattningar som kan användas för att utvärdera andra system, och vi har därför fokuserat på metoder som utnyttjar data från hela körsekvensen för att skatta trajektorierna. Forskningen har huvudsakligen utförts av en doktorand på Chalmers tekniska högskola. Doktoranden har gjort ett stort antal

signifikanta bidrag till litteraturen och har dessutom skrivit en avhandling och tagit ut en doktorsexamen. Utöver arbetet som doktoranden gjort har vi anordnat och handlett ett flertal examensarbetet, både på Chalmers och Zenseact, som ytterligare bidragit med resultat till projektet.

Projektet koordinerades av Zenuity AB från början och togs över av Zenseact AB från juli 2020. Koordinator på Zenuity AB och Zenseact AB var Dr. Daniel Svensson och senare blev Dr. Maryam Fatemi koordinator för projektet. Forskningen har huvudsakligen utförts av Yuxuan Xia, en doktorand som handledes av Prof. Lennart Svensson vid Chalmers universitet. Dr. Karl Granström som var på Chalmers högskola i början av detta projekt bidrog också till detta projekt. Doktoranden avslutade sina studier framgångsrikt och gjorde betydande insatser på sin resa.

3. Background

This project aims to address parts of vehicle environment perception, which is a key enabling technology to both Advanced Driver Assistance Systems (ADAS) and autonomous drive (AD). Environment perception is the general understanding of the environment that the vehicle operates in and it involves several sub-problems including: 1) Detecting different types of objects, e.g., vehicles, pedestrians, and cyclists. 2) Tracking of objects, i.e., the estimation of their positions, their dynamic properties, as well as any other properties that are of interest. 3) Prediction of objects, for the purpose of understanding where it is likely that they will be in the immediate future. All these tasks are imperative to safely operate a self-driving vehicle in situations where other dynamic objects are present.

The objective of the project is to obtain state trajectory estimates that are sufficiently accurate, such that they can be used to develop and evaluate online perception (tracking) algorithms. Towards this aim, in this project, we developed trajectory estimation techniques to use all available data to extract accurate estimates of state trajectories of all dynamic objects that are visible to the host vehicle.

4. Purpose, research questions and method

The overall purpose of this project is to develop methods for automatically estimating the trajectories of dynamic objects surrounding an ego vehicle. The main objectives related to this overall purpose are described in Section 5 of this report. The main part of the research was carried out in the context of a PhD thesis, and the details of the research are described in the thesis, accessible to the public via this link . In addition, one can turn to the papers, Licentiate and master theses mentioned in Section 7.2 of this report for more details.

5. Objective

The main goal of the project was to simplify, advance and support the development of the environment perception layers in vehicles. We aimed to do so by
1. Designing tools and strategies to automatically obtain accurate estimates of vehicle properties and trajectories. The ambition is to enable extraction of ground truth estimates in very large data sets.

2. Developing models and deep learning algorithms for multi-object tracking (trajectory estimation) for offline/batch problems. Knowledge about these is expected to be useful also for online tracking.

3. Collecting and curating a large data set that would become publicly available. The data set would contain measurements from internal sensors in the host vehicle, as well as LIDAR and camera sensors. The objective was to provide ground truth trajectory estimates for all dynamic objects in the field of view of the vehicle.

The first goal has been the main focus of the research for the PhD student in this project and is achieved by related knowledge through his publications. There are some papers and master theses on the second goal, as a result of which follow-up PhD projects have been defined. The third goal was set aside, as new publicly available data sets, such as NuScenes, serving the same goal, emerged before this project reached a point when it was time to put focus on developing a public data set.

From an academic perspective, this project aimed to
1. Establish a theoretical framework for trajectory estimation of multiple dynamical objects.

2. Analyze how to optimally combine deep learning techniques with statistical inference and prior knowledge about, e.g., vehicle dynamics. Traditional multi-object tracking methods provide tools to incorporate such prior knowledge, but it is possible that a deep learning solution would perform better by ignoring such prior information and instead learning about vehicle dynamics from training data.

3. Produce several conference and journal papers in relevant venues.

4. Contract a student who will write and defend a licentiate thesis halfway through the project, and then write and defend a doctoral thesis, at the end of the project.

This project has been very successful when it comes to fulfilling its academic goals. More specifically, the PhD student who was contracted in this project, made significant contributions to establishing a theoretical framework for trajectory estimation. Within the course of this project, in total, 6 master theses, one Licentiate thesis, one PhD thesis, 13 journal papers and 7 conference papers have been written and published (two more journal papers are still under review). It should also be mentioned that the second academic goal was partly fulfilled, and follow-up PhD theses have been formulated as a result of preliminary research carried out in this project.

6. Results and deliverables

This project is divided into four work packages.

WP1. Project leadership: Coordination and leadership of the activities
Project leadership (WP1) was carried out throughout the project by Zenuity and later Zenseact.

The PhD student's work is divided into three WPs, with gradually increasing complexity.

WP2. Single object in a controlled environment
WP3. Extension to more complicated and realistic settings
WP4. Data acquisition

The deliveries of the WP2 and WP3 are summarized in the table below. WP4 was not carried out as the emergence of other publicly available datasets served the goal for this work package and the research instead focused on WP3.

Work Packages	Goals	Deliveries	Publications*
WP2: Single object in controlled environment	M2.1 Detection methods tailored to LIDAR and camera	L2.1. A comprehensive report/paper describing the methods studied and developed along with evaluation reports on the simulated data and the data set collected from the test track	[25], [26], [27]
	M2.2 Fusion of detections from different times	L2.2. A comprehensive report/paper describing the methods studied and developed along with evaluation reports on the simulated data and the data set collected from the test track.	[1], [28]
	M2.3 Fusion of LIDAR and camera	L2.3. A comprehensive report/paper describing the methods studied and developed along with	[2], [3]

		evaluation reports on the simulated data and the data set collected from the test track.	
WP3: Extension to complicated and realistic settings	M3.1. Estimate trajectories of a known number of objects	L3.1 A comprehensive report/paper describing the methods studied and developed along with evaluation reports on the simulated data and the data set collected from the test track.	**
	M3.2. Estimate trajectories of an unknown number of objects	L3.2 A comprehensive report/paper describing the methods studied and developed along with evaluation reports on the simulated data and the data set collected from the test track.	[4] to [24] [29] [30]

* References are detailed in Section 7.2
** Note that this case is a special and simpler case of M3.2 and can be considered to be addressed by all the publications under L3.2 .

Results of this project can be used in development of self-driving technologies. These results have the potential of reducing the cost and speed of development and therefore can contribute to the competitiveness of the Swedish industry in this field. In addition, the deliveries mentioned above, have been published in high-quality scientific journals and presented at international conferences. This has resulted in forming international collaborations and dissemination of knowledge. These points have contributed to key aspects of FFI programs, namely, internationalization and competitiveness. Moreover, the results of this project can contribute to the development of more accurate perception solutions, which in turn can make self-driving technologies safer and, consequently, result in safer transport solutions. These aspects are related to FFI goals, namely,

1. FFI has demonstrated solutions that make society's road transport fossil-free, safe, equality and efficient.
2. FFI has developed sustainable solutions that have been implemented and accepted by users and society.
3. FFI has contributed, through innovation, partnership and collaboration, to the development of skills, infrastructure, policy, regulatory frameworks and business models in the road transport 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	
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		

7.2 Publications

This project has important academic contributions and resulted in numerous publications. More specifically, this project produced 15 journal papers, of which two are still under review, seven conference papers, one Licentiate thesis, one PhD thesis and six master theses. The list of journal papers is as follow

[1] Granström K, Bramstång J. Bayesian smoothing for the extended object random matrix model. IEEE Transactions on Signal Processing. 2019 Jun 3;67(14):3732-42.

[2] L. Caltagirone, M. Bellone, L. Svensson, M.Wahde and R. Sell, "Lidar-Camera Semi-Supervised Learning for Semantic Segmentation", Sensors, 21(14), July 2021.

[3] L. Caltagirone, M. Bellone, L. Svensson and M. Wahde, "LIDAR-camera fusion for road detection using fully convolutional neural networks", Robotics and Autonomous Systems, 111: 125–131, Mar. 2019.

[4] Ángel F. García-Fernández, Lennart Svensson, "Trajectory PHD and CPHD filters", IEEE Transactions on Signal Processing, vol. 67, no. 22, pp. 5702-5714, Nov. 2019.

[5] Xia Y, Granstrom K, Svensson L, Garcia-Fernandez A, Williams J. Multi-Scan Implementation of the Trajectory Poisson Multi-Bernoulli Mixture Filter. Journal of Advances in Information Fusion. 2019 Dec 1.

[6] Granström K, Svensson L, Xia Y, Williams J, García-Fernández ÁF. Poisson multi-Bernoulli mixtures for sets of trajectories. arXiv preprint arXiv:1912.08718. 2019 Dec 17.

[7] Xia Y, Wang P, Berntorp K, Svensson L, Granström K, Mansour H, Boufounos P, Orlik PV. Learning-based extended object tracking using hierarchical truncation measurement model with automotive radar. IEEE Journal of Selected Topics in Signal Processing. 2021 Feb 9;15(4):1013-29.

[8] García-Fernández ÁF, Svensson L, Williams JL, Xia Y, Granström K. Trajectory poisson multi-Bernoulli filters. IEEE Transactions on Signal Processing. 2020 Aug 17;68:4933-45.

[9] García-Fernández ÁF, Williams JL, Svensson L, Xia Y. A Poisson multi-Bernoulli mixture filter for coexisting point and extended targets. IEEE Transactions on Signal Processing. 2021 Apr 8;69:2600-10.

[10] Xia Y, Granström K, Svensson L, Fatemi M, García-Fernández ÁF, Williams JL. Poisson multi-Bernoulli approximations for multiple extended object filtering. IEEE Transactions on Aerospace and Electronic Systems. 2021 Sep 10;58(2):890-906.

[11] Xia Y, Svensson L, García-Fernández ÁF, Williams JL, Svensson D, Granström K. Multiple object trajectory estimation using backward simulation. IEEE Transactions on Signal Processing. 2022 Jun 22;70:3249-63.

[12] Pinto J, Xia Y, Svensson L, Wymeersch H. An uncertainty-aware performance measure for multi-object tracking. IEEE Signal Processing Letters. 2021 Aug 12;28:1689-93.

[13] Xia Y, García-Fernández ÁF, Meyer F, Williams JL, Granström K, Svensson L. Trajectory PMB Filters for Extended Object Tracking Using Belief Propagation. arXiv preprint arXiv:2207.10164. 2022 Jul 20.

[14] Á. F.García-Fernández, and L. Svensson. "Tracking multiple spawning targets using Poisson multiBernoulli mixtures on sets of tree trajectories." IEEE Trans. on Signal Processing 70 (2022): 1987-1999.

[15] J. Liu, L. Bai, Y. Xia, T. Huang, B. Zhu and Q. -L. Han, "GNN-PMB: A Simple but Effective Online 3D Multi-Object Tracker without Bells and Whistles," in IEEE Transactions on Intelligent Vehicles, 2022, doi: 10.1109/TIV.2022.3217490.

Following is the list of conference papers,

[16] Yuxuan Xia, Karl Granström, Lennart Svensson, Ángel F. García-Fernández, Jason L. Williams, "Extended target Poisson multi-Bernoulli mixture trackers based on sets of trajectories", Proceedings of the 22nd International Conference on Information Fusion,

2019

[17] Ángel F. García-Fernández, L. Svensson, "Spooky effect in optimal OSPA estimation and how GOSPA solves it" in 22nd International Conference on Information Fusion, 2019.

[18] Xia Y, Wang P, Berntorp K, Boufounos P, Orlik P, Svensson L, Granström K. Extended object tracking with automotive radar using learned structural measurement model. In 2020 IEEE Radar Conference (RadarConf20) 2020 Sep 21 (pp. 1-6).

[19] Xia Y, Svensson L, García-Fernández ÁF, Granström K, Williams JL. Backward Simulation for Sets of Trajectories. In2020 IEEE 23rd International Conference on Information Fusion (FUSION) 2020 Jul 6 (pp. 1-8).

[20] García-Fernández ÁF, Svensson L, Williams JL, Xia Y, Granström K. Trajectory multi-Bernoulli filters for multi-target tracking based on sets of trajectories. In 2020 IEEE 23rd International Conference on Information Fusion (FUSION) 2020 Jul 6 (pp. 1-8).

[21] Granström K, Svensson L, Xia Y, García-Femández ÁF, Williams J. Spatiotemporal constraints for sets of trajectories with applications to PMBM densities. In 2020 IEEE 23rd International Conference on Information Fusion (FUSION) 2020 Jul 6 (pp. 1-8).

[22] Pinto J, Hess G, Ljungbergh W, Xia Y, Svensson L, Wymeersch H. Next generation multitarget trackers: Random finite set methods vs transformer-based deep learning. In2021 IEEE 24th International Conference on Information Fusion (FUSION) 2021 Nov 1 (pp. 1-8).

Finally, the following theses have been published during the course of this project,

[23] Licentiate thesis: Xia Y. Conjugate Priors for Bayesian Object Tracking, Supervised by Lennart Svensson at Chalmers University.

[24] PhD thesis: Xia Y. Poisson Multi-Bernoulli Mixtures for Multiple Object Tracking. Supervised by Lennart Svensson at Chalmers University.

[25] Master Thesis: Berg Marklund O, Hulthén O. 3D object detection for autonomous driving using deep learning. supervised by Karl Granström.

[26] Master Thesis: Almér O, Andersson E. Deep learning uncertainties for monocular 3D object detection. Supervised by Lennart Svensson.

[27] Master Thesis:Hyrefeldt J, Viberg B. Semi-automatic annotation for 3D object detection using Bayesian smoothing. Supervised by Lennart Svensson.

[28] Master Thesis: Bohnsack E, Lilja A. Multi-object tracking using either end-to-end deep learning or PMBM filtering. Supervised by Karl Granström.

[29] Master thesis: Chen D, Li L. Deep Dencentralized Multiple Object Tracking. supervised by Yuxuan Xia and Lennart Svensson.

[30] Master thesis: Carlsson C, Ekelund H. Sequentially connected 2D assignment problems solved using Lagrangian dual methods. supervised by Yuxuan Xia and Lennart Svensson.

8. Conclusions and future research

This project was shaped by identifying that the development and verification of self-driving technologies require large amounts of ground truth/annotated data and that there need to be methods for automatically generating this ground truth/annotations for the sake of development speed, cost reduction and project viability. This project has been successful in delivering model-based methods for estimating trajectories of dynamic objects. In addition, smaller research was conducted on the use of deep learning for object tracking and the use of techniques developed in model-based methods for designing deep neural nets.

As the research focus of both industry and academia is shifting to the use of learning-based methods for both object tracking and trajectory estimation, the need for large amount of automatically generated annotations/ground truth is even bigger today than when this project started. At the same time, new learning paradigms, such as, self-supervised learning offer solutions to mitigate this need and facilitate more efficient learning methods. Consequently, these areas of research are very much active and much further investigations in related venues are needed.

Subsequent to this project, and in some cases as a result of research conducted in this project, more research projects in related fields have been defined at both Zenseact and Chalmers. These and similar projects in Swedish companies and universities are needed to secure the future of Swedish industry in a rapidly evolving world of self-driving technologies.

9. Participating parties and contact persons

Participating parties in this project have been Zenuity/Zenseact and Chalmers University of Technology. Dr. Daniel Svensson (formerly with Zenuity and Zenseact) and Dr. Maryam fatemi (maryam.fatemi@zenseact.com) managed the project at Zenuity/Zenseact. From Chalmers university of Technology, Prof. Lennart Svensson (lennart.svensson@chalmers.se), Dr. Karl Gränstrom (formerly with Chalmers) and Dr.

Yuxuan Xia (yuxuan.xia@chalmers.se) participated in the project. Yuxuan Xia conducted his PhD under the supervision of Lennart Svensson at Chalmers university.