

Machine learning based multi-object tracking without dynamic models and hard association metrics

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Abstract—In this paper, we develop Machine Learning (ML)-based methods for Multi Object Tracking (MOT) within the context of Advanced Driver Assistance Systems (ADAS). Given the increasing complexity and demand for precise and efficient object tracking systems in the automotive industry, this work focuses on the integration of ML techniques into established tracking methodologies. Key contributions encompass the creation and evaluation of three specialized neural networks: (i) the Single Prediction Network (SPENT) for predicting the trajectories of tracked objects, (ii) the Single Association Network (SANT) for associating incoming sensor objects with existing tracks, (iii) and the Multi Association Network (MANTa) for associating multiple sensor objects with existing tracks. We combine our ML methods with a traditional Kalman filter framework, offering a data driven approach to address MOT challenges while maintaining the modularity and interpretability of classical filter approaches. We assess both, the performance of all three models alone as well as their impact on the performance when they are integrated in the Kalman framework. Replacing single components allows us to get a clear evaluation of the impact of each ML model on the overall tracking system while maintaining the modularity of the system. The results reveal a modular, robust, and maintainable tracker, underscoring the potential of ML integration in ADAS.

Index Terms—Article submission, IEEE, IEEEtran, journal, LATEX, paper, template, typesetting.

I. INTRODUCTION

THE ongoing evolution of Advanced Driver Assistance Systems (ADAS) has brought the need for precise and reliable Multi Object Tracking (MOT) into the spotlight [1], [2]. In complex and dynamic environments, as encountered in urban traffic, it is crucial to simultaneously and accurately capture the positions and movements of multiple objects - a key challenge in computer vision (CV).

In the commonly used Tracking-by-Detection (TbD) paradigm, a tracker fuses detected sensor objects (SO) to create consistent object tracks over time. A key challenge within this paradigm is associating the incoming measured SO with their corresponding existing object tracks or initializing new object tracks.

Tracking frameworks form the heart of ADAS systems that are used in millions of vehicles around the globe. The vast majority of these frameworks rely on classical approaches

such as the Kalman filter (KF) or its variants. These classical tracking theories have the great benefit of being modular and interpretable. The task is split into clearly separated subtasks such as the prediction of currently tracked objects and the association with newly measured ones. Furthermore the math and the theory itself is often clean and comprehensible. However, in the automotive industry these tracking systems need to be applied to a variety of different car models with different sensor sets, different installation heights of the sensors, different countries and always perform for a wide range of driving scenarios. This often leads to the increasing implementation of heuristics and parameters that tweak the tracking system for specific configurations and situations. But hand-engineered parameters and heuristics are hard to maintain and develop further from a software engineering point of view. Furthermore, performance of classical approaches can reach its limits in challenging situations.

In this work, we propose a data driven approach to tracking frameworks, which would allow the same system to be fine tuned for specific configurations relying only on data, thus increasing maintainability and adaptability. We do this preserving one of the biggest strengths of classical approaches: its modularity, by replacing only single tracking components with ML models.

In comparison to the Kalman filter, our Single Prediction Network (SPENT) is capable of predicting the state of individual objects without the need for a predefined state or observation model at runtime. SPENT holds the potential, particularly in terms of adaptability to various scenarios and the ability to effectively handle nonlinearities. Many conventional tracking systems rely on static methods for data association, often based on simple heuristics or fixed thresholds. In contrast, Single Association Network (SANT) employs machine learning to automate these processes and adapt more effectively to different scenarios. As a result, within the Tracking-by-Detection (TbD) MOT framework, SANT replaces the calculation of a distance metric and the Hungarian algorithm for the corresponding assignment. Furthermore, we integrate SPENT and SANT into an existing tracking system and demonstrate their performance through multiple tests and comparisons with established methods.

II. RELATED WORK

A. Real time applications

ADAS are embedded real-time applications where it is crucial to predict the state of objects immediately after their

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detection. This rules out offline tracking methods as presented in [3] that process the entire video material at once in a batch process. Therefore, most recent approaches for tracking multiple objects rely on online methods that do not depend on future image information. Online methods use various features to estimate the similarity between the recognized objects and the existing tracks. This can be done on the basis of their predicted positions or even similarities in appearance [1], [2], [4], [5], [5]–[10].

B. Tracked object prediction

One fundamental problem in TbD frameworks is the prediction of the states of the already tracked objects. In many approaches Kalman filters and their variants have proven to be effective for state prediction. However, they reach their limits in more complex scenarios, particularly in the presence of non-linear motion patterns and interactions among multiple objects. In this work, we introduce a novel MOT approach that leverages Machine Learning (ML) to overcome these challenges. We specifically focus on the development and implementation of Neural Networks (NN), which can enable more precise and flexible data-driven object tracking.

C. Association

Another fundamental problem in TbD framework is data association. For this some approaches only consider the current state of the tracks, while others integrate temporal information such as the track history. This aggregate of temporal information can be done for example using attention mechanisms as used in [8], [9] or recurrent neural networks (RNNs) as in [4], [6]. The latter is what we are also pursuing in this work. Similar to the problem statement in Mertz et al [6], the aim of our work is to develop a data-based approach that can learn to completely solve the combinatorial Non Deterministic Polynomial Time (NP) hard optimization problem of data association. Mertz et al [6] use a distance matrix based on the Euclidean distance measure as input for the developed association network, thus replacing an association algorithm such as the Hungarian Algorithm (HA). It can be assumed that the Euclidean distance measure was used as the basis for calculating the ground truth (GT) training data (distance matrices) and for the evaluation. However, this is not explicitly stated. When the Euclidean distance is used to calculate the training data, the network will only learn to follow this logic. This deprives the network of the opportunity to follow a different association logic. In the context of this work, we put forward the hypothesis that a Gated Recurrent Unit (GRU)-based association network can be designed and trained using an undefined distance measure. This can increase the assignment of the temporal memory component, i.e. the history, and thus boost performance.

The goal of this work was therefore to develop an association network that is intended to solve the assignment of one or more sensor objects (SO) to an existing number of object tracks without a defined distance measure.

III. OVERVIEW OF OUR PROPOSED MODELS

Our primary contribution is the development and evaluation of three NN that we labeled: (i) the Single Prediction Network (SPENT), (ii) the Single Association Network (SANT), and (iii) the Multi Association Network (MANTa). Figure 1 provides an overview of our approach (i) and (ii). The input for the proposed Single Prediction Network (SPENT) are the sensor objects (SO) in every time step. These objects consists of a fixed-dimensional state vector that contains information such as object position, orientation and dimension. SPENT predicts all vectors to the next time step where they are used as input to the Single Association Network (SANT) to build target trajectories or object tracks.

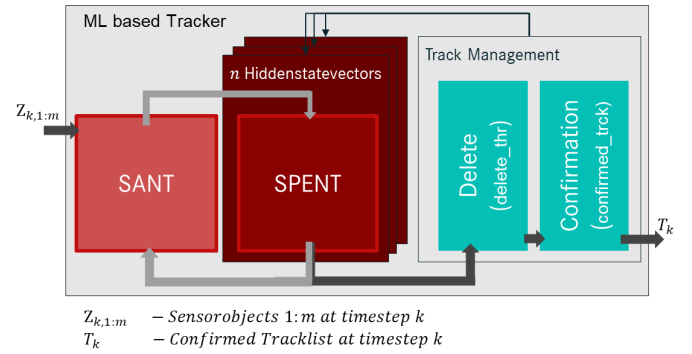


Fig. 1. Schematic representation of the two integrated networks SPENT and SANT in a tracking-by-detection (TbD) framework.

This work provides new insights and advancement in the development of Advanced Driver Assistance Systems (ADAS), contributing to the further evolution of technologies for autonomous driving (AD).

IV. TRACKING WITH PREDICTION AND ASSOCIATION NETWORKS

We apply the tracking-by-detection (TbD) paradigm, in which a tracker fuses object fuses the object detections to generate object tracks that are consistent over time. [11], for example, provides a framework for analyzing tracking approaches that follow the TbD paradigm. This was used accordingly in this study.

To enable our models to incorporate temporal information, we use Long Short-Term Memory (LSTM) and bidirectional Long Short-Term Memory (BiLSTM) networks. Both for the prediction (SPENT) and the association (SANT) of the sensor objects (SO) to the existing tracks.

A. Single Prediction Network (SPENT)

Most existing tracking methods associate incoming detections pairwise with object states predicted by a simple motion model, e.g. a constant velocity model, using a Kalman filter [1], [2], [11]. However, recent work has demonstrated that aggregating temporal information as well as contextual information can improve the tracking of multiple objects by utilizing higher order information in addition to pairwise similarities between detections [4], [6]–[8]. Our approach is

to use the hidden states of the LSTM layer as an object-specific parameter set. The values of the hidden states of the LSTM layer are updated in each time step based on the received measurement data. These updates therefore results in an internal correction over the course of the sequence.

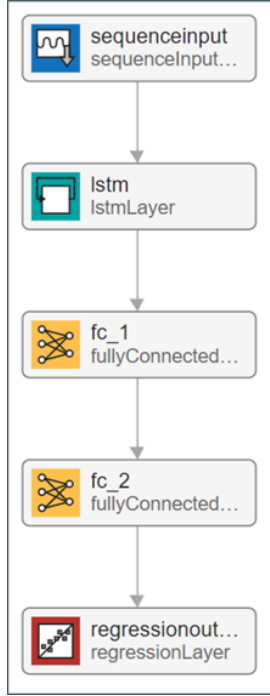


Fig. 2. Schematic representation of the generic network structure of SPENT.

a) Data preprocessing: Corresponding ground truth (GT) data from the KITTI data set was used for the development. A GT Track contains the information of an object over time, starting with its appearance and ending with its exit from the sensor detection range. In order to achieve better generalisation and to increase the chance that the training converges, the track state values at time t (predictors) and track state values at time $t+1$ (targets) were normalised. After [12], normalisation can be performed so that the predictors and targets have a mean value of zero and a unit variance. The mean value μ and the standard deviation σ were calculated for all tracks using the following formulae:

$$\mu = \frac{1}{N} \sum_{i=1}^N A_i \quad (1)$$

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^N |A_i - \mu|^2} \quad (2)$$

Pre-padding was also applied. [13] shows how padding influences the performance of neural networks in sequence-based tasks. The study suggests that although both pre-padding and post-padding are feasible, the choice of padding technique can have a significant impact on the efficiency of the model, especially for LSTM networks where the sequence context is crucial.

b) Network development: The Single Prediction Network (SPENT) was developed using the open-loop method, this means that the network predicts values for a future time step based on previously received data. For use in an online MOT process, the network is therefore able to make a prediction about the probable next state values using the state values received for an SO. The internal values (hidden states) of the LSTM layer are updated per time step based on the measurement data received. This updating process therefore provides an internal correction over the course of the sequence of each track.

The regression layer used (regressionoutput) calculates the loss of the mean square error for regression tasks. The mean square error (MSE) indicates the average of the squared difference between the model prediction and the target value. This value can be used as a measure of the quality of an estimator. For a single observation, the mean square error is given by:

$$MSE = \sum_{i=1}^R \frac{(t_i - y_i)^2}{R} \quad (3)$$

where R is the number of responses, t_i is the target output and y_i is the prediction of the network for sample i . For sequence-to-sequence regression networks such as SPENT, the loss function of the regression layer is half the mean square error of the predictions for each time step, normalised by S , not by R :

$$loss = \frac{1}{2S} \sum_{i=1}^S \sum_{j=1}^R (t_{ij} - y_{ij})^2 \quad (4)$$

where S is the sequence length. During training, the average loss is calculated using the observations in the mini-batch. Where S is the mini-batch length. In relation to the KITTI data set (cars and vans), an RMSE of 0.025 was achieved for the position prediction of all objects in the dataset.

B. Single Association Network (SANT)

SANT stellt einen datenbasierten Ansatz dar, welcher lernen kann, das kombinatorische Non Deterministic Polynomial Time (NP) hard Optimierungsproblem der Datenassoziation vollständig zu lösen. Im Vergleich zu den meisten Assoziationsverfahren [4] [6] [6] stellt SANT einen Ansatz dar, welcher als Inputdaten keine definierte Distanzmatrix erhält, sondern die bestehenden Tracks sowie jede neue Messung (SO) erhält. Damit entfällt die Definition eines Abstandsmaßes, womit dem Netzwerk die Freiheit gegeben wurde, einer eigenen Assoziationslogik zu folgen bzw. diese datenbasiert zu lernen. Somit ersetzt SANT die Berechnung eines Abstandsmaßes sowie einen Assoziationsalgorithmus wie z.B. den Hungarian Algorithm (HA).

a) Datenvorverarbeitung: Für die Entwicklung des Single Association Networks (SANT) wurde die Datenassoziation als zeitlich gegliedertes Problem (Sequenz-zu-Vektor) betrachtet. Das Datenassoziationsproblem beschreibt somit die Zuordnung von einem SO zu einem Set von Tracks. Die entsprechenden Tracks wurden aus dem KITTI Datensatz der gelabelten Kameraaufzeichnungen extrahiert. Allerdings

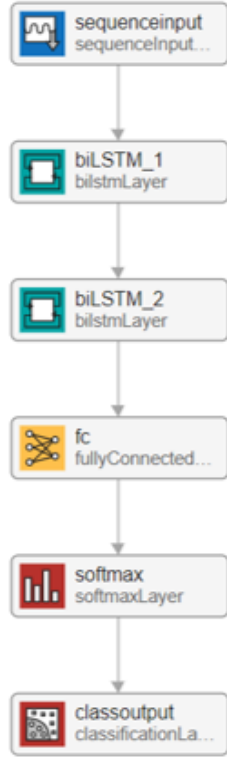


Fig. 3. Schematic representation of the generic network structure of SANT.

existieren für das betrachtete Problem der Assoziation keine realen GT Daten. Um sicherzustellen, dass die Zuordnung eines Sensor Objekts (SOs) zu einem Track eines Tracksets genau eine korrekte Lösung besitzt, wurde das SO in einem Zeitschritt aus dem bestehenden Trackset eines Zeitschritts erzeugt. Die Daten wurden entsprechend künstlich verrauscht, um aus den GT Daten realistische Sensordaten zu erzeugen. Das Datenformat wurde entsprechend gewählt, um eine indexbasierte Trackzuordnung für das Single Association Network (SANT) zu ermöglichen. Die Größe der Inputmatrix entspricht daher $m * n$. Mit $m = 2 * \text{AnzahlZustandswerte}$ und $n = \text{Trackanzahl}(t)$.

b) *Netzwerkentwicklung*: Das Netzwerk (Fig. 3) ist als Sequenz-to-Classification ausgelegt, wobei der sequenceinput die beschriebene Inputmatrix pro Zeitschritt darstellt.

BILSTM,... Die vollständig verknüpfte Schicht (FC) gibt über die Anzahl der der Ausgabewerte die Klassenanzahl n vor. Die n Klassenwerte werden in der Softmax Schicht durch Anwendung der Softmaxfunktion in eine eindeutige Wahrscheinlichkeitsverteilung berechnet (wie in Kapitel 2.2.1 beschrieben). Durch Anwendung der Cross-Entropie-Operation in der Ausgabeschicht (Classout) konnte SANT auf einen korrekten Zuordnungswert (GT Klassenindex) trainiert werden.

Die Cross-Entropie-Kostenfunktion (Kreuzentropie) berechnet den Cross-Entropie-Verlust zwischen Netzvorhersagen und Zielwerten für die eindeutige Zuordnungsaufgabe (für sich gegenseitig ausschließende Klassen). Dabei wird mittels One-Hot-Kodierung die Klasse binär in einem Vektor dargestellt

und somit ein 1-zu-n Code generiert. Nach folgender Formel werden die Crossentropie-Verlustwerte für jeden Eingabewert Y_j und zugehörigen Zielwert (Targetvalue) T_j elementweise berechnet:

$$\text{loss}_j = -(T_j \ln Y_j + (1 - T_j) \ln(1 - Y_j)) \quad (5)$$

Um einen Skalar loss zu erhalten werden alle Verlustwerte loss_j aufsummiert und durch die Anzahl der Samples N geteilt. Optional können die Verlustwerte von definierten Samples mit dem Gewichtungsfaktor w_j gewichtet werden:

$$\text{loss} = \frac{1}{N} \sum \text{loss}_j w_j \quad (6)$$

Eine entsprechende Nutzung des Gewichtungsfaktors w_j kann bei Datensätzen mit unausgewogenen (imbalanced) Klassenverteilung hilfreich sein.

C. Multi Association Network (MANTa)

- a) *Datenvorverarbeitung*:
- b) *Netzwerkentwicklung*:

V. EXPERIMENTAL EVALUATION

... KITTI-Car Benchmark.

VI. CONCLUSION

The conclusion goes here.

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This should be a simple paragraph before the References to thank those individuals and institutions who have supported your work on this article.

APPENDIX

PROOF OF THE ZONKLAR EQUATIONS

PROOF OF THE FIRST ZONKLAR EQUATION

Appendix goes here.

PROOF OF THE SECOND ZONKLAR EQUATION

And here.

REFERENCES

- [1] Jenny Seidenschwarz, Guillem Brasó, Victor Serrano, Ismail Elezi, Laura Leal-Taixé, "Simple cues lead to a strong multi-object tracker," *Paper*, 2022.
- [2] Alex Bewley, Zongyuan Ge, Lionel Ott, Fabio Ramos, Ben Upcroft, "Simple online and realtime tracking," *Paper*, 2016.
- [3] Roberto Henschel, Laura Leal-Taixé, Daniel Cremers, Bodo Rosenhahn, "Fusion of head and full-body detectors for multi-object tracking," *Paper*, 2017.
- [4] Anton Milan, Seyed Rezatofighi, Anthony Dick, Ian Reid, Konrad Schindler, "Online multi-target tracking using recurrent neural networks," *Paper*, 2016.
- [5] Qi Chu, Wanli Ouyang, Hongsheng Li, Xiaogang Wang, Bin Liu, Nenghai Yu, "Online multi-object tracking using cnn-based single object tracker with spatial-temporal attention mechanism," *Paper*, 2017.
- [6] H. L. H. Z. C. Mertz, "Deepda: Lstm-based deep data association network for multi-targets tracking in clutter," *Paper*, 2019.
- [7] Johannes Fitz, "Datenassoziation für multi-objekt-verfolgung mittels deep learning," *Paper*, 2020.

- [8] W.-C. H. H. K. T.-Y. L. Y. C. R. Yu, “Soda: Multi-object tracking with soft data association,” *Paper*, 2020.
- [9] Q. C. W. O. H. L. X. W. B. L. N. Yu, “Online multi-object tracking using cnn-based single object tracker with spatial-temporal attention mechanism,” *Paper*, 2017.
- [10] T. M. A. K. L. L.-T. C. Feichtenhofer, “Trackformer: Multi-object tracking with transformers,” *Paper*, 2022.
- [11] Ba-Tuong Vo, “code set for research use: Multi-sensor multi-target tracking,” 2013. [Online]. Available: <https://ba-tuong.vo-au.com/codes.html>
- [12] I. G. Y. B. A. Courville, *Deep Learning*. MIT Press, 2019.
- [13] D. M. R. N. V. S. Reddy, “Effect of padding on lstms and cnns,” *Paper*, 2019.