Sensor Object Plausibilization with Boids Flocking Algorithm

Christopher Knievel
University of Applied Sciences HTWG Konstanz
Alfred-Wachtel-Str. 8, 78462 Konstanz, Germany
Email: cknivel@htwg-konstanz.de

Lars Krueger
Continental - A.D.C. GmbH
Lise-Meitner-Str. 10, 89081 Ulm, Germany
Email: Lars.2.Krueger@continental-corporation.de

Abstract—Driver assistance systems are increasingly becoming part of the standard equipment of vehicles and thus contribute to road safety. However, as they become more widespread, the requirements for cost efficiency are also increasing, and so few and inexpensive sensors are used in these systems. Especially in challenging situations, this leads to the fact that target discrimination cannot be ensured which in turn leads to a false reaction of the driver assistance system. Typically, the interaction between moving traffic participants is not modeled directly in the environmental model so that tracked objects can split, merge or disappear. The Boids flocking algorithm is used to model the interaction between road users on already tracked objects by applying the movement rules (separation, cohesion, alignment) on the boids. This facilitates the creation of semantic neighborhood information between road users. We show in a comprehensive simulation that with only 7 boids per traffic participant, the estimated median separation between objects can improve from 2.4 m to 3 m for a ground truth of 3.7 m. The bottom percentile improves from 1.85 m to 2.8 m.

I. INTRODUCTION

Active safety measures such as Advanced Driver Assistance Systems (ADAS) are an elementary component of road-safety, especially with high market penetration [1]. In order to further increase road safety, the EU regulation 2019/2144 [2] obliges all OEMs to install an emergency brake assist (EBA) as well as lane departure warning system. Hence, as vehicles need to be equipped with the necessary sensors, the main goal is on cost efficiency, utilizing as few sensors while offering as many functions possible. As a consequence, the comfort function adaptive cruise control (ACC) becomes a default function also in the lower segments. Adaptive cruise control and other SAE-L1 advanced driver assistance systems have been studied extensively, see also [3].

For ACC, radar-only as well as radar+camera solutions are often used as sensor configurations. Despite budget sensors, the expectation especially on comfort function is high. Ambiguities of the radar sensors due to low angular resolution are predominant and cannot be resolved completely by the camera. As a consequence, target association is increasingly hard which leads to so-called ghost objects and/or lateral position ambiguities [4]. As a result of these ambiguities, false reactions of the system can occur, such as driver-take over scenarios from a field-operation test, which have been investigated in [5]. The cause is often not only a missing detection of the ACC-relevant vehicle but of a false interpretation of the scenario, i.e. that the detected vehicle has been falsely assessed to be not relevant, due to, for example, a false lane association. Target discrimination focuses on the correct lane association of vehicles to corresponding lanes [6, 7].

We propose to use the Boids flocking algorithm [8, 9], which has been introduced by Reynolds to model the motion of bird flocks or fish school, to model the interaction between traffic participants with each other as well as with the environment. A flocking algorithm has been used in [10] to derive a control algorithm for multiple non-holonomic cars. Each car has been modeled as an individual boid which behaves according to the movement rules of the typical boid model, which are cohesion, alignment, and separation. The proposed control managed a collision-free path of all boids, however, the usecase was limited to a straight highway and, eventually, the assumption that all cars driving in the same direction will converge to the same speed does not hold in reality.

In this paper, an individual flock of boids is created to follow each detected vehicle, i.e. for \( N \) vehicles, \( N_f \) flocks with \( N_b \) boids each are generated. The corresponding detected vehicle acts as a lead for the swarm to follow. The aforementioned movement rules are applied to each boid of each flock. In addition, a further rule is introduced in order to repel the individual flocks to each other in lateral direction. Thereby ensuring that the flocks maintain a lateral distance as long as they are within a given longitudinal distance. Since the boids of a flock are affected not only by the detected lead vehicle but also by the other boids of its own flock as well as by the neighboring flocks, the effects of the position uncertainties of an object on the target discrimination can be mitigated by using the average lateral distance between flocks.

The remainder of this paper is organized as follows: Sec. [II] introduces the Boids flocking algorithm including the proposed extensions in order to facilitate an object plausibilization. Additionally, the complexity of the proposed flocking algorithm is analyzed with respect to the flock size. Simulation results are presented in Sec. [III] Finally, Sec. [IV] draws the conclusion.

II. OBJECT PLAUSIBILIZATION WITH THE BOIDS FLOCKING ALGORITHM

A. Boids Flocking Algorithm

Reynolds [8] introduced three main rules describing the movement of boids as an interaction between the individuals of one flock. The movement of each boid is influenced by
• **Separation**: The tendency of a boid to maintain a certain distance from the other boids within the visible range.
• **Cohesion**: The tendency of a boid to move to the average position of the boids within the visible range.
• **Alignment**: The tendency of a boid to align itself with the boids within the visible range with respect to orientation and velocity.

The three basic rules are applied to each boid and each flock within a certain radius are listed below and depicted in Figure 1.

![Fig. 1: Three main rules for boid movement within a flock.](image)

We define the boids of the $j$-th flock as

$$B_j = \{b_{1,j}, b_{2,j}, \ldots, b_{N_b,j}\}$$ \hspace{1cm} (1)

with $j = 1, \ldots, N_f$, where $N_f$ is the number of flocks. Each boid $b_{i,j}$ contains the longitudinal and lateral position as well as velocity. For the sake of readability, we omit the index $j$ of the flock, as boids do not contain flock-specific information, i.e. $b_i = [p_i, v_i]^T$, with $p_i = [x_{i}, y_{i}]^T$, $v_i = [v_{x,i}, v_{y,i}]^T$.

As can be seen in Fig. 1, the visible range of a boid (field-of-view) is modeled as an ellipse, opposed to typically a circular view) is modeled as an ellipse, opposed to typically a circular section (cf. [9]), in order to consider the fact that vehicles are typically driving within the driving lanes. As a consequence, any boid that deviates too far laterally from the swarm is no longer considered by the swarm. The deviating boid can nevertheless perceive the swarm and is influenced by it in its movement.

Therefore, the set of boids, which are within the field-of-view of the $i$-th boid, is given by

$$B_{FoV,i} = \{b_j \mid (p_j - p_i)^TM^{-1}(p_j - p_i) \leq 1\}$$ \hspace{1cm} (2)

with

$$M = \begin{bmatrix}
\cos \varphi_i & -\sin \varphi_i \\
\sin \varphi_i & \cos \varphi_i \\
\end{bmatrix} \begin{bmatrix} a^2 & 0 \\
0 & b^2 \\
\end{bmatrix} \begin{bmatrix}
\cos \varphi_i & -\sin \varphi_i \\
\sin \varphi_i & \cos \varphi_i \\
\end{bmatrix}^T,$$

where the parameter of the ellipse are:

- $\varphi_i$, the orientation angle of the boid given by $\arctan(v_{y,i}/v_{x,i})$; Note that the coordinate system according to ISO 8855 [11] is used, which means that the $x$-coordinate is in longitudinal and the $y$-coordinate in lateral direction.
- $a$, the length of the first principal axis of the ellipse;
- $b$, the length of the second principal axis of the ellipse.
- $|B_{FoV,i}|$, the cardinality of the subset: $N_{b,FoV,i}$. Note that the $i$-th boid is not included in the set $B_{FoV,i}$; therefore, $|B_{FoV,i}| < |B|$.

In the following, the main steering rules are described.

### B. Movement and interaction rules

**Separation**: Each boid has a tendency to keep a certain distance from the other boids in the flock, thus, avoiding a collision. This behavior ensures that the flock is spread both in longitudinal and lateral direction, effectively, enlarging the field-of-view of the swarm. As described earlier, we assume that vehicles travel mainly within the driving lanes and the separation of the flock should also take this into account in the way that the boids have a larger separation in the longitudinal direction than in the lateral direction. However, this is not directly considered in the separation rule but in the weighting factor of the rule (see also [2]). Several variations of the separation rule exists, whereas we follow the implementation of [12]:

$$f_{sep} = - \sum_{j=1}^{N_{b,FoV,i}} p_i - p_j.$$ \hspace{1cm} (3)

This means, that the position of all boids visible to the $i$-th boid is subtracted by the position of the $i$-th boid.

**Cohesion**: Each boid is attracted towards the perceived center of the flock. This attraction counteracts the separation rule and causes the boids not to spread throughout the space. Otherwise, the boids would quickly lose the interaction with each other, due to the restricted field-of-view. The cohesion force is calculated by averaging the position of the $N_{b,FoV,i}$ boids and subtracting the result from the position of the $i$-th boid:

$$f_{coh} = \frac{1}{N_{b,FoV,i}} \sum_{j=1}^{N_{b,FoV,i}} p_j - p_i.$$ \hspace{1cm} (4)

Next to the attraction of each boid towards its perceived center of mass of the visible swarm, additional rules have been introduced in [9] with the rule **Leader Following** of particular interest, as it describes the tendency of a boid to move closer to a designated leader without actually overtaking the leader. In our proposed approach, each detected vehicle is a natural designated leader, which are followed by the boids of the corresponding swarm. Hence, the attracting force of the leader is given by

$$f_{coh,1} = p_l - p_i.$$ \hspace{1cm} (5)

**Alignment**: Since every boid of a flock is supposed to follow the same designated leader, it stands to reason that eventually every member of the flock should have the same velocity. The alignment rule is calculated similarly to the cohesion rule, where the average of the perceived velocity is calculated first and the velocity of the $i$-th boid is subtracted from it:

$$f_{ali} = \frac{1}{N_{b,FoV,i}} \sum_{j=1}^{N_{b,FoV,i}} v_j - v_i.$$ \hspace{1cm} (6)
C. Flock repulsion rule

An interaction between flocks is introduced in this paper, which is described by the flock repulsion behavior. The idea is that the repulsive forces of the neighboring flock supports a clear separation of the boids and thus of the swarms, so that target discrimination is facilitated even if the object position is imprecise. The flock repulsion is denoted by \( F_{\text{rep}} \) and is calculated in two steps.

First, the perceived center of the neighboring flock from the point-of-view of the \( i \)-th boid is calculated by

\[
R_{\text{rep},i}(\cdot,k) = \frac{1}{N_{\text{b},\text{FoV}}(k)} \sum_{j=1}^{N_{\text{b},\text{FoV}}(k)} p_j.
\]

Note here, that multiple flocks, for example on the left and right lane, can be perceived by one boid. It follows that the perceived center of mass of the neighboring swarms \( R_{\text{rep},i} \), are represented in a matrix of size \([2 \times N_{\text{f}}]\), with \( N_{\text{f}} \), the number of visible flocks by the \( i \)-th boid.

The repulsing force can then be calculated with an exponential function whose value is exponentially decreasing with increasing distance of the swarms, with

\[
F_{\text{rep}} = \pm \exp\left( \gamma_{\text{rep}} - |p_i - R_{\text{rep},i}| \right), \tag{8}
\]

where the sign \( \pm \) depends whether the flock is on the left or right side, respectively. The value of the factor \( \gamma_{\text{rep}} \) was chosen so that the repulsive force is close to zero when the swarms have a distance of approximately one lane width. Contrary to the other rules, the repulsing flock rule has a strong effect on the position of the boids when the distance is small. The rule is exemplary depicted in Fig. 2. Although the rule is formulated generally in both longitudinal and lateral direction, the separation of flocks is only carried out in lateral direction and is considered in the weighting factor \( W_{\text{rep}} \), which is explained in the following.

D. Position Update

The presented five behavioral rules are combined in an updated velocity vector \( v_i' \) of the \( i \)-th boid and added to the velocity vector \( v_i \) of the previous cycle:

\[
v_i' = v_i + w_{\text{coh}} f_{\text{coh}} + w_{\text{coh},1} f_{\text{coh},1}
\]

\[
+ w_{\text{all}} f_{\text{all}} + w_{\text{sep}} f_{\text{sep}} + W_{\text{rep}} F_{\text{rep}}^T,
\]

where the weighting factor \( W_{\text{rep}} \) for the repulsive behavior is given by

\[
W_{\text{rep}} = \begin{bmatrix} w_{x,1} & w_{x,2} & \cdots & w_{x,N_{\text{f}}} \\ w_{y,1} & w_{y,2} & \cdots & w_{y,N_{\text{f}}} \end{bmatrix}
\]

with \( w_{x,j} := 0 \) and \( w_{y,j} := \text{sgn}(p_{y,j} - R_{\text{rep},j}(y,\cdot)) \). The remaining weighting factors are optimized heuristically and the chosen values can be found in Table I.

Given the updated velocity vector, the new position of the \( i \)-th boid can be calculated straightforward by

\[
p_i' = p_i + v_i'.
\]

E. Life-cycle of Boids

Unlike other publications using Boids flocking algorithm, it is assumed in this paper, that boids have a rather short lifetime, meaning a boid is spawned and will eventually cease to exist within a duration of a few hundred update cycles, whereas each cycle is assumed to have a duration of about 80 ms.

As soon as a lead vehicle is consistently tracked, boids will be spawned by the lead vehicle every 100 ms until \( N_{\text{b}} \), boids per flock exist. The position of the lead-vehicle as well as the lateral and longitudinal velocity from the previous cycle will be provided to the new boid and serve as initial values.

F. Reachability analysis with Dubins path

Simulating the movement of the boids of each flock according to (9) and (11), it can be seen that the resulting path of each boid is only \( C_0 \)-continuous and that boids may "jump" sideways. In order to constrain the movement of boids and keeping in mind that boids shall follow vehicles with non-holonomic constraints, the reachability of the updated position of a boid is checked by a path generated using a Dubins path [13]. Dubins paths consist only of straight paths (‘S’) and curve segments with a restricted radius, i.e. left curve (‘L’) and right curves (‘R’), respectively.

The minimum radius \( r_{\text{min}} \) is given by the longitudinal velocity \( v \) and a fixed maximum lateral acceleration \( a_{\text{lat,max}} \):

\[
r_{\text{min}} = \frac{v^2}{a_{\text{lat,max}}}. \tag{11}
\]

The maximum lateral acceleration for each boid is chosen to be 9 m/s², which results in a radius of about 60 m at a velocity of 23 m/s. In order to calculate a Dubins path from the current position to the updated target position of a boid, the start and target pose need to be determined, where as the orientation angles of start \( \varphi_i \) and target pose \( (\varphi_i') \) of a boid are calculated by

\[
\varphi_i = \text{atan} 2 \left( \frac{y_i}{x_i} \right), \quad \varphi_i' = \text{atan} 2 \left( \frac{y_i'}{x_i'} \right) \tag{12}
\]

which yields \( \xi_i = [p_{x,i}, p_{y,i}, \varphi_i]^T \). With the given start and target pose as well as maximum radius, the resulting Dubins path will be evaluated. Exemplary evaluations are depicted in Figure 3 whereas valid paths are given in green and invalid paths in red. It can be seen that as soon as detours
are required to reach the target pose, this pose is discarded either due to its position and/or orientation. Instead, in an iterative process, the target pose is changed in both position as well as orientation within a small radius — and thus speed in lateral and longitudinal direction — until the target pose can be reached without detours or until a maximum number of iterations is reached, which can be used to reduce false reactions of driver assistance systems.

III. NUMERICAL RESULTS

A three-lane highway scenario with three target vehicles is considered in the following with one vehicle driving in each lane and shown in Figure 4. The course includes gentle curves as well as straight sections. The ego vehicle and the preceding vehicle in the same lane (ID:2) are driving with the same velocity of $v_{ego} = v_2 = 25$ m/s at a distance of about 30 m, which results in a timegap of $T_G = d_2/v_2 = 1.2$ s; a typical headway distance of an ACC system. A slightly slower vehicle (ID:3) is driving on the right lane while a faster vehicle (ID:1) is approaching the ego vehicle from behind, eventually overtaking the ego vehicle and the other two vehicles. The parameters of the simulation setup are summarized in Table I. A standard sensor setup for advanced driver assistance systems is chosen for the ego vehicle, comprising a long range radar as well as a monocular camera. The detection of each sensor are subsequently fused providing qualified tracked objects. These tracked objects serve as potential leaders to create the individual flock of boids.

As the chosen velocities of the target vehicles (ID:2) and (ID:3) differ by only 2 m/s, the reflections of the radar sensors of the two vehicles are ambiguous and false associations are likely. As a consequence, the lateral position of a tracked object may be shifted in lateral direction or worse, reflections of two vehicles are merged into one tracked object.

![Fig. 4: Usecase description](image4)

![Fig. 5: Split-violin plots for the distribution of the lateral distance between vehicles on the ego and left lane (Ego-Left) as well as vehicles on the ego and right lane (Ego-Right). Lateral distance of boids in blue (left violin), lateral distance of tracked objects (i.e. inputs) in red (right violin).](image5)
The intention of the boids is not to determine a better estimate of the ground truth position compared to the tracked objects but to mitigate the shortcomings of the sensors by providing additional information about the relative position of the vehicles. Hence, the relative distance between the vehicles is taken as a measure for the target discrimination. The distance will be taken from the two pairs of target vehicles, whereby ‘Ego-Left’ refers to the target combination (ID:1 and ID:2) and ‘Ego-Right’ to the target combination (ID:2 and ID:3).

The numerical results are shown in Figure 5 for increasing swarm sizes, combining a boxplot with the probability distribution, which allows for a better comparison of the two setups. For the visualization of the numerical results, violin plots [14] are chosen. Each subplot compares the distribution of the lateral separation determined by the tracked objects (in red) and determined by boids (in blue). The median of the distribution is given by the black horizontal in the center of the notch, whereas the mean value is denoted by the black star. Correspondingly, first and third quartile are represented by the borders of the dark colored area, while the light colored region ranges from the first to the 99th percentile.

As expected, due to the setup of the scenario, the lateral separation of the right pair ‘Ego-Right’ is worse than that of the pair ‘Ego-Left’ due to the smaller relative velocity and therefore increased difficulty for the target discrimination in the environmental model. The smallest swarm size, with \( N_b = 3 \) (cf. Fig. 5a), shows a performance that is inferior to that of the tracked objects. This becomes clear by the smaller median of the distribution (2.4 m compared to 3 m) as well as stronger outliers for the Ego-Right pair.

With increasing swarm size, e.g. \( N_b = 7 \) (cf. Fig. 5b), the median of the lateral separation increases for the boids slightly above 3 m for the Ego-Right pair which approaches the true lateral separation of 3.7 m. The medians for the Ego-Left pair for both boids as well as tracked objects are comparatively close together, which was expected since the target vehicles (ID:1 to 3) drive parallel to each other only for a short time due to the higher relative velocity. However, the outliers for the tracked objects below a lateral separation of 2 m could be mitigated.

Interestingly, the results are not exclusively improving with a further increasing swarm size, see Fig. 5c for \( N_b = 14 \). The separation rule forces the boids to split along the longitudinal axis, which leads to an increased distance between first and last boid and thus a decreased influence on the average swarm position due the limited field-of-view of each boid.

| Velocity ego vehicle ID:0 \( v_{ego} = 25 \text{ m/s} \) | Velocity black car ID:1 \( v_1 = 24 \text{ m/s} \) |
|-----------------------------------------------------|---------------------------------------------|
| Velocity black car ID:2 \( v_2 = 25 \text{ m/s} \) | Velocity truck ID:3 \( v_3 = 23 \text{ m/s} \) |
| Lateral separation ID:1-ID:2 \( d_{12} = 3.2 \text{ m} \) | Lateral separation ID:2-ID:3 \( d_{23} = 3.4 \text{ m} \) |
| \( w_{rep} \) \[0.15, 0.6, 0.8] \| \( w_{coh} \) \[0.4, 0.4, 1] \| \( w_{coh,1} \) \[0.4, 0.2, 1] \| \( w_{all} \) \[0.3, 0.3, 1] \| \( T_{rep} \) 1.5 |

**TABLE I: Parameters of the considered usecase as well as for the flocking algorithm.**

The average lateral position information of a swarm can be used either for lane association or for the improvement of a lane change detection in low-cost driver assistance systems. So far, only moving traffic participants have been used to create new flocks of boids. In the future, also static infrastructure, such as guard rails, lane markings, etc. shall be used to create flocks of boids. In combination with the flock repulsion rule, it will be investigated whether the target separation of parallel driving vehicles can be improved even further.

**REFERENCES**

[1] J. Lundgren and A. Tapani, “Evaluation of safety effects of driver assistance systems through traffic simulation,” *Transportation Research Record*, no. 1953, pp. 81–88, 2006. [Online]. Available: [https://www.researchgate.net/publication/228899228_Evaluation_of_Safety_Effects_of_Driver_Assistance_Systems_Through_Traffic_Simulation](https://www.researchgate.net/publication/228899228_Evaluation_of_Safety_Effects_of_Driver_Assistance_Systems_Through_Traffic_Simulation)

[2] Regulation (EU) 2019/2144, “Type-approval requirements to ensure the general safety of vehicles and the protection of vulnerable road users,” 2019.

[3] A. Eskandarian, “Research Advances in Intelligent Collision Avoidance and Adaptive Cruise Control,” *IEEE Intelligent Transportation Systems Magazine*, vol. 4, no. 3, pp. 143–153, 2003.

[4] F. Folest and H. Rohling, “Data association and tracking for automotive radar networks,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 6, no. 4, pp. 370–377, 2005. [Online]. Available: [https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1549841](https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1549841)

[5] M. Weinberger, “Adaptive cruise control field operational test – the learning phase,” *JSAE Review*, vol. 22, no. 4, pp. 487–494, oct 2001.

[6] D. Zhang, K. Li, and J. Wang, “Radar-based target identification and tracking on a curved road,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 226, no. 1, pp. 39–47, sep 2012.

[7] M. Song, C. Kim, M. Kim, and K. Yi, “Robust lane tracking algorithm for forward target detection of automated driving vehicles,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 233, no. 7, pp. 1930–1949, jun 2019.

[8] C. W. Reynolds, “Flocks, Herds, and Schools: a Distributed Behavioral Model.” *Computer Graphics (ACM)*, vol. 21, no. 4, pp. 25–34, 1987.

[9] ——, “Steering behaviors for autonomous characters,” *Game Developers Conference*, pp. 763–782, 1999.

[10] Y. Hayashi and T. Namerikawa, “Flocking algorithm for multiple nonholonomic cars,” *2016 55th Annual Conference of the Society of Instrument and Control Engineers of Japan, SICE 2016*, pp. 1660–1665, nov 2016.

[11] “ISO 8855:2011, road vehicles — vehicle dynamics and road-holding ability — vocabulary,” 2011.

[12] C. Hartman and B. Beneš, “Autonomous boids,” *Computer Animation and Virtual Worlds*, vol. 17, no. 3-4, pp. 199–206, jul 2006.

[13] L. E. Dubins, “On Curves of Minimal Length with a Constraint on Velocity,” *American Journal of Mathematics*, vol. 21, no. 4, pp. 25–34, 1987.

[14] J. Lundgren and A. Tapani, “Evaluation of safety effects of driver assistance systems through traffic simulation,” *Transportation Research Record*, no. 1953, pp. 81–88, 2006. [Online]. Available: [https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1549841](https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1549841)