Collision Prediction for a Mining Collision Avoidance System

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Abstract. Accidents caused by wheeled mining machines contribute to approximately 30% of injuries and fatalities in the global mining industry. Wheeled mining machines have limited driver assist features when compared to the passenger vehicle market and are typically limited to collision avoidance by braking. These products are often subject to false positive interventions leading to production losses, increased wear, and resistance to adopt the technology by end users. This study proposes a sampling-based method to expand the collision avoidance by braking approach to include steering. The sampling method is based on the vehicle's kinematics and the application of a Gaussian distribution to the steering rate to determine the probability of a collision occurring. Initial results indicate that the inclusion of steering rate on the collision prediction model may increase the operator's situational awareness, leading to fewer false positives.

Keywords: Automatic emergency braking · mining safety · collision avoidance system · situational awareness · heavy vehicle dynamics

1 Introduction and Background

New technologies are transforming the mining industry, making it cleaner and safer. One of the focus areas is the safe operation of mine transport and mobile equipment. The International Council on Mining and Metals (ICMM) reports that approximately a third of all fatalities at their member company operations are due to transport and mobile equipment accidents [1].

Mining machine Collision Avoidance Systems (CAS) are under the spotlight in South Africa, where the use of Collision Prevention Systems (CPS) is regulated [2]. Where a significant risk of injury exists due to collisions between mining machines and pedestrians (for underground mines) and between mining machines (for surface mines), mines are required to implement CPS. The regulation stipulates three distinct stages of the interaction and the subsequent response by the CPS: 1) The remote object is detected, 2) the operator(s) and pedestrian(s) (if applicable) are given an effective warning and (3) the machine is slowed and stopped [2]. Within the South African context, mobile machines include any self-propelled machine used for the purpose of mining, transport, or associated operations. Effectively, this means that all wheeled vehicles,

G. Mastinu et al. (Eds.): AVEC 2024, LNME, pp. 756–762, 2024.
https://doi.org/10.1007/978-3-031-70392-8_107

such as light vehicles, forklifts, load-haul-dumpers (LHDs) and haul trucks are subject to these regulations. At the time of writing, South Africa is the only region in the world that regulates the use of collision avoidance technology [3].

Mining collision avoidance products currently available on the market are almost exclusively retrofits that are installed on existing mining machines. Collision avoidance is provided by interfacing with the machine's SAE J1939 CAN-bus through a standardized interface [4]. The standardized interface only makes provision for the application of the machine's braking system. This limits the collision avoidance system to a single degree of freedom (effectively only half a degree of freedom since the throttle cannot be applied). Any action other than slowing and stopping the machine is left up to the operator. Existing systems typically do not instruct the operator to change direction; rather, they rely on instructions such as 'warning' or 'caution' before automatically applying the brakes [3].

The result of limiting the automatic intervention to braking, and only warning the operator, is that mining collision avoidance systems tend to be very conservative, erring on the side of caution. The result is that numerous false positives are reported, resulting in increased wear and tear, production losses and resistance to adoption from the end users [5]. It is hypothesized that improved situational awareness of the operator through increasing the design envelope of the collision avoidance system, may result in fewer false positive detections, resulting in improved performance and wider adoption.

2 Approach

Collision prediction is a vital part of CAS. Without an accurate collision prediction model that can provide a computationally inexpensive solution, a collision can be falsely predicted or neglected. Both situations are dangerous and could lead to a collision, an injury or/and a reduction in the productivity of the mining operations. The proposed method will be explained with a passing scenario. This is a scenario that frequently occurs on mining sites and is included in the User Requirements for CPS developed by the Minerals Council South Africa [6]. Figure 1 shows the passing interaction scenario, with the ego and actor vehicles indicated.

2.1 Trajectory Prediction

Collision prediction works on the principle that the future states of one vehicle are compared to the future states of another vehicle. If the predictions simultaneously occupy the same location, it is assumed that the machines will collide [7]. For this reason, a trajectory must be predicted for all relevant vehicles.

The proposed approach uses linear kinematic equations (see Eq. (1) to (7)) to predict the vehicles' future states. By applying different steering rates to a geometric Ackermann steer single-track model in conjunction with kinematic equations for yaw and the predicted x and y Cartesian coordinates, the future states of a vehicle are predicted. This provides a range of predicted vehicle states at the center of gravity of the vehicle within the kinematic constraints and steering rate limits of the vehicle. Figure 1 shows the result of the sampling-based prediction method.

Equations (1), (2), (3), (5), (6) and (7) represent the kinematic equations that calculate the predicted x and y Cartesian coordinates. Equation (4) computes steering angles by integrating different steering rates over a small time increment Δt. Equations (8), (9) and (10) represent the equations for the geometric Ackermann single-track model, which is used to constrain the maximum steering angle based on the maximum allowable lateral acceleration a_y, chosen to be 0.3 g.

$$\mathrm{x} = \mathrm{x}_0 + \mathrm{V}_\mathrm{x}\Delta\mathrm{t} \tag{1}$$

$$\mathrm{y} = \mathrm{y}_0 + \mathrm{V}_\mathrm{y}\Delta\mathrm{t} \tag{2}$$

$$\psi = \psi_0 + \dot{\psi}\Delta\mathrm{t} \tag{3}$$

$$\delta = \delta_0 + \dot{\delta}\Delta\mathrm{t} \tag{4}$$

$$\mathrm{V}_\mathrm{x} = \mathrm{V}\cos(\psi) \tag{5}$$

$$\mathrm{V}_\mathrm{y} = \mathrm{V}\sin(\psi) \tag{6}$$

$$\mathrm{V} = \dot{\psi}\mathrm{R} \tag{7}$$

$$\delta = \frac{\mathrm{L}}{\mathrm{R}} \tag{8}$$

$$\mathrm{a}_{\mathrm{y}_{\max}} = \frac{\mathrm{V}^2}{\mathrm{R}} \tag{9}$$

$$\delta = \frac{\mathrm{a}_{\mathrm{y}_{\max}}\mathrm{L}}{\mathrm{V}^2} \tag{10}$$

2.2 Trajectory Uncertainty

Trajectory prediction also includes the modelling of the uncertainty of the predicted states. Common methods include applying a Gaussian distribution to the predicted x and y Cartesian coordinates [8].

This study applies a Gaussian distribution to the steering rate of the vehicle. Figure 1 shows the trajectory prediction model for the head-on passing scenario with blue areas indicating lower probabilities. By integrating the Gaussian distribution, the probability for each steering rate is computed and applied to each predicted future vehicle state accordingly. To ensure that the predicted states of the vehicle fully represent the spatial domain, samples are added based on the width, length and heading angle of the vehicle.

The next step is a detailed analysis of the trajectory probabilities. The Euclidian distance between the predicted states of different vehicles at a certain predicted time increment is used to construct a uniform grid of collision probabilities. Using the Euclidean

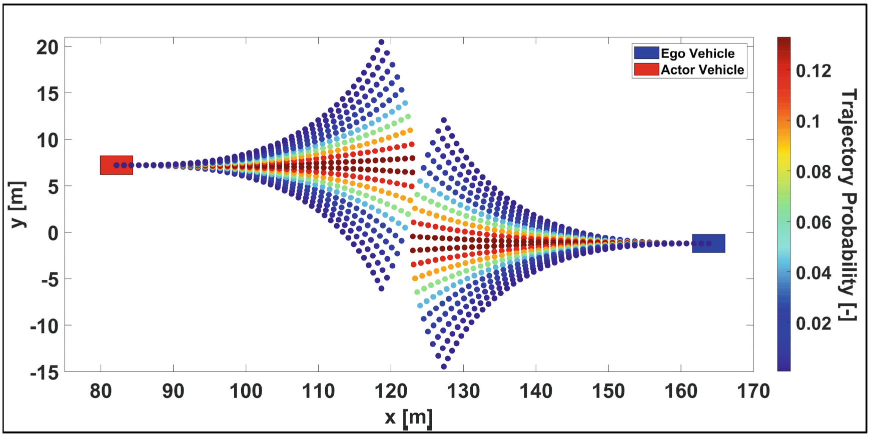

Fig. 1. Trajectory prediction for the ego and actor vehicles for a passing scenario.

distance between the predicted future states, a uniform probability grid is populated with the probabilities of each trajectory. The maximum probabilities in relevant regions of the grid are kept with a convolutional moving maximum method [9], ensuring a conservative uncertainty model. The probabilities must be normalized for all the vehicle grids to ensure consistency. Figure 2 shows the probability grids for the ego and actor vehicles, where the blue areas indicate the lowest trajectory probabilities.

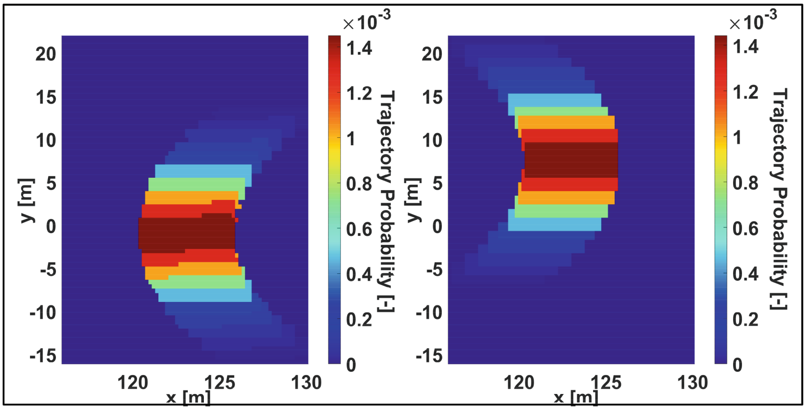

Fig. 2. Ego (left) and actor (right) vehicle trajectory probability for passing scenario.

Considering the uncertainty of the trajectory based on the steering rate of the vehicle, the safest steering direction can be determined, based on the collision prediction metric. From this information an effective warning can be supplied to the driver. This may improve the situational awareness of the operator.

2.3 Collision Metric

Common collision prediction metrics integrate probability distributions over a region to determine the probability of a collision based on the joint probability distribution of multiple vehicles [8]. The proposed model introduces a novel collision metric based on the highest trajectory probability of the different vehicles. Since it is impossible to convert the probability distributions based on the steering rate to a grid of probabilities without influencing the probability distribution, the following method is proposed: multiplying the probability grids based on the trajectory of different vehicles, a new probability grid is created. This is referred to as the collision probability grid. Since this produces very small numbers due to the multiplication of probabilities, a method is developed to provide a collision metric between 0 and 100, based on the probability of the steering rate, which can be converted to a percentage (Eq. (11)). P(ego) and P(actor) are all the probabilities across each uniform probability grid for the ego and actor vehicles.

$$\text{Max Collision}\ \% = \max\left(\frac{P(\text{ego})P(\text{actor})}{\max(P(\text{ego})P(\text{actor}))} \times 100\right) \tag{11}$$

This collision metric provides a percentage value which can be seen in Fig. 3. By applying a threshold to the proposed collision prediction metric, a collision can be predicted.

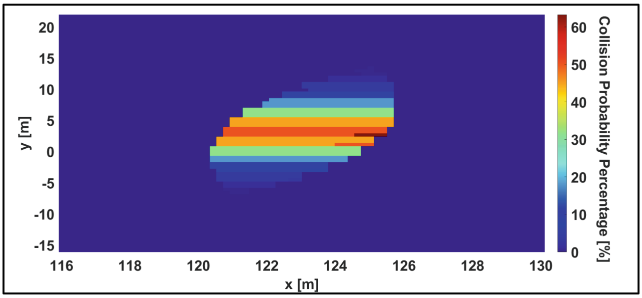

Fig. 3. Collision prediction metric for passing scenario.

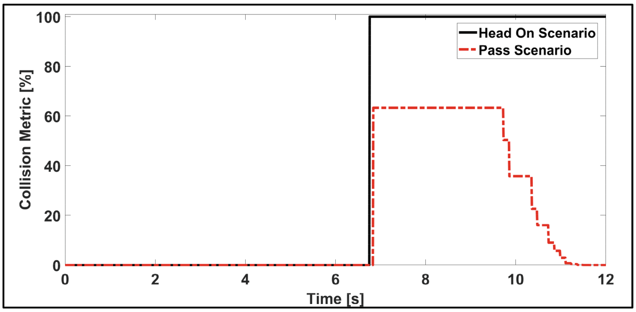

Fig. 4. Collision metric vs simulation time for different scenarios.

3 Initial Results

A passing and head-on scenario, based on [6], are modelled and simulated in RoadRunner [10]. These scenarios are used to do initial tests of the model, specifically to investigate the use of a collision prediction metric threshold to predict a collision. Figure 4 shows the collision metric of the two scenarios. The results indicate that the maximum collision metric is notably different for the two scenarios. This indicates that, for these two scenarios, it is possible to apply a threshold to the collision prediction metric, such that the head-on scenario and passing scenario will not both state that a collision will occur. The threshold can be tuned based on the maximum allowable separation distance between the different vehicles.

4 Discussion

This paper introduced a physics constrained, sampling-based collision prediction method for mining CAS. The collision prediction model used a maximum possible percentage collision probability method to determine whether a collision will occur, while the trajectory uncertainty is modelled using the steering rate. Initial results indicate that the collision prediction model has potential in terms of predicting collisions, but further investigation is needed to apply a reasonable threshold to the collision metric and test the robustness of the model. Since the probability is applied to the steering rate of the vehicle, this approach has the potential to increase the situational awareness of the operator.

It is important to note that the Gaussian distribution applied to the steering rate has a significant influence on the collision prediction metric and must be carefully chosen. The grid size, predicted steering rate samples and predicted time increment, all significantly influence the performance and computational efficiency of the proposed method and needs to be investigated in more detail.

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