Time-optimal collision avoidance of automatically guided vehicles

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Extended abstract

Collision avoidance is a main issue in applications employing free-ranging, computer-controlled vehicles. In this paper we look at the regulation of locally crossing traffic. Collisions are typically avoided by changing speed and/or changing route, but– to keep efficiency high– as minimal as possible.

If we look at humans going by foot in crowded areas or driving by car in urban traffic, we observe a high degree of flexibility. The challenge is to reach the same flexibility with computer controlled driver systems. Preliminary research on dynamic ways of traffic control [1] has indicated that considerable improvements can be reached in comparison to the more static approach of traditional zone claiming methods, in particular in case of busy traffic.

When searching for the best solutions there are many criteria to consider: time delay, throughput, total travel time, planned arrival time, energy consumption, comfort, et cetera. We will limit our selves to a single optimality criterion: *minimal time delay*. Even then we are faced with a huge space-time resource allocation problem [2].

In the paper, first we analyze the passage of two vehicles that drive on a conflicting course as depicted in the left part of Fig. 1.

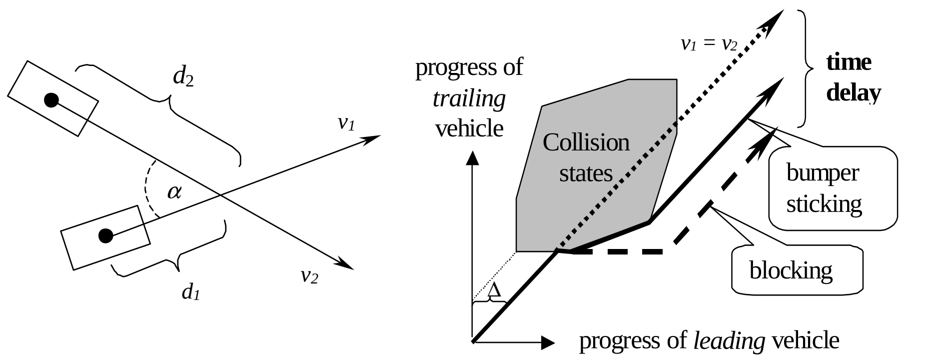

Fig. 1. Joint motion state diagram (shown on the right) of two vehicles crossing with angle α (as shown on the left) with the leading vehicle having advantage $\Delta = d_2 - d_1$ and the trailing vehicle adjusting its speed ($v_2 \leq. v_1$).

Basically, the following options for collision avoidance exist: (1) speed adaptation, (2) route deviation by one vehicle only, (3) route deviation by both vehicles and (4) combined speed and route adjustment. In the case of speed adjustment generally only the vehicle driving behind (i.e. the “trailing” vehicle) will slow down (or make a temporary stop). The resulting delay depends on the passing strategy: a minimal delay is obtained if the *trailing* vehicle immediately advances after the *leading* vehicle (“bumper sticking” mode). For safety reasons one may require that the trailing vehicle only proceed if its pathway is completely cleared (“blocking” mode). The observed time delay can be visualized in a state diagram representing the joint motion (right part of Fig. 1). The indicated area of collision states depends on the vehicle sizes and the crossing angle [5].

In Fig. 2 we show two ways of vehicle passing by route deviation. In the left drawing only one vehicle makes a detour by changing its direction three times. In the right drawing both vehicles make a detour along a (virtual) roundabout.

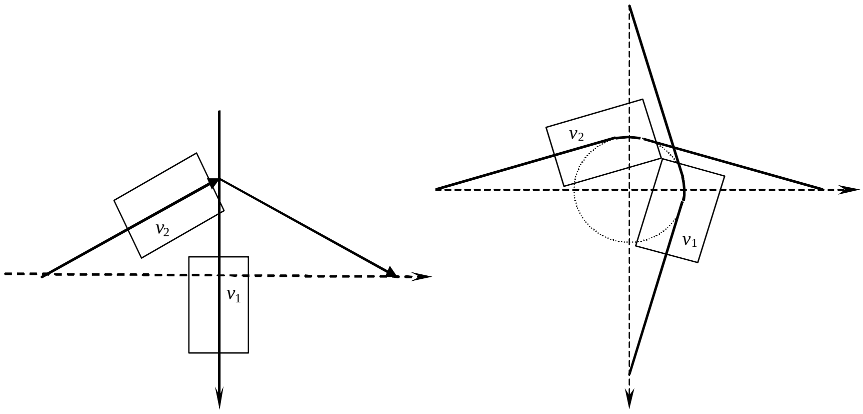

Fig. 2. Examples of unilateral and bilateral collision avoidance detours.

Under certain symmetrical assumptions the optimal avoidance maneuver of two vehicles giving minimal mean delay has been determined. If conditions become asymmetric due to unequal priorities or different destination distances, it becomes more difficult to pinpoint the optimal solution.

An important aspect of the result obtained for two passing vehicles is that it indicates an approach to guide multiple conflicting vehicles in passing each other efficiently. By means of simulation experiments it has been shown in [2] that this approach leads to quite natural avoidance detours for all kinds of multiple robot crossing patterns. The solution method very much contrasts to the usual approach of planning motion paths sequentially in some optimal priority order [4].

The shape of the optimal avoidance maneuver of two vehicles can be found by global arguments. During an optimal avoidance detour the vehicles will come “in close contact” somewhere (without colliding), otherwise a shorter detour is possible. The fastest way to reach the first close contact configuration (the “meeting” state) will be along a straight line from the starting points. The same holds for the fastest way to leave the last close contact configuration (the “greeting” state) in order to approach the destination. In between "meeting" and "greeting" the vehicles remain in close contact. Otherwise they would make a relative movement that – given some maximal speed - slows down reaching the greeting state.

As long as vehicles move along straight lines, their orientation will remain invariant. However, the detour implies orientation changes that in the end have to sum to zero. In the case of equal distances from start to destination the vehicles will make a symmetric and synchronized detour. To compensate for the orientation deviations at the starting and destination points (with respect to the direct route) the vehicles – being in close contact – will rotate simultaneously, i.e. move as a coupled pair along a virtual roundabout as shown in Fig. 3.

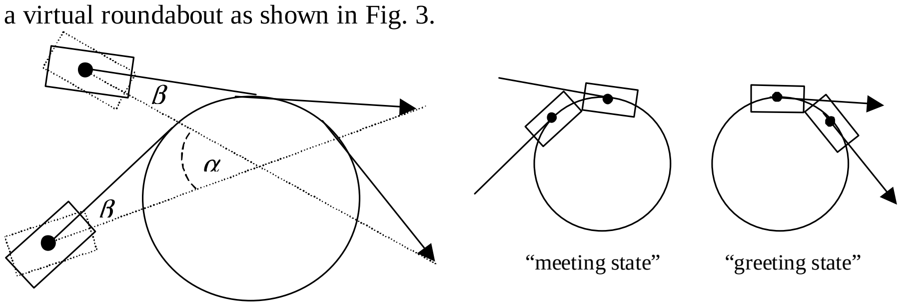

Fig. 3. Time optimal avoidance detour over equal distances.

The shape of the vehicles determines the size of the roundabout, as they must fit to the roundabout. The placement of the roundabout is determined uniquely as the vehicles must meet on the roundabout at the same time. As a consequence, the optimal deviation angle β and the length of the detour route can be calculated. The delay is found by comparing the detour route with the direct route.

If the travel distances to the destinations differ, deviation angles will also differ. Hence, the turning to compensate for the orientation changes will not be equal. Making different turns along a common roundabout is certainly a near-optimal solution. However, it is not yet clear if this maneuver is also optimal.

An obvious property of the optimal avoidance detour is that it remains optimal at any intermediate state as long as the destinations do not alter. Therefore, steering the vehicles at any instant along the optimal deviation route will lead automatically to the optimal passing maneuver. Consequently, reactive control can be applied to reach optimal avoidance. Reactive control has the additional advantage that it is stable with respect to errors. Moreover, it will adapt to changes of the destinations. Hence, it can be applied fruitfully to vehicle control systems with dynamically changing goals like for instance robot soccer.

The optimal passing maneuver of two vehicles provides a strong "heuristic" to attack the case of multiple controllable robot vehicles. For each pair of robots the optimal deviations necessary to avoid a collision are known. Of course, if more robots are involved, different and sometimes incompatible avoidance courses have to be satisfied. The best strategy will be to find some acceptable compromise, for example taking the largest deviation needed. Clusters of colliding robots have to be identified of which the deviations must be coordinated. The strategy comes down to finding the best "virtual roundabout" that solves the mutual conflicts within the cluster. It has been shown that applying the deviation control in an iterative, reactive manner does work effectively in most cases [3].

Pure route deviation without speed adaptation could in case of multiple conflicts lead to large, undesirable detours. Also avoiding a non-cooperative robot by unilateral route deviation may be less favorable than lowering speed. Good heuristics for the optimal mixture of route deviation and speed adaptation still have to be discovered. Robot soccer [6] provides a perfect test environment both for unilateral collision avoidance (in case of opponent players) as for cooperative avoidance (in case of team mates).

It is conjectured, but not yet rigorously proven, that in the case of mutual avoidance (1) any "unequal-delay" solution leads to a higher mean delay compared to the *minimal mean delay* obtained by the "equal delay" cooperative solution, and (2) route deviation at full speed can always outperform any solution with speed reduction.

Optimal reactive control for mutual avoidance provides a powerful heuristic for a multiple vehicle avoidance strategy. For all conflicting vehicles the mutual, optimal deviation course can be calculated. These courses can be recombined in a conservative and consistent manner to get a global solution that approaches the pair wise optimal avoidance as much as possible. Combining and merging the individual interests of multiple traffic participants needs further research.

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