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EFFICIENT AND SAFE NON-COOPERATIVE ALGORITHM FOR MOVING ALONG THE GIVEN ROUTE IN CITY TRAFFIC

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ABSTRACT

Any algorithm of automatic motion that is intended to be used in city traffic must have its safety proven. That is, it is necessary to prove that all dangerous situations (i.e. potential collisions) will be detected and avoided by the algorithm.

Currently, such solution does not exist. Cooperative algorithms are not usable in the real city traffic, since it is not possible to deploy such algorithms on all road users. The most effective and intelligent automatic traffic motion non-cooperative algorithms are based on machine learning and therefore could not have their safety proven, or merely do not address a safety issues.

This paper presents an algorithm based on satisficing games theory. Such theory allows for proving that if the safe strategy exists, it would be found by the algorithm. Similar algorithms, which are used in airborne non-cooperative collision detection and avoidance systems constraint behavior of the moving objects based on the laws of physics only. They appear to be unusable in the city traffic due to its high congestion.

We have introduced traffic rules as limitations in a model of the road traffic. Such improvement allows for constraining possible trajectories of the road users. In most of the situations this is enough for the algorithm to generate safe collision avoidance strategy.

The route is given as a list of consequent road sections. The algorithm uses readings of vehicular on-board sensors to determine current traffic situation and produces a sequence of control actions to move vehicle along the route avoiding potential collisions with obstacles and other road users.
To take into the account road users who do not follow the traffic rules, the algorithm is able to detect users who violate the rules. For possible trajectories of such road users, only physical constraints are applied when detecting and avoiding the potential collisions.

To validate the algorithm, a simulation model of city traffic has been developed within the REPAST simulation framework. Both algorithms (with and without road regulations) have been implemented and compared using the simulation model. In a course of simulation experiments, it was shown that our algorithm finds efficient solutions in most of the road situations. Safety of the solutions generated by the algorithm is proven based on satisficing game theory apparatus.

TECHNICAL PAPER

INTRODUCTION

Development of the automatic car control system is a life-long dream of the automotive industry. Such system must perform several tasks. Namely, they are:

1) Global route planning (finding an optimal path between the starting point and the destination),
2) Local route planning (finding the trajectory of safe movement on the designated route),
3) Automatic motion (using control levers to make car moving on a desired trajectory).

There are feasible algorithms for global route planning (1, 6) and automatic motion tasks (4-5). There are still a lot of research directions towards finding optimal solutions (2, 3), but known algorithms are suitable for the automotive industry. Path-finding algorithms usually are implemented in navigating software. Automotive driving algorithms are implemented in modern driving aid systems: antiskid braking systems, adaptive cruise control, car-following systems, automatic parking and overtaking.

However, there is a gap that prevents car manufacturers to create automatic car control. The main problem is solving the local route planning task. In a course of movement along a designated route, the car interacts with objects which were unknown on the global route planning stage. Such objects include other road users, pedestrians, fixed obstacles and traffic limitations[1], which are not marked on a city map.

Modern perception ant scene analysis facilities allow the vehicle to obtain information about its physical environment (8-11). Thus, the control system of a car can get all the data on the traffic situation. Based on these data, in a course of local planning it should plan the trajectory of the car according to the traffic situation. The trajectory must be safe for the car, its passengers and other road users. Additional optimality criteria may also be imposed: minimization of traffic rules infringement, moving time, fuel consumption, vehicle wear and tear and so on.

Either cooperative or non-cooperative approaches (7) are possible to solve the local route planning task. In the cooperative case, cars take a negotiated solution based on either centralized or distributed algorithm. In the non-cooperative case, car that is running the ACS decide independently, based on the traffic situation, without interaction with other road users.

Purely cooperative solution of the local route planning task is not of practical interest, if only because of the presence of the pedestrians on the road. Simultaneous adoption of ACS by other road users is also hardly possible. Thus, only non-cooperative approaches are appealing from the viewpoint of practical application and implementation in the automotive industry. Cooperative techniques could be used to enhance and optimize obtained solutions, but should not be in their base.

All approaches to local route planning can be grouped in rule-based and sample-based (i.e. learning). Learning approach to the ACS cannot be employed in civilian cars. The reason is that learning algorithms inherently lack of decision feedback, i.e. information on how the algorithm takes a decision. This makes it impossible to verify the work of the algorithm and

[1] Road signs, markings and traffic lights.

prove it is safe, whereas ACS algorithms that are used in city traffic must have their safety proven. “Safety” here means that 1) the algorithm will not lead the car in the state of an inevitable collision, and 2) when the algorithm detects a potential conflict, if the safe trajectory to avoid the collision exists, it will be found. As with cooperative approaches, the use of heuristics and learning is acceptable only for optimization of the constructed solution. The fact that if a safe solution exists, then it will be found must be strictly proven.

Top systems that have taken prizes in DARPA Urban Challenge (9-11) employ rule-based approaches with heuristic-based optimization, yet they do not address safety of the obtained solutions.

THE PROPOSED APPROACH TO LOCAL PLANNING IN CITY TRAFFIC

The task similar to the local route planning for city traffic is solved in air traffic management (7, 12-15). In this domain, there are known safe non-cooperative algorithms for conflict detection and resolution (CD&R). These algorithms guarantee 1) detection of all potential conflicts and 2) finding of an existing safe trajectory in case of a potential conflict exists (15). However, the direct application of these algorithms for the automatic car control in city traffic is impossible.

In CD&R for the air traffic, “conflict” means the hazardous proximity of aircrafts, defined by air traffic regulations. The corresponding CD&R algorithms assume that the possible trajectories of other aircrafts are limited only by the laws of physics. A relatively low density of the air traffic allows such algorithms to obtain safe and feasible solutions (i.e. sequences of actions, which drive a plane along a safe trajectory) (15).

When applying similar algorithms to the city traffic, a number of features of this domain must be taken into account:

1) Conflict is defined as the inevitable collision, not the hazardous proximity. To identify inevitable collision, a special cone of trajectories is constructed for each road traffic participant. This cone consists of such trajectories, that if the car under ACS control got itself into this cone, it won’t be able to avoid collision. Therefore, conflict detection for city traffic requires more computer resources.
2) Greater number of neighbor traffic participants and greater traffic density. This also increases the computational complexity of the local planning and imposes harder requirements on the scalability of the algorithms.

However, increased complexity is not the main problem here. The main problem is that if the possible trajectories of other road users are limited only by the laws of physics, then solutions obtained by the ACS would not be feasible. Moreover, for many trivial traffic situations there will not be safe solutions at all.

For instance, consider the car running ACS is moving in the left lane of a two-way road, with another car moving at high speed in the left oncoming lane. At the time of their closest proximity, the ACS will not be able to prevent their collision in case the oncoming car suddenly changed its trajectory and crossed into the wrong lane. Actually, no one will be able to prevent such collision. Therefore, the ACS based only on the laws of physics in this situation decides to change lanes to the right, in order to go around the oncoming car with a large margin. In a narrow roadway the ACS will decide to park and wait until the oncoming car has passed. Moreover, in case of dense headway traffic, there will not be a safe decision at all. The same thing will happen in case of local planning in road congestion.

Lack of acceptable solutions in the situation described above – is a result obtained on a strict basis of the laws of physics. Does that mean it is not possible to build a safe trajectory for a car in city traffic? No. It only means that the notion of "safety" based only on laws of physics is too hard for use in city traffic.

City traffic exists in its present form, with such density and number of road users, just because the laws of physics are not the only limitation to the possible trajectories of vehicles. Other limitations, which are the key for the city traffic, are the traffic rules. It is the traffic rules and the assumption that all road users follow them allows the oncoming cars to move at high speed with small margin. Only due to the regulations cars in a traffic jam can safely and non-cooperatively move on such a small distance between each other. If the traffic rules are not strict or are not followed by road users, city traffic can exist only in cooperative form with extensive interaction between drivers using shouts, horns and distance lights – as can be seen in many developing countries.

Of course, we should forget the fact that, unlike the laws of physics, the traffic rules can be violated by human drivers. However, in reality, drivers solve this problem with ease. If the traffic behavior of a car is normal (i.e. does not violate the traffic rules), then we expect the same in the evaluation of possible trajectories of its motion. For a driver who has violated the regulations in our scope of view, more stringent criteria of evaluation are applied. Most likely, we will go around him with a large margin, slow down in order to avoid the collision or even park and wait until it has passed.

Similar principles are in the basis of the proposed local route planning algorithm. The detection and resolution of potential conflicts is performed using algorithms similar to those used in air traffic management (15). This ensures that if a safe trajectory exists, then it will be found. It is important that the safety is guaranteed, provided that the behavior of other road users satisfies the given limitations. In evaluation of possible trajectories of road users whose observed behavior is consistent with the traffic rules, strict limitations arising from the regulations are applied. That allows ACS to build an efficient and feasible route. For possible trajectories of road users found to have violated the rules, the ACS applies weaker limitations, provided only by the laws of physics.

THE MATHEMATICAL MODEL OF CITY TRAFFIC

For description and analysis of local route planning algorithms, a mathematical model of city traffic is used (6). The model allows for specification of the road network, road users and obstacles. Also it defines the concepts of maneuver, collision, and conflict (i.e. the inevitable collision). The notion of a safe route is stated as such trajectory of a car, that the car does not go in into a conflict state for all points of the trajectory. The model (6) with minor additions from (16) is outlined below.

The model considers a finite set of *objects* Q in two-dimensional Euclidean space W. Each object $a \in Q$ defines a closed polygon in W. Each point from a has a fixed position in some coordinate system F_a. The *state* s of object a is defined by quadruple a position (x, y) of F_a in W, rotation θ of X-axis of F_a in W and velocity v of F_a in W: $s = (x, y, \theta, v)$. Set of the possible states of the object is denoted by S. A polygon that corresponds to an object $a \in Q$ in a state $s \in S$ in space W is denoted by $p_S(a, s)$.

A *continuous motion function* (or *trajectory*) $a(t)$ is defined for any $a \in Q$. State of $a \in Q$ at time τ is denoted by $a(\tau)$. Therefore, a polygon of $a \in Q$ at time τ in W is denoted by $p_S(a, a(\tau))$. There is the isolated object $A \in Q$, which has the *starting point*, *destination* and *global route*. Other objects are called obstacles and denoted by $B = Q \setminus \{A\}$.

State s_A of the object A is a *collision with object B* in state s_B if their polygons intersect:

$$p_S(A, s_A) \cap p_S(B, s_B) \neq \emptyset$$

Any object o in any state s_o is able to perform a discrete set $U(s_o)$ of *actions*. *Action* (u^ξ, u^v) is defined by a change in velocity u^v and direction of motion u^ξ. Therefore, a *motion* of object A is defined as $\frac{\partial s}{\partial t} = f(s(t), u(t))$, where $s(t) \in S$ define a state of the object, $u(t) = (u^\xi, u^v) \in U$ define a maneuver ($u(t)$ is a continuously differentiable function), $f: S \times U \to S$ (16).

Maneuver is a timed sequence of actions $\psi: [t_0, t_f] \to U$. Object A that performs at time $t \in [t_0, t_f]$ a maneuver ψ, which has been started in state s_0, is denoted by $\psi(s_0, t)$. An object with the starting velocity equal to zero and the maneuver that is identically equal to zero is called a *fixed obstacle*. Its position in W is constant and does not change over time.

Further it is assumed that there is a distance function $J: S \times S \to \mathbb{R}$ for object states. An example of such function is a geometric distance $J(s_1, s_2) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$.

THE NOTION OF INEVITABLE COLLISION AND SAFETY

State s is called an *inevitable collision*, or a *conflict, for a given maneuver* $\psi: [t_0, t_f] \to U$ **iff** during the maneuver a collision happens (17): $\exists t \in [t_0, t_f]: \psi(s, t)\ is\ a\ collision$

For some object a and maneuver $\psi: [t_0, t_f] \to U$, a set of states $ICO(a, \psi)$ is called *inevitable collision with an obstacle during the maneuver* ψ (17), if the maneuver ψ from state s leads the car to the collision: $ICO(a, \psi) = \{s \in S | \exists t, \psi(s, t) \in a(t)\}$

A set of states $ICO(a)$ is called an *inevitable collision with obstacle* if there is no maneuver such that it does not lead to the collision (17): $ICO(a) = \{s \in S | \forall\psi\exists t, \psi(s, t) \in a(t)\}$

State s is called an *inevitable collision*, or *conflict*, iff any possible maneuver from this state leads to the collision: $\forall\psi\exists t_c: \psi(s, t_c)$ is a collision.

A trajectory corresponding to the starting state s_0 at time t_0 and the maneuver $\psi: [t_0, t_f] \to U$ is *safe* **iff** it does not contain conflict states: $\forall t \in [t_0, t_f], \nexists a: s(t) = \psi(s_0, t) \in ICO(a)$.

Let s at time t_0 be an inevitable collision. Let t_c is a collision time with a for some maneuver ψ. Then any state between t_0 and t_c is also an inevitable collision: $\forall t \in [t_0, t_c], s(t) = \psi(s, t) \in ICO(a)$ (proven in (17)).

For any trajectory on $[t_0, t_f]$, if: 1) the trajectory does not contain collision states, and 2) the trajectory does not lead to the inevitable collision state ($\forall a, s(t_f) \notin ICO(a)$), then it is safe (proven in (17)).

INTRODUCING TRAFFIC LIMITATIONS

The model (6) allows for specifying the laws of physics that restrict the possible trajectories of road users. To specify the limitations arising from road signs, marking and the traffic rules, the concept of *limitation* is introduced in this paper. The limitations are geometrically tied to areas of the carriageway. In general, limitations restrict possible actions of the car in a designated area of the carriageway. There are several groups of limitations identified, as follows.

Static limitations specify permanent limitations on possible vehicle trajectories. Examples of such limitations are speed limitations, road signs and obstacles. A static limitation is defined as a pair $C_S = (P, R)$, where $P \subseteq W$ is an area of the carriageway, $R \subseteq S_P \times 2^U$ is a set of actions, allowed for objects in states S_p within P. If $R \equiv \emptyset$, then the static limitation is a fixed obstacle.

Dynamic limitations specify a set of limitations and a set of time intervals, which define when a particular limitation is applied. An example of such limitation is a traffic light. A dynamic limitation is defined as a triple $C_D = (P, R, T)$, where P and R are defined as above and T is a time interval when the limitation is applied.

Simple static and dynamic limitations specify rules that apply to all road users. In some cases, the applicability of traffic rules depends on a set of conditions. For example, driving on a yellow sign is allowed, if the driver cannot stop without emergency braking. To account for such rules, *conditional limitations* are introduced. A conditional limitation is defined as $C_C = (P, C, R_T, R_F, T)$, where C is a Boolean condition, R_T is applied when C is true, R_F is applied otherwise, P and T are defined as above.

All the limitations described above are tied to some stationary object (e.g. a fixed obstacle, a road sign, road marking). Regulations that limit trajectories of road users relative to each other are specified using *object limitations*. An example of such limitations is traffic priority rules. An object limitation is a special case of conditional limitation.

For each type of the limitations introduced above, the operation of *reduction to the general form of limitation* is defined. It is shown that the set of limitations in general form is closed under the reducrion operation. Thus, a notion of *general limitation* is introduced, which is a superposition of all static, dynamic and conditional limitations in the local area $W_L \subseteq W$.

A PROBLEM OF LOCAL PLANNING A SAFE ROUTE

Within the model described above, the problem of continuous planning a safe route is formulated as follows.

Given: a moment of time $\hat{t} \in T$ and:
1. $\hat{g}$ - general limitation,
2. a set of moving objects B, such that $s(t), t \in [0, \hat{t}]$ and possible actions U are defined,

3. the starting state s_0 of the object A,
4. the set of destination states $S_f \subset S$ for A,
5. route planning time interval T,

Calculate: a maneuver $\psi(t)$, such that trajectory $s(t)$ is safe and leads from the starting state s_0 to a state from S_f. Among all safe trajectories, the trajectory with minimal distance from $s(\hat{t})$ to S_f is chosen.

In practice, the continuous problem has a very high computational complexity and does not have a solution in case of insufficient information about other road users. It is therefore proposed to search a safe maneuver are regular time intervals. A problem of discrete planning a safe route with limitations is formulated as follows:

Given:
1. a set of possible states S, defined by a general limitation $\hat{g}$,
2. a set of obstacles B and their possible trajectories $B(t)$,
3. the starting state s_0 for the object A,
4. the set of destination states $S_f \subset S$ for A,
5. route planning time interval T,
6. time interval Δ between two consequent actions,

Calculate: a sequence of actions $\psi = (u_1, \ldots, u_k),\ k = \frac{T}{\Delta}$, such that $s(t)$ is safe. Among all safe trajectories, the trajectory with minimal distance from $s(k)$ to S_f is chosen.

AN APPROACH TO CONFLICT DETECTION AND RESOLUTION IN CITY TRAFFIC

A problem of discrete local planning a safe route reduces to a problem of detecting potential conflicts and resolving them (i.e. finding a safe trajectory), solved at regular time intervals. Existing approaches to solving the problem of conflict detection and resolution (CD&R) can be categorized by the following criteria:
1. cooperative/non-cooperative;
2. centralized/decentralized;
3. an approach to generating the solutions: either choose from a list of rules (18-19), or minimize the cost function (15,20), or solve a system of equations (21), or interact with a driver (22);
4. coverage: distinct solution for each road user in the local area or single general solution for all road users in the local area.

As stated above, for ACS in city traffic only non-cooperative decentralized algorithms that do not involve human interaction are feasible. This paper employs a method of collision avoidance based on satisficing games (15). This means when planning a safe route, the goal is not the best solution, but a solution that is sufficient (acceptable) for the greatest possible number of the road users.

The main idea of the algorithm (15) is that any action (e.g. maneuver) of the car controlled by the ACS is evaluated in terms of its usefulness and cost. The usefulness of a maneuver is inversely proportional to the distance to the route destination after the maneuver. The cost of a maneuver is proportional to a probability of getting into a conflict with other road user. The difference between these estimates provides a fair assessment of the impact of the action. At each step, the algorithm considers all possible maneuvers and selects a maneuver that has the maximal impact.

Algorithm that implements the proposed approach to local route planning differs from the original algorithm (15) by the presence of additional limitations corresponding to the traffic rules. These limitations are taken into account when constructing a set of possible maneuvers for all road users in the local area. Maneuvers that violate the limitations are not included to the set of possible maneuvers for the road users that are assumed to follow the regulations.

When constructing a set of the possible actions for the car controlled by the ACS, the limitations are taken into account in two ways. The restrictions that cannot be violated (e.g. the boundaries of the carriageway) are taken into account when constructing a set of possible maneuvers. Limitations that admit violation in order to avoid the collision are taken into account when calculating the cost and usefulness of the maneuvers. For instance, if crossing into the oncoming lane is the only way to avoid a collision, it would be performed, though it violates the traffic rules.

The complexity of the algorithm depends on a number of road users in the local area. Using known algorithms (23-25) to solve certain subtasks, the overall complexity can be roughly estimated as $O(\log(C_{SDC}) + K)*\log(R) + C_O)$, where is the total number of static, dynamic and conditional limitations, K is a number of road users, R is the maximum number of possible maneuvers of the car under ACS control, C_O is the number of object limitations.

PROOF-OF-THE-CONCEPT IMPLEMENTATION

The proposed algorithm of local route planning was validated by a computer simulation. The simulation model is based on REPAST Simphony simulation environment (26) and provides tools to:

- describe the road network with a set of static limitations (obstacles, road marking and signs),
- define the global route as a sequence of adjacent road sections from the starting point to the destination,
- specify a set of road users along with their moving scenarios,
- simulate the given scenario until the car controlled by the ACS has reached the destination. ensuring no collisions have happened.

The main goal of the simulation was to show that CD&R algorithm that takes into account traffic rules find safe solutions in such traffic situations that do not have solutions using the original algorithm (15), thus validating efficiency of the proposed approach. Only core traffic rules were considered for this purpose.

FURTHER WORK

The main directions of further work are: additional analysis of the proposed approach, fighting the computational complexity of the algorithm and discovering new applications of the proposed mathematical model and algorithm. All the directions are discussed below.

There a lot of experiments should be conducted beyond “proof of the concept” validation presented in this paper. It is necessary to analyze the proposed approach in the following directions:

- Optimal set of enabled traffic rules. Existing traffic rules have been developed for human drivers. A set of rules for an automated decision-making algorithm may differ from the

existing one. Moreover, the traffic rules for city traffic which rely on ACS may differ. This topic should be thoroughly explored.
- Granularity of traffic rules infringement. To obtain more efficient solutions, more sophisticated approach of traffic rules infringement analysis is likely to be required. The traffic rules should be split in several groups, as well as human drivers who violate them. That will allow for more fine-grained construction of the possible trajectories set.
- A number of experiments must be conducted to assess effectiveness of the algorithm. The effectiveness of an obtained solution could be evaluated as a degree of deviation from the "ideal" route, constructed with regard to the traffic rules.

One of the main obstacles to the applicability of the proposed local route planning algorithm is its high computational complexity. It may be reduced as a result of study the following topics:
- Most likely, the collision detection and avoidance task to be investigated not for all road users in the local area of the car, but only for those who directly confronted with it. Thus, a heuristic may be offered to begin search for the most successful maneuver with the closest car, or to show that not all road users have a significant impact on the safety of the maneuver. The latter is very similar to a problem of checking temporal formula on a labeled transition system (28), which emerges in a field of software verification. In the model checking (28), the complexity of such problem is reduced by using so called Binary Decision Diagrams (BDD) (29). The main idea is that to check the formula, it is sufficient to explore only significant arguments of the formula rather to perform a full search. It seems interesting to apply the similar idea for the searching of the safe maneuver. This will require developing a geometry-based extension of the BDD, which is an interesting task by itself.
- It may turn out that if the geometric size of a road user is bounded below, then for the two-dimensional case a number of road users that affect safety of the car is bounded above and does not depend on a size of the local area. Then a proper multi-core or vector on-board computer could dramatically reduce the computational complexity. Checking of the object and conditional limitations is a well parallelized task. Therefore, at each cycle the algorithm could perform independent concurrent checking of object limitations and then proceed to the concurrent checking of conditional limitations.
- It is also necessary to investigate the question whether it is possible to analyze changes in the local traffic situation for an interval of time elapsed since the previous cycle of the algorithm. In case of the positive answer, the algorithm could be adjusted to perform calculations to modify the already constructed solution to accommodate these changes.

There are a lot of interesting tasks that could employ the mathematical model of the traffic rules and the local route planning algorithms proposed in this paper. The examples are:
- Study of the completeness and consistency of the traffic rules,
- Research towards a system for automatic registration of traffic rules violations,
- Comparison of different systems of traffic rules and regulations.

CONCLUSIONS

This paper proposes a rule-based approach to local route planning for autonomous moving along the designated route in city traffic. To ensure safety of the obtained solutions, the approach relies on the on satisficing games algorithm (15), which guarantee finding of the winning strategy. Supplemented by a mathematical model of city traffic (6, 16), which defines a notion of safety, the local routes produced by the algorithm are safe. That is, 1) the solution is based on physical limitations, 2) it takes into account other road users and obstacles and 3) it reasons over an infinite time-horizon (16, 27).

To make the algorithm feasible in city traffic, the limitations arising from laws of physics were supplemented by limitations arising from the traffic rules. To keep the solutions safe, the latter rules are applied only to road users, who demonstrate legitimate behavior (i.e. do not violate the traffic rules).

The proof-of-the-concept implementation and testing has been performed using REPAST Simphony simulation environment (26). However, there are a lot of things to do towards efficiency and complexity the proposed approach. Nevertheless, only provably safe automatic control system could be implemented in city traffic, and the approach described in this paper is the most promising for this task.

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