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Self-organizing Control Framework for Driverless Vehicles

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Abstract — **Development of in-vehicle computer and sensing technology, along with short-range vehicle-to-vehicle communication has provided technological potential for large-scale deployment of autonomous vehicles. The issue of intersection control for these future driverless vehicles is one of the emerging research issues. Contrary to some of the previous research approaches, this paper is proposing a paradigm shift based upon self-organizing and cooperative control framework. Distributed vehicle intelligence has been used to calculate each vehicle's approaching velocity. The control mechanism has been developed in an agent-based environment. Self-organizing agent's trajectory adjustment bases upon a proposed priority principle. Testing of the system has proved its safety, user comfort, and efficiency functional requirements. Several recommendations for further research are presented.**

I. Introduction

INTELLIGENT autonomous vehicles are an emerging technology that will radically change the fundamental premises of future transportation systems. The development of in-vehicle computer technology, vehicle sensors, and short-range vehicle-to-vehicle and vehicle-to-infrastructure communication has provided a unique technological opportunity for development of the autonomous vehicle [1]. Vehicles today already have higher power reserves, can have more than 20 built-in microprocessors [2], and can store large amounts of data [3]. With these technological tendencies, the vehicles of the future will have computational power comparable to personal computers [4]. In addition, there is a continuous development of inter-networking technologies as an implementation of Wireless Local Area Networks (WLAN) in vehicles [5]. This technology enables communication between vehicles (V2V), and between vehicles and infrastructure (V2I), both referred to as V2X. These devices enable transfer of periodic or activated messages, that can inform the surrounding vehicles and infrastructure of e.g., speed, position, and direction of the vehicle [3].

The new computing, sensing, and communication technologies in the future vehicles will introduce significant benefits and expand the paradigm of traffic safety [6, 7]. In addition to the continuous developments in the area of safety features for driverless vehicles, the community of transportation engineers has a unique opportunity to reinvent the traffic control principles. This opportunity is especially significant considering that potentially all the vehicles will be completely autonomous in the next couple of decades.

This paper is focusing on presenting a distributed agent-based framework for self-organizing and cooperative control of driverless vehicles. The intention is to propose a next-generation control framework for intersection control of driverless vehicles. Second section of the paper provides detailed overview of the state-of-the-art research and development. Third section presents the control mechanism developed in agent-based environment. Later paper sections present findings from system testing and conclusions.

II. Previous Research

For almost a decade, the communities of computer science and industrial systems engineers have tried to develop novel approaches for intersection control. The first research approach for autonomous vehicle control was established in 2004 with the development of the reservation system [8]. This system bases on the interaction between vehicle and intersection manager agent through message exchange. The vehicle agents calculate time of the arrival at the intersection and then informs the intersection. This advanced "call" by the vehicle is supposed to reserve the n x n grid of the intersection. The intersection manager simulates the crossing of the intersection by the agent vehicle, thus determining the occupied grid tiles in each simulation step. The intersection manager reserves the tiles only if there are no required tile occupied by another vehicle from a previous reservation. The same core group of researchers improved the original model in the recent years and expanded it to stop controlled intersections and network control [9, 10]. The reservation system primarily bases upon first-in first-out queuing principle.

Another approach for intersection control mechanism focused on implementing economic principles. One research group focused on developing intersection control mechanism as an auction-based system [11]. This initial time-slot auction is valuation-aware, basing on the valuation $v_j(t)$ each driver agent is willing to pay if he waits t seconds less. Each driver's valuation is different, and each driver has a budget b_j. Another group of researchers proposed the

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development of intersection control model as economic market [12], where the right-of-way is "sold".

Among some of the most recent developments, there is a proposed system of decentralized control, which maintained the first-in first-out operating principle [13]. In addition, another recent research approach focused on controlling the approach speed of driverless vehicles under the goal of minimizing total delay of users [14].

The potential drawbacks of the control principles introduced in the previous research are threefold:

1. *Centralization of the control decision.* Majority of the previous control approaches require the existence of intersection or central controller that will determine the right-of-way for individual vehicles. The centralized control approach has already proven as sub-optimal for large transportation networks with many intersections [15]. In addition, considering the share size of transportation networks, investing in intersection controllers at each intersection can be an enormous investment. Finally, centralized approach is not utilizing the computational capabilities future vehicles will have.
2. *First-in first-out operating principle*. An example for drawback of this principle is considering a case where there are n vehicles, but vehicle 1 has a conflict with all the other vehicles, while no other vehicles have conflicts with each other. If the vehicle 1 sends the request first, all the other n-1 vehicles will need to wait for that vehicle simply because of arrival time [16].
3. *Competition among the vehicle agents.* Introducing competition among the agents might not always result in an optimal solution. For example, models might be very sensitive to assumptions on the auctioning order and actions' constraints [17, 18]. In addition, the auction-based system assumes that the travel budget of each drives is high enough, and that each driver bids and subsidizes his valuation per second of reduced waiting time. Realistically, it can happen that the budget is low and that a driver-assistance agent cannot afford to offer a price which corresponds to its true valuation [19].

III. Agent-Based Distributed Control Mechanism

The research presented here is trying to eliminate the need for centralized controller, and propose a mechanism for distributed intelligence with cooperative communication and computation performed by individual vehicles. Self-organizing control has a potential for higher computational efficiency, robustness against failure, scalability for expansion, and smaller communication capacity requirements. The framework for this next-generation control bases upon the assumption of computational intelligence in vehicles, envisioning vehicles as independent agents. Based on that, vehicle agents will be able to perform domain-oriented reasoning and adapt their own actions to changing environments [20].

The control framework is envisioned to be decomposed over many task-oriented and independent agents [21]. In addition, the framework is envisioned to have three cooperation layers: Network, Route, and Intersection. These are not control layers, since all the computation is performed in-vehicle. These layers are primarily used for cooperative inter-vehicle communication, where vehicles exchange information on their environment. At the highest hierarchical level, the central information point will disseminate information on global network events. Individual vehicles will use this information to plan routes. At the route level, depending on the selected route, vehicles will be joining cooperative platoons. This will be coordinated with vehicle leaders at the beginning of the platoon.

The most important procedure is at the intersection level, and this paper will primarily focus on describing this part of the framework. At the intersection level, vehicle agents or their respective cooperative platoons will focus on determining the right-of-way at the intersection. The self-organizing in-vehicle computation bases upon the information sensed or communicated from surrounding vehicles. The rules for assigning right-of-way will be according to their time of arrival and cooperative rules, while ensuring the safety of conflicting directions through the intersection.

A. Approaching trajectory adjustment

Each vehicle agent performs a continuous calculation of its approaching velocity. This continuous calculation allows for sudden changes in the vehicle's environment. The rule for resolving conflicting vehicles bases upon the Priority Level (PL) that each vehicle agent has. This PL can be determined based on vehicle occupancy, vehicle type (e.g., emergency vehicle), vehicle's dynamic characteristics (e.g., vehicle's breaking capabilities), or constraining intersection characteristics (e.g., approach grade, queuing capacity). The detailed rules for calculating PL will be presented elsewhere, considering that the focus of this paper is on presenting the distributed control framework. However, it is important to emphasize here that these rules will be uniform across all the vehicles of the same type.

PL values for individual vehicle agents are used for conflict resolution upon simultaneous arrival. This principle allows for taking into consideration the actual user characteristics, besides just serving the vehicle that arrived first. In addition, this principle can clearly distinguish vehicles with higher priority, such as emergency or public transportation vehicles. Furthermore, PL principle can allow for development of cooperative platoons of vehicles with similar characteristics on the route level.

PL principle is derived from the priority queuing principles [22]. The assumption of the model is there are N priority classes, with class 1 having the highest priority. Under this queuing discipline, a user is selected for service if it is the member of the highest priority class. However, the users within a class are selected on a first-in first-out basis. The interarrival times of users of each class and users of different classes are mutually independent, and identically (Poisson) distributed random variables.

In priority queues, the priority assignment for each class is in the increasing order of $c_i\mu_i$, with c_i being the cost of a user of priority class i, and μ_i the respective service rate. Thus, the highest priority is assigned to the user class with the highest value of $c_i\mu_i$. This PL function takes into consideration the user or vehicle characteristics mentioned above (e.g., number of occupants, emergency of the trip, etc.). However, contrary to the queuing theory approach, vehicles cannot be assigned back to queue, so the proposed model is expanded to take into consideration vehicle's approaching trajectory to the intersection. Each vehicle agent can calculate its own PL and obtain PL from the other vehicles, and thus determine the order in which vehicles should receive the right-of-way through intersection. Stepping further from the reservation first-in first-out principle, the concept of in-vehicle computation based on PL can accommodate for different user, vehicle, or intersection characteristics.

Each vehicle agent is performing a continuous calculation of its own desired velocity, to accommodate for incidents or different vehicle dynamics. This calculation is performed in-vehicle, every 1/10 of a second, based on the subject vehicle's parameters and based on the parameters communicated from the surrounding vehicles. Each vehicle agent can calculate conflicting vehicle trajectories, since it receives information from surrounding vehicles. In addition, the vehicle has predefined information on the intersection's geometry, and consequently on conflicting areas. Conflict determination is performed based on the estimated time of arrival and estimated time of departure from the conflict zone. The underlying principle is that the rear end of vehicle with higher Pl has to leave conflict area before the vehicle with lower PL can enter the conflict area. This requires that the respective entrance and exit times (in absolute values) for conflicting vehicles need to be equal. Consequently, the adjusted velocity of the vehicle with lower PL is:

$$V_i = V_j * \frac{EnterDis_i}{ExitDis_j} \quad (1)$$

where:

V_i – approaching velocity of the subject vehicle

V_j – approaching velocity of the conflicting vehicle

$EnterDis_i$ – distance to entering conflict zone for the subject vehicle

$ExitDis_j$ – distance to exiting conflict zone for the conflicting vehicle

Vehicle with the highest PL will always maintain its original desired velocity, while the vehicles with the lower PL will reduce their approaching velocity accordingly (by decreasing). Vehicles are not allowed to have approaching velocity higher than the set up speed limit, that is determined based on the safety constraints of the intersection geometry. The control principle is presented on the Figure 1. This figure shows vehicle agents 1 and 3 approaching the intersection with reduced desired and real velocities. Both vehicle agents had to reduce the speed comparing to vehicle 4, which has cleared the intersection. Vehicle 4 maintained its desired velocity of 50 km/h, and crossed through the intersection in the previous time steps. The assigned right-of-way for vehicle 4 over vehicle 3, and for vehicle 3 over vehicle 1 bases upon the PL of each agent. Vehicle 1 (in blue) had a smaller PL value than vehicle 2 (in green), and this is the reason its desired speed was highly reduced. However, both vehicle agents 1 and 3 had to reduce respectively their velocity compared to vehicle agent 4.

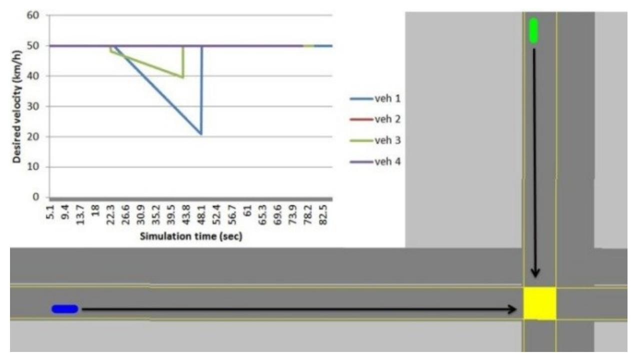

Fig. 1: Reduction of agents' desired velocities based on their PL

The pseudo-code for the continuous in-vehicle computation is as following:

IF communication has been established with other vehicle agents AND WHILE agent is approaching intersection

CALCULATE the arrival and exit time from conflict areas with other vehicle agents

CALCULATE conflict based on arrival time AND exit time overlap

IF conflict exists

CALCULATE AND COMPARE Priority Levels of vehicle agents and determine individual right-of-way

CALCULATE new desired velocity

Proposed agent-based control framework is modeled in VISSIM traffic simulation environment. The control

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algorithm has been implemented using application programming interface (API) [23]. The API programming has enabled a development of a fully connected environment, with each vehicle agent having identical computational capabilities, as if equipped by on-board computer. The self-organizing control logic in each vehicle agent is developed using external driver model dynamic link library (DLL). During each simulation step (10 Hz), VISSIM calls DLL code for each driver agent. VISSIM passes the current state of the vehicle agent and its surrounding agents to the DLL. Each vehicle agent DLL computes its new parameters. These new parameters are then sent back to VISSIM in the next simulation step for each individual agent. The information communicated and computed by vehicle agents includes the real and desired velocity, GPS coordinates, simulation time (GPS clock time), route, and Priority Level parameters. Based on these parameters for subject agent and information from the other surrounding vehicles and intersection, the DLL computes desired velocity for the subject vehicle's next time step. This calculation is performed for all the vehicle agents in the communication range around the intersection (200 m).

The control algorithm implemented in each agent bases primarily on using desired velocity as a VISSIM control variable. This variable is different from the actual agent's velocity. The desired velocity represents agent's calculated velocity, calculated based upon the right-of-way assignment for each agent. The actual agent's velocity depends upon the acceptable acceleration/deceleration rates, and fluctuations of the vehicle's engine control mechanism.

IV. System Testing

In order to test the proposed control framework, the testing requirements were defined as:

- The system needs to secure absolute user safety
- The in-vehicle system needs to be able to operate away from the intersection proximity and allow for acceptable acceleration/deceleration of users
- The system needs to result in the greater efficiency benefits than the conventional traffic control system

The proposed control framework has been tested at an isolated intersection. The testing intersection consisted of the four single lane approaches. The approach speed limit was 50 km/h. The testing considered simultaneous vehicle arrival on each approach, with passenger vehicles. Testing was performed over 1000 simulation runs, for validity reasons. PL for each vehicle was generated randomly, using uniform distribution.

A. Safety analysis

As the most important principle for any intersection control mechanism is its safety, the proposed system was developed including safety buffers in spatial and temporal calculations performed in-vehicle. To test the safety of these calculations and the resulting vehicle trajectories, research team performed a conflict analysis using Surrogate Safety Assessment Model (SSAM) [24]. The automated conflict analysis used VISSIM-generated trajectory files for each simulation run.

The analysis focused on the frequency and character of narrowly averted vehicle-to-vehicle collisions. The parameters used included the maximum time-to-collision (TTC), maximum post-encroachment time (PET), and conflict angles. TTC is the minimum time to collision observed during the conflict, and its threshold value was set up to 1.5 sec. PET is the minimum time between when the first vehicle last occupied a position and the second vehicle subsequently arrived at the same position. The threshold for PET was set to 5.0 seconds. Both TTC and PET values were selected as the upper limits for time during potential conflicts. For example, SSAM calculated values of 0 seconds would indicate an actual collision, and any value below the threshold would signify a dangerous vehicle-vehicle conflict. In addition, conflict angle variable is an approximate angle of hypothetical collision between conflicting vehicles, based on the estimated heading of each vehicle agent. The threshold for rear angle conflict was set up to 30.0º and for crossing angle conflict to 80.0º.

After 1000 simulation runs were analyzed, no conflict values below the defined thresholds were found between vehicle's trajectories. This is an indication that developed control mechanism has fulfilled safety requirements.

B. Velocity adjustment analysis

As a second part of the testing procedure, research team has tested whether the system is able to operate by adjusting the vehicle's velocity under the acceptable users' acceleration/deceleration rates (Figure 2). The upper part of this figure shows the adjustment of desired while the lower shows the adjustment of real velocity.

Proposed framework was also tested for vehicles arriving with different approach speeds. As you can see from the Figure 3, vehicle agents 1 and 2 are arriving with 60 and 50 km/h, respectively. On the contrary, vehicle 3 and 4 are arriving with 40 km/h. However, since the PL of vehicle 3 and 4 are higher, vehicle agents 1 and 2 had successfully accommodated their approaching velocity. Figure 2 and 3 are two examples of adjusted vehicle trajectories. The mean value of desired acceleration for 1000 simulation runs was 1.2 m/s^2, while mean value of desired deceleration was 1.1 m/s^2. Maximum value was 3.5 m/s^2 for both variables. These acceleration/deceleration rates are acceptable from the user comfort perspective.

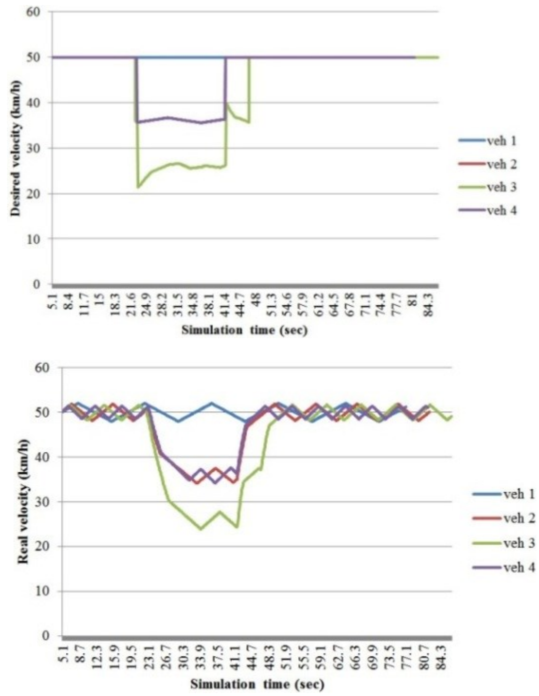

Fig. 2: Desired and real velocity adjustment

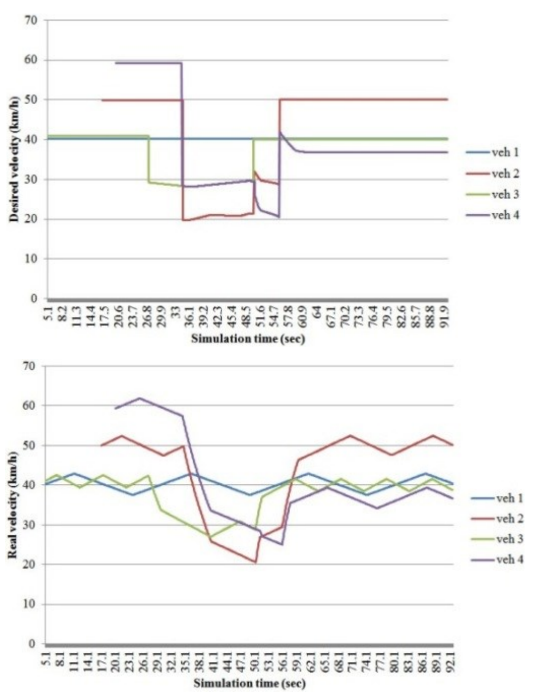

Fig. 3: Velocity adjustment for different arrival profiles and PLs

C. *Operational analysis*

In the final step of the testing procedure, research team has deployed software-in-the-loop simulation (SILS) for comparing the proposed control framework with the conventional signal control principles. SILS is a system of microscopic simulation model, virtual traffic controller and interface for communication between these two components [25]. The virtual replica of traffic signal controller used in the simulation has identical operational logic as real traffic controller software. Virtual replica consists of dynamic-link library that microscopic simulation software uses to simulate signal control logic of D4 2070 controller. This virtual traffic signal controller has been integrated within VISSIM microscopic simulation, with controller resolution of 10 Hz, as implemented in the actual field controllers. Simulated signalized intersection was fully-actuated, operating in Free mode. Minimum green time for each of the phases was set up to 5.0 sec and maximum green time had the value of 20.0 sec. Vehicle extension was assigned a value of 1.0 sec. Stop bar detectors are 15 m long. Intersection was also equipped with Preemption (PE) check-in/check-out detectors. PE check-in detectors were placed 200 m before the stop bar (identical with accepted communication range for the proposed framework). However, PE programming requires assignment of priority for specific PE input signal, thus limiting the flexibility of PE operation.

There were two tests of conventional control operation: regular actuated operation and PE operation. In the first case, all the vehicles arriving at the intersection are detected only by regular detectors, respecting the controller parameters. In the second case, the vehicles arriving are represented with emergency vehicles, which activate PE call 200 m before the intersection. PE has been tested as one of the state-of-the-art principles that allow signal activation ahead of the intersection.

Simulating proposed control framework, each vehicle agent had certain PL calculated based on vehicle occupancy, vehicle type, vehicle's dynamic characteristics, or intersection characteristics. Based on this PL, the desired and real arrival velocity is adjusted. All three cases (normal actuated operation, PE operation, and proposed distributed control framework) were tested under the identical vehicle, driver, and road characteristics, and using the identical random seed in all 1000 simulation runs. The following Figure 4 represents total delay experienced in all the three test cases in each of the simulation runs. The blue line represents total delay for the proposed control framework, green line is total delay for normal actuated operation, and red line is PE operation. It is observable that proposed control framework is more efficient than both of the conventional control mechanisms. In addition, proposed control mechanism can efficiently resolve conflict at the intersection, even from a standpoint of individual vehicle delay. Under proposed control mechanism, the vehicle with the highest PL experiences no delay, while vehicles with lower PL experience smaller delay compared to conventional control. On the contrary, normal actuated operation distributes the delay over all the vehicles. Finally, PE operation allows no delay for the vehicle with the highest PE priority, but the transition out of PE significantly affects delay of all the other vehicles.

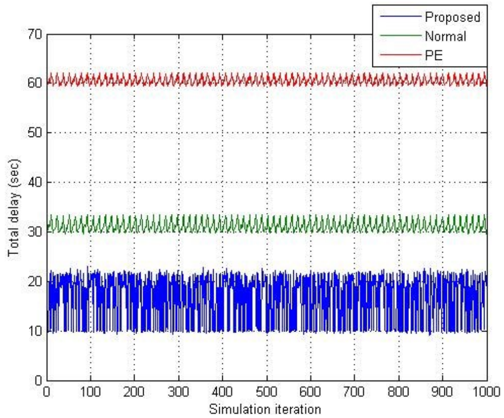

Fig. 4: Total delay for actuated, PE, and proposed control

V. Conclusion and Future Work

Computation, inter-vehicle communication, and increased sensing capabilities will enable vehicles of the future to dynamically adapt to environment conditions and thus reduce the driver’s role. Previous research focused on centralized, first-in first-out, and competition control principles. This paper is proposing a novel control framework for self-organization of driverless vehicles, building upon the potentials of distributed in-vehicle computing power connected via wireless communications. Furthermore, the framework proposed a PL system for determining the right-of-way through the intersection. The PL principle extends queuing theory to include for vehicle, user, or intersection characteristics (e.g., vehicle type, vehicle’s breaking capabilities, trip type, approach grade, etc.). In addition, the framework bases upon principles that allows cooperation among vehicles on the route or network level. Proposed control framework has proven to be without safety conflicts, with acceptable acceleration/deceleration, and reduced delay for all users. In the future, this research will be expanded to accommodate variable traffic volumes and patterns, with extending the procedure for PL calculation.

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