

# Social Autonomous Vehicles: Mutually Cooperative Motion Control Method

Seiya Nakano<sup>†</sup>

<sup>†</sup>AISIN AW

Naoto Iwahashi<sup>‡</sup>

<sup>‡</sup>Okayama Prefectural Univ

## 1 Introduction

Driving a car is a social activity with egocentric and cooperative aspects. The egocentric aspect is characterized by self-adaptive behaviors to surrounding environments while following traffic rules. The cooperative aspect is characterized by mutually adaptive behaviors with other agents (e.g., vehicles and bicycles). The examples of egocentric and mutually cooperative situations are shown in Fig.1.

While automatic driving is rapidly improving in the egocentric aspect [1, 2, 3], there are still problems to be solved in the cooperative aspect. A few studies have addressed the prediction of the motions of other vehicles [4, 5]. However, there is no study on mutually cooperative motion control among self and other vehicles. To solve these problems, it is necessary to build a mathematical model of the mutual and embedded dependency among the social behaviors of vehicles: the motions of other vehicles can be changed by modifying the motion of self vehicle, which is generated adaptive to the motions of other vehicles.

This paper presents a mutually cooperative motion control method. To the best of our knowledge, this is the first method developed to address the motion control of vehicles in the cooperative aspect. The general model for mutually cooperative activity among multiple agents in a physical space can be represented as Fig.2. Each agent infers the current state of the entire activity based on its observation from the physical space and the previous inferred state, and it acts based on the observation from the physical space and the current inferred state. The difficulty exists in the inference of the state of the entire activity: the inferred state can be referred as mutual beliefs. Iwahashi investigated the mathematical modeling of mutual beliefs [6] and synchronous mutually cooperative activity [7] in the domain of multimodal human-robot interaction. By applying Iwahashi's models, we

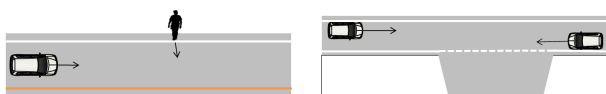


Figure 1: Two typical situations for social driving activity. **Left:** Egocentric situation with a pedestrian. **Right:** Mutually cooperative situation with an oncoming vehicle.

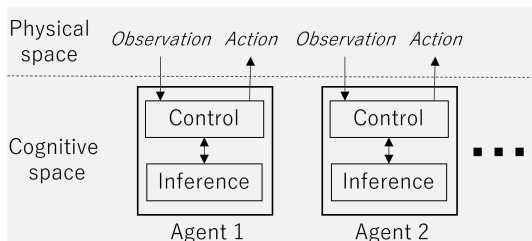


Figure 2: General model for mutually cooperative activity among multiple agents that interact with each other in the physical space.

present a novel motion control method for mutually cooperative, *i.e.*, social, autonomous vehicles. Our method is characterized by the following: (1) multi-agent position-velocity state space; (2) an objective function for mutually cooperative motions; (3) priority adjustment.

## 2 Method

The motion of a self vehicle is optimized mutually with the prediction of the behaviors of surrounding multiple agents. This optimization is done with priority adjustment among the self vehicle and other agents considering their social relationship.

### 2.1 Formulation

The motion plan of the self vehicle for duration  $T$  in current time is represented as

$$Z_0 = [x_0^0, x_1^0, \dots, x_T^0],$$

where  $x_t^0 = [p_t^0, v_t^0]$ .  $p_t^0$  and  $v_t^0$  are position and velocity vectors, respectively. The prediction of the motion of other agents is represented as

$$Z_i = [x_0^i, x_1^i, \dots, x_T^i], \quad i = 1, \dots, N_a,$$

where  $N_a$  denotes the number of agents around the self vehicle. The set of all motions,  $Z = [Z_0^T, Z_1^T, \dots, Z_{N_a}^T]$ , is simultaneously optimized in the multi-agent position-velocity state space.

### 2.2 Multi-agent position-velocity state space

The multi-agent position-velocity state space,  $S$ , is defined as

$$S = \{S_0, S_1, \dots, S_T\},$$

$$S_t = \{S_t^0, S_t^1, \dots, S_t^{N_a}\},$$

$$S_t^i = \{[p_j, v_k] \mid j \in \{1, \dots, N_p\}, k \in \{1, \dots, N_v\}\},$$

where  $N_p$  and  $N_v$  denote the numbers of discrete values for position and velocity, respectively.  $x_t^i \in S_t^i$  for all  $i, t$  are selected by minimizing the objective function under physical constraints with no collision.

### 2.3 Objective function

The objective function,  $F$ , is defined by the sum of the norm of the acceleration of each time for each agent as

$$F(Z) = \sum_{i=0}^{N_a} w_i \left( \sum_{t=1}^T |v_t^i - v_{t-1}^i|^{p_2} \right)^{p_1},$$

where  $w_i$  denotes the weight for the  $i$ th agent's priority.  $p_1$  and  $p_2$  are used to smooth out costs among the agents and time series, respectively.  $p_1$  is important for the priority adjustment.

## 2.4 Priority adjustment

The priorities of agents should be assigned appropriately according to changing situations to realize comfortable social motion control. The priorities can be controlled by adjusting weights  $w_i$ ,  $i = 0, \dots, N_a$ . If  $w_i$  for the  $i$ th agent is set to be higher than those for other agents, the agent is assigned high priority and allowed to move with less restrictions.

## 3 Experiments

The multi-agent position–velocity state space was defined with a quantization resolution of  $0.5\text{ m}$  and  $1.0\text{ m/s}$  for position and velocity, respectively. Fast search with limited beam width was used to optimize  $Z$  with  $F(Z)$ .

The experiments were conducted for four typical situations under which mutually cooperative motion control would be inevitable. The initial velocities of participant vehicles were set as  $6.0\text{ m/s}$  for V, PV-I, and PV-II and  $4.0\text{ m/s}$  for 2V. The results are depicted in Figs.3–6 and described below.

**An oncoming vehicle (V).** High priority was assigned to the oncoming vehicle. As a result, the self vehicle moved to a side vacant lot to clear the oncoming vehicle, and the oncoming vehicle could move with less constraints.

**Two intersecting vehicles (2V).** The three vehicles avoided collision with minimal effort.

**Pedestrians and an oncoming vehicle (PV-I).** The self vehicle avoided a collision with the pedestrians and a frontal collision with the oncoming vehicle.

**Pedestrians and a following vehicle (PV-II).** The self vehicle avoided a collision with the pedestrians and a rear-end collision with the following vehicle. A rear-end collision would have been unavoidable if the self vehicle had avoided the pedestrians through abrupt deceleration.

## 4 Discussion

We shedded light on the significance of the sociality of autonomous vehicles. Sociality is an important key that increases the potential of autonomous vehicles and becomes a foothold for ethical issues [8].

It was clearly shown that the proposed method was extremely powerful in mutually cooperative motion control. It should be noted that the method does not depend on learning with a database in a specific domain, and therefore, it would have flexible capabilities for using priority adjustment in numerous domains / situations. In this paper, the calculation of the motion plan only in current time was presented. The synchronous adaptation of the motion plan according to the observation of the actual motions of involved agents is a future research topic.

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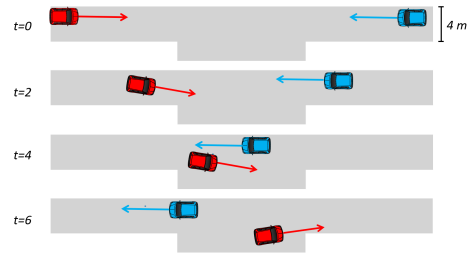


Figure 3: **An oncoming vehicle.** Red: A vehicle to control. Blue: A vehicle involved.

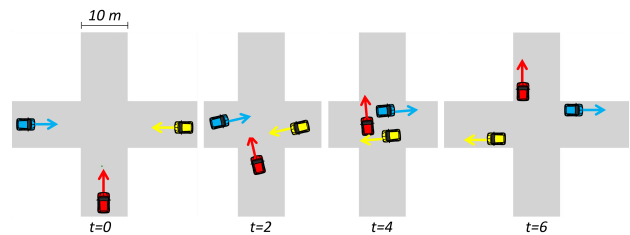


Figure 4: **Two intersecting vehicles.** Red: A vehicle to control. Blue and yellow: Vehicles involved.

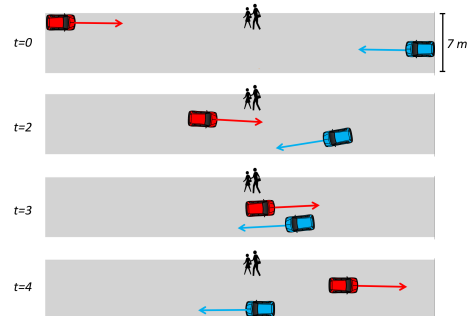


Figure 5: **Pedestrians and an oncoming vehicle.** Red: A vehicle to control. Blue: An oncoming vehicle.

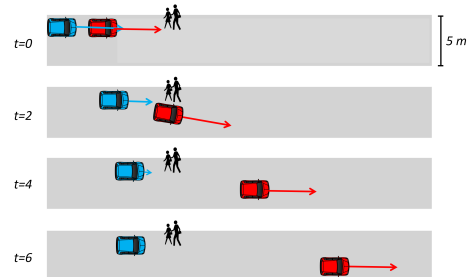


Figure 6: **Pedestrians and a following vehicle.** Red: A vehicle to control. Blue: A following vehicle.