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Safe Teleoperation of the Vehicle through Delay Compensation Combined Speed and Separation Monitoring with Potential Field Approach

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Abstract: Recent applications of autonomous vehicles have introduced teleoperation technology in order to supplement incomplete performance of the autonomous driving. The study focuses on the application of Speed and Separation Monitoring combined with the potential field approach for meeting the safety requirements in teleoperation during collision-free scenarios. To enhance the efficiency of the Speed and Separation Monitoring and potential field approach applications, a continuous adaption of the vehicle's relative velocity to obstacles is proposed in this study. The research investigates the impact of communication delays on the mobility of teleoperated unmanned ground vehicles and evaluates a newly developed delay compensation theory. Through repeated simulation analysis, it is concluded that the vehicle's path and velocity were modified with respect to communication delays and maintained protective separation distance.

Keywords: Teleoperated vehicle, Smart mobility, Delay compensation, Speed and separation Monitoring, Potential field

1. INTRODUCTION

In the teleoperated system depicted in Fig. 1,path planning for collision-free is crucially essential. At the same time, the presence of multiple communication devices, as illustrated in Fig. 1, introduces signal delays, leading to noise and disruptions in the transmitted signals. To improve interactions, mobile robots can convey specific intents or conditions by replicating motion attributes observed in Obstacles.

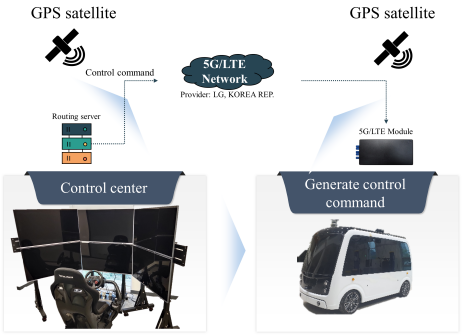

Fig. 1. Schematic diagram of the teleoperation service using the ego vehicle and visualization components. Teleportation services enable to control the autonomous vehicle in case of emergency. However, delay management is the most important issue of the teleoperation system

Previous research has explored the use of visual communication elements from obstacles to compensate for the delayed interactions [1]. However, some of the limitations exist such as implementing path planning techniques within robotics for teleoperation purposes [2]. Several research studies have focused on mobile robot path planning resulting in significant advancements in various techniques [3]. Upper techniques include path planning based on genetic algorithms, sample-based motion planning [4], neural network [5], fuzzy logic [6], Support Vector Machines (SVM) [7], and Artificial potential field (APF) [8]. Mentioned approaches have contributed to the field of mobile robot navigation and have been regarded as successful in achieving effective path planning.

However, the majority of related studies address that path planning implications in human-robot interaction have primarily concentrated on generating collision-free paths. This indicates that path-planning techniques were originally aimed to find optimal paths considering such as distance, time, or energy efficiency. However, it has been rarely discussed about communication delays and compensation to improve the performance of teleoperation.

Therefore, our research focuses on an approach of teleoperation scheme by considering the aspect of vehicle-obstacle regarding safety issues due to communication delays. Unlike previous studies, our focus lies on incorporating communication delay and its compensation algorithms in the signal elements into the trajectory planning process, allowing the ego-vehicle safely.

2. METHODOLOGY

2.1 Potential Field Approach (PFA)

This section presents a path-planning approach for collision-free navigation using potential fields, while also considering communication delays in a teleoperated vehicle. Additionally, this section addresses Speed and Separation Monitoring (SSM) with consideration for these communication delays.

Following a series of incidents involving teleoperated vehicles, the field of vehicle safety has not been given sufficient attention and standardization efforts. Therefore, in this framework, an effort was given to establish guide-

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lines that ensure a safe distance between active vehicles and obstacles when communication delay is coexisting as shown in Fig. 2.1

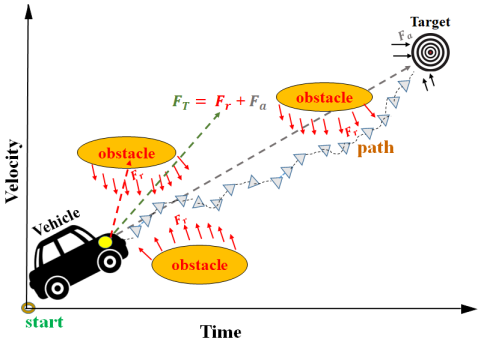

Fig. 2. The concept of the potential field for the teleoperated vehicle. The proposed concept consists of the attractive force (f_{a}) towards the target, the repulsive force (f_{r}) against the obstacles, and the total force (f_{t}) which is the sum of the attractive and the repulsive forces. All of the forces consisting potential field for the teleoperated vehicle should be calculated in the potential field process planning in order to avoid possible obstacles

The proposed method incorporates object locomotion attributes for navigating the teleoperated vehicle in dynamic, and unfamiliar environments, where the target exerts an attractive force on the vehicle and obstacles generate repulsive force fields to prevent collisions. Note that an actual attractive force is replaced by the manual control signal driven by the teleoperator existing in the control center remotely.

The main assumptions in this study are vehicle geometry is rectangular in shape, and the position and the velocity of both vehicle and object are preliminary known information. Let the attractive potential function as (1) which consists of the velocity of the vehicle and assures the nonlinear motion:

$$U_{\mathrm{a}}(x, v_{\mathrm{v}}, v_{\mathrm{t}}), \tag{1}$$

where U_{a} is the attractive force, x is the vehicle position, $v_{\mathrm{v}}, v_{\mathrm{t}}$ are the velocities of vehicle and target at time t. Therefore the attractive force can be written as f_{a}:

$$f_{\mathrm{a}}(x, v_{\mathrm{v}}, v_{\mathrm{t}}) = -\nabla U_{\mathrm{a}}(x, v_{\mathrm{v}}, v_{\mathrm{t}}). \tag{2}$$

Next, the repulsive potential function U_{r} is expressed as

$$U_{\mathrm{r}}(x, v_{\mathrm{v}}, v_{\mathrm{o}}), \tag{3}$$

where $v_{\mathrm{v}}, v_{\mathrm{o}}$ are the velocity vectors of the vehicle and obstacle respectively. Therefore, the corresponding repulsive force can be expressed as f_{r}:

$$f_{\mathrm{r}}(x, v_{\mathrm{v}}, v_{\mathrm{o}}) = -\nabla U_{\mathrm{r}}(x, v_{\mathrm{v}}, v_{\mathrm{o}}). \tag{4}$$

Finally, the total control forces f_{TOTAL} is the summation of the attractive and the repulsive forces based on the above equations respectively [9]:

$$f_{\mathrm{total}} = f_{\mathrm{a}}(x, v) + f_{\mathrm{r}}(x, v). \tag{5}$$

2.2 Speed and Separation Monitoring

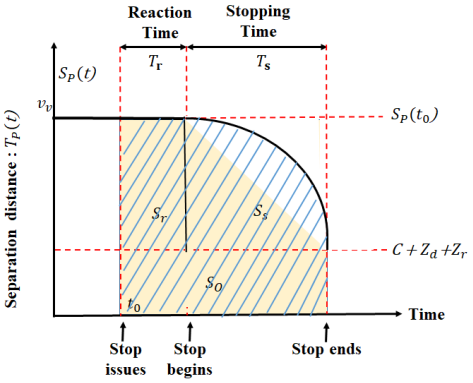

Fig. 3. Diagram for the modeling of speed and separation monitoring. Protective separation distance consists of the minimum permissible distance between the vehicle and the obstacle, S_{h} is the distance that vehicle moves from stop issued until the vehicle stops. S_{r} denotes the vehicle moves until it reacts and S_{s} is the distance that vehicle moves during braking, C is the intrusion distance and Z_{r} and Z_{s} are the uncertainties measurement

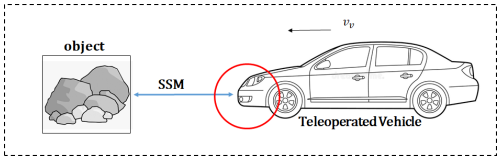

Fig. 4. Speed and Separation Monitoring distance between the obstacle and the vehicle must be identified by the sensors and teleoperated vehicle must react based on the SSM

In the traditional approach, collaborative robots and human safety are upheld by creating a physical separation between the workforce and active machinery. However, as shown in Fig. 2,22,2SSM can be potentially utilized as a functional safety function in order to maintain a protective distance between the vehicle and the obstacles. S_{p} is the protective separation distance traveled by the vehicle while in the decelerate condition is given as follows:

$$S_p = S_{\mathrm{o}} + S_{\mathrm{v}} + S_{\mathrm{s}} + C + Z_{\mathrm{r}} + Z_s, \tag{6}$$

where S_{o} is the protective separation distance accounting for the obstacle, S_{v} represents the reaction distance of the vehicle until the stop signal is issued by safety-related sensors. S_{s} is the vehicle travel distance and it is dependent on the stopping performance of the vehicle. C is the intrusion distance to alert the safety functions based on hazard zone etc. Z_{r} and Z_{s} are the measurements of uncertainties of positions of vehicle and obstacle.

In order to apply the basic equation form to the proposed model then the following equation as (6) is expressed as:

$$S_p(t_0) = v_{\mathrm{v}}(t_0)(T_{\mathrm{r}} + T_{\mathrm{s}}) + v_{\mathrm{r}}(t_0)T_{\mathrm{r}} + S_{\mathrm{s}} + M, \tag{7}$$

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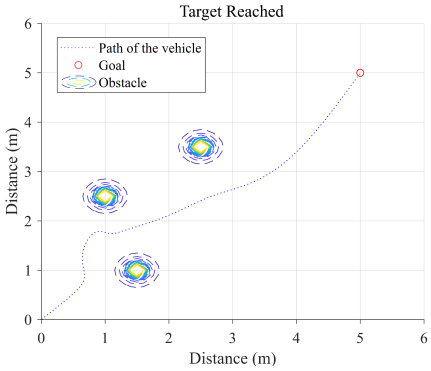

Fig. 5. Path trajectory of condition one. The positions of the obstacles were tested with two cases where (1.5,1),(1, 2.5),(2.5,3.5)

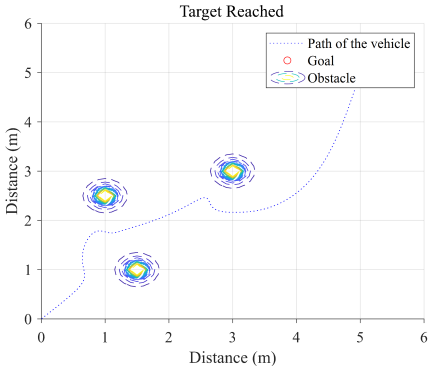

Fig. 6. Path trajectory of condition one. The positions of the obstacles were tested with two cases where (1.5,1),(1, 2.5),(3.0,3.0)

where, C is the intrusion distance. z_r and z_s are the vehicle position uncertainty and the obstacles position uncertainty respectively. These three parameters were combined and denoted as margin factor M. The value T corresponds to the overall stopping performance of the system and is determined by the sum of the time between sensing actuation T_{s} and the response time of the machine T_{r}.

3. SIMULATION

3.1 Modelling

A simulation was performed in the MATLAB simulation with the graphical user interface. The first position of the vehicle was set as (0,0) m, and the position of the goal was set as (5,5) m. The initial velocity of the vehicle was set as (0,0) m/s and the maximum velocity of the vehicle was set as (0.3,0.3) m/s. Finally, the positions of the obstacles were tested with two cases where (1.5,1),(1, 2.5),(2.5,3.5) and (1.5,1),(1, 2.5),(3.0,3.0). As for the comparison, path trajectory, vehicle forces computed by the proposed approach, and relative distance to the obstacles were investigated. It should be noted that the interval time of the simulation was 0.01 s, and the simulation was finished if the position of the vehicle reaches the goal.

4. RESULTS

4.1 Path trajectory analysis

Fig. 5 and 6 show the path trajectory of each condition. It can be known that the obstacle was avoided by the proposed method.

4.2 Force and relative distance analysis

Fig. 7 shows force analysis of the attractive force and the repulsive force of the vehicle when condition one is applied. Fig. 8 shows the total force induced to the vehicle and the relative distance to each of the obstacles.

Fig. 9 shows force analysis of the attractive force and the repulsive force of the vehicle when condition two is

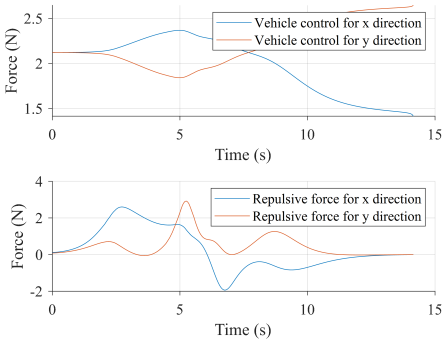

Fig. 7. Force analysis of the attractive force and the repulsive force of the vehicle. It can be known that depending on the relative distance to the obstacle, the vehicle is influenced by the repulsive force

applied. Fig. 10 shows the total force induced to the vehicle and the relative distance to each of the obstacles.

5. CONCLUSION

This paper introduces an instance motion planning method utilizing the approach of the potential field (PFA) combined with speed and separation monitoring (SSM). The contribution of this study lies in incorporating obstacles attributes between the teleoperated vehicle and the target considering the communication delays. The proposed method offers several advantages, including path planning with collision avoidance combined with speed and separation monitoring. The future work of this study includes sensitivity analysis among the preliminary defined parameters and the magnitude of the communication delays.

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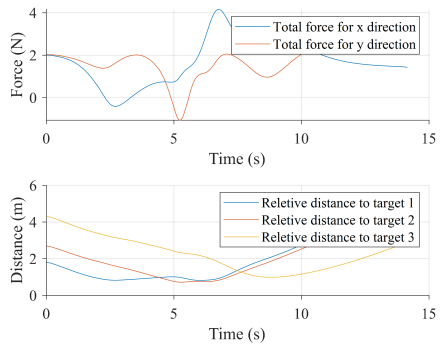

Fig. 8. Total force analysis in x and y directions was influenced by the relative distance corresponding to target 1, target 2 and target 3 respectively when condition one is applied

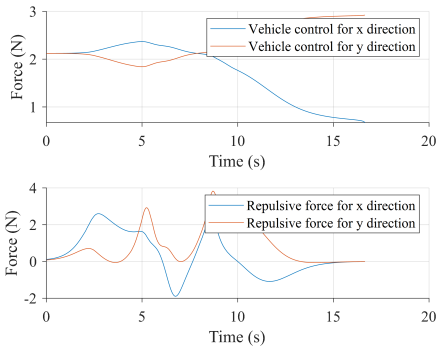

Fig. 9. Force analysis of the attractive force and the repulsive force of the vehicle. It can be known that depending on the relative distance to the obstacle, the vehicle is influenced by the repulsive force when condition two is applied

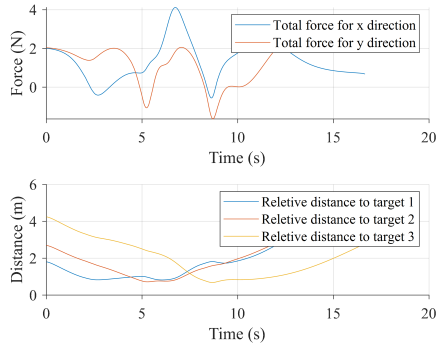

Fig. 10. Total force analysis in x and y directions was influenced by the relative distance corresponding to target 1, target 2, and target 3 respectively when condition two is applied

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