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Proposal and Evaluation of a Dynamic Path Finding Method Using Potential Values Considering Time Series in Automatic Driving

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Abstract

Many studies have been conducted using obstacle hazard values, called potential method, for connected autonomous vehicle. However, most studies were conducted for static obstacles, and those for dynamic obstacles assumed an environment without oncoming or crossing vehicles. In this study, we devise an algorithm for generating potential values considering time series characteristics using information that can be obtained through inter-vehicle communication and propose a path finding algorithm that uses these potential values. As an evaluation of the usefulness of the proposed method, we compare it with existing potential methods. The results show that, in some situations, the route derived by the proposed method is superior to the route derived by the existing potential method in terms of safety and timer to reach the destination.

Keywords: Automatic Driving Autonomous vehicle Path finding Artificial potential method .

1. Introduction

Although the number of traffic accidents is decling, approximately 300,000 accidents are reported annually. According to a survey conducted by the Japan National Police Agency, approximately 40% of traffic accident fatalities are caused by mutual vehicles.

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In recent years, research on automated driving and driver assistance systems has attracted attention for reducing traffic accidents, and systems such as automatic braking and Adaptive Cruise Control (ACC) [1], which follows the vehicle ahead, have been developed. Many studies have used potential methods for these systems [2][3]. However, most studies target static obstacles, and the studies targeting dynamic obstacles assume an environment without oncoming vehicles on a wide road such as an expressway.

Therefore, in this study, we devise a potential value generation algorithm that considers time series characteristics using information obtainable through inter-vehicle communication, and propose a route search algorithm that uses the potential values.

2. Related Work

2.1. Artificial potential method

The artificial potential method [4] (hereafter referred to as the potential method) is a method used for path planning in autonomous mobile robots and other vehicles to avoid obstacles. The potential field is constructed by defining an attraction potential function U_d for the destination and repulsion potential function U_o for the obstacle, and then weighing the potential functions together. Based on the gradient of the configured potential field, the motion plan is repeated sequentially to move to the destination while avoiding collisions with obstacles.

A representative example of an attraction potential function is shown in Equation 1, and a representative example of a repulsion potential function is shown in Equation 2.

$$U_d = w_d \sqrt{(x-x_d)^2 + (y-y_d)^2} \tag{1}$$

$$U_o = w_o \sum_{i=1}^{n} \frac{1}{2\pi\sigma^2} \exp\left[-\frac{(x-x_i)^2 + (y-y_i)^2}{2\sigma^2}\right] \tag{2}$$

where (x_d, y_d) is the destination coordinates, (x_i, y_i) the obstacle coordinates, and w_d and w_o the weights. The basic model of the potential method is shown in Equation 3.

$$U = U_d + U_o \tag{3}$$

The operation plan is also determined based on Equation 4.

$$F = -\nabla U = -\left(\frac{\partial U}{\partial x}, \frac{\partial U}{\partial y}\right) \tag{4}$$

As an example, Figure 2 shows the potential field where the destination (Dest) is arranged as shown in Figure 1 (the blue point) and obstacles (Obst) are the red points.

2.2. Moving Obstacle Potential

Hoshino et al. [5] proposed a potential function that considers the direction of movement and velocity of moving obstacles. By modeling the characteristics of moving obstacles with a von Mises distribution [6], this method generates an artificial potential field with a biased distribution in the direction of the obstacle's movement. The proposed potential function is shown in Equation 5.

$$U_o(r,\theta) = \sum_{i=1}^{n} \frac{\exp\{k\cos(\theta_i - \mu_i)\}}{2\pi I_0(k)} \alpha \frac{\exp[-\frac{r_i}{2\sigma}]}{2\pi\sigma} \beta |v_i| \tag{5}$$

where r is the distance from the robot to the obstacle, θ the relative angle between the robot and the obstacle, μ the direction of movement of the obstacle, σ the dispersion with respect to the radial direction, α the coefficient, and β the coefficient with respect to velocity v.

The first term in Equation 5 represents the von Mises distribution, and the direction of the distribution can be adjusted by parameter k. Figure 3 shows the potential field when moving in the positive direction of the x axis.

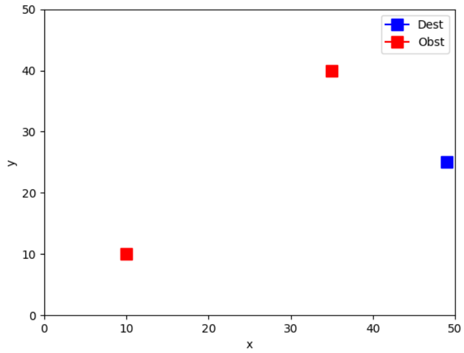

Figure 1: Arrangement diagram of destinations (blue) and obstacles (red)

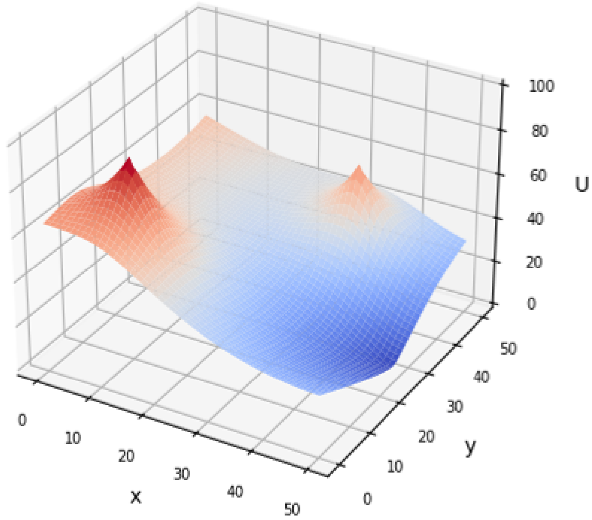

Figure 2: Potential field in Figure 1

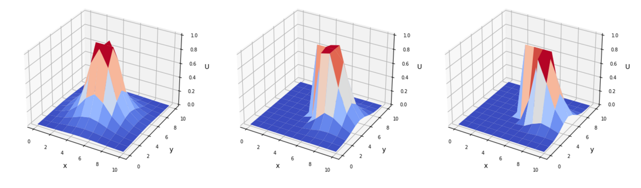

Figure 3: Potential field of the model when considering moving obstacles

2.3. Positioning of this study

In this study, a system was created to derive a route using the potential value as the cost of $A*$ [7]. In this experiment, we compared the derived paths using a potential function that does not take velocity into account and a potential function that takes velocity into account proposed by Hoshino et al.

3. Method

Based on information obtained through inter-vehicle communication using methods such as the vehicular ad hoc network (VANET)[8][9], potential values reflecting the degree of danger at points where moving obstacles are likely to move are calculated. Based on the value, a path is calculated using a method based on A* to derive a driving route that avoids collisions with various moving obstacles.

3.1. Algorithm

The flow of the proposed method is described below, and a schematic is shown in Figure 4.

1. Obtain information about the starting and finishing points, obstacles that do not move (hereinafter referred to as walls), and moving obstacles.
2. Prepare an Open list of priority queues to store nodes that are being calculated and a Close list to store nodes that have already been calculated.
3. Add start node $(s, 0)$ to the Open list.
4. Obtain the node (n, t) with the smallest $f(n, t)$ among the nodes stored in the Open list (if the Open list is empty, the search fails).
5. If node (n, t) is the destination point, the search terminates. Otherwise, add node (n, t) to the Close list.
6. Perform the following operations on all nodes adjacent to node (n, t) (let the adjacent node be $(m, t{+}1)$).
   (a) Compute $f(m, t+1) = g(n, t) + U(m, t+1)$, where $g(n, t)$ is the cost incurred to move node (n, t) from the starting node, $U(m, t + 1)$ the potential value of node $(m, t + 1)$, and $U(m, t + 1)$ is expressed by the following equation.

$$U(m, t + 1) = U_d(m) + U_w(m) + U_o(m, t + 1) \tag{6}$$

   where U_d is the potential value to the goal, U_w the potential value from the wall, and U_o the potential value from the obstacle.
   (b) Perform the following operations depending on the status of m.
   - If m is not stored in the Open or Close list, add m to the Open list.
   - If m is already in the Open list and the new node has a lower cost, update it with the new node information.
   - If m is already in the Close list and the new node has a lower total cost, remove the corresponding node from the Close list and add m to the Open list.
7. Repeat from 4.
8. After the search completes, the path from the start to the goal is obtained by sequentially tracing the parent from the goal node.

4. Experiment

In this study, experiments were conducted for three situations. Two potential functions were used for moving obstacles, and the paths derived by the proposed method were compared. The first was the potential function proposed by Hoshino et al. that considers the direction of movement and velocity, and the second was a potential function that does not consider velocity. In the experiment, each vehicle moves according to its speed at each step. The proposed method moves forward to an adjacent node in one of four directions: up, down, left, and right.

The paths derived when the cost used in the proposed method is used in the potential method are compared with the proposed method. However, the range that can be moved in one step is 1, and the derived path is node-independent.

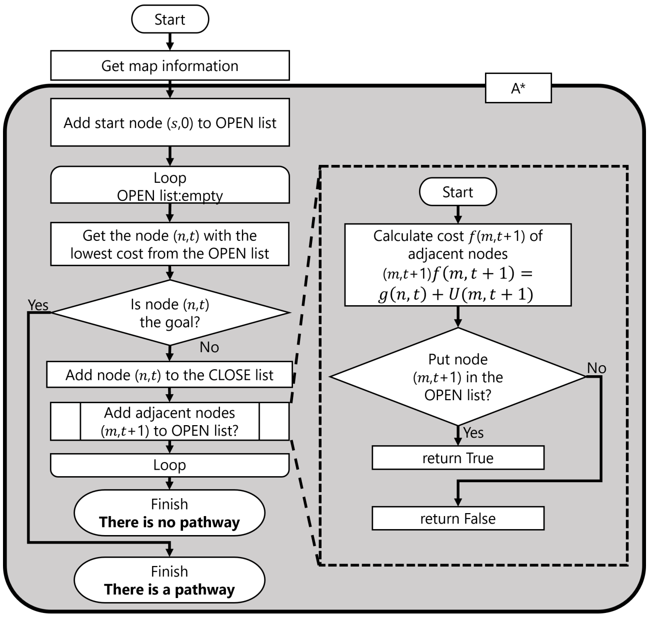

Figure 4: Schematic of the proposed method

4.1. Potential function

In this study, Equation 7 was used as the destination potential function, Equation 8 was employed as the wall potential function, Equation 9 was used as the obstacle potential function without considering the direction of movement and speed, and Equation 10 was used as the potential function for the obstacle considering the direction of movement and speed.

$$U_d(x,y) = w_d \sqrt{(x-x_d)^2+(y-y_d)^2} \tag{7}$$

$$U_w(x,y) = w_w \sum_{i=1}^{n} \frac{1}{2\pi} \exp\left[-\frac{(x-x_{wi})^2+(y-y_{wi})^2}{2}\right] \tag{8}$$

$$U_o(x,y) = w_o \sum_{i=1}^{n} \frac{1}{2\pi} \exp\left[-\frac{(x-x_{oi})^2+(y-y_{oi})^2}{2}\right] \tag{9}$$

$$U_o(x,y,\theta) = w_o \sum_{i=1}^{n} \frac{\exp\{k|v_i|\cos(\theta_i-\mu_i)\}}{2\pi I_0(k|v_i|)} \times \frac{\exp\left[-\frac{\sqrt{(x-x_{oi})^2+(y-y_{oi})^2}}{2}\right]}{2\pi} \tag{10}$$

In addition, the potential values at the coordinates of the obstacle and wall were allowed to diverge infinitely in this experiment.

For the adjustment parameter k of the direction of distribution, the value when the time required to reach the destination was the shortest among 1 to 9 was adopted for the proposed method (considering speed) and potential method.

4.2. Experiment 1

This experiment was conducted to simulate a situation in which multiple obstacles simultaneously cross the road from both sides at an intersection while the vehicle proceeds straight. Figure 5 overviews the situation. Table 1 lists the parameters used in this experiment.

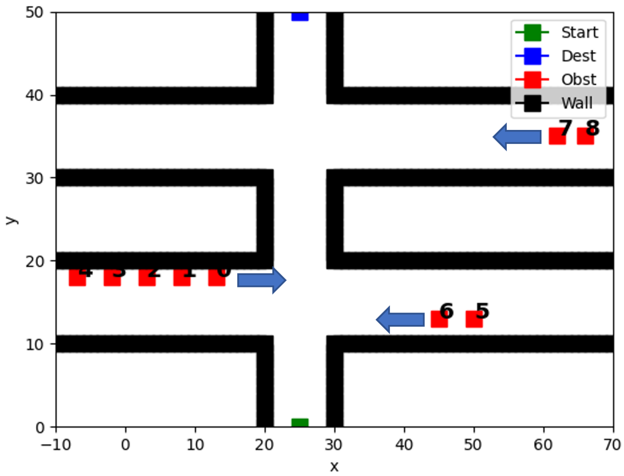

Figure 5: Experiment 1: Situation

Table 1: Experiment 1: Parameters

	Proposal Method	Potential method
Weight (Destination) w_d	0.01	
Weight (Obstacle) w_o	1000	
Weight (Wall) w_w	100	
Obstacle 0 (x, y, v_x, v_y)	(13,18,1,0)	
Obstacle 1 (x, y, v_x, v_y)	(8,18,1,0)	
Obstacle 2 (x, y, v_x, v_y)	(3,18,1,0)	
Obstacle 3 (x, y, v_x, v_y)	(-2,18,1,0)	
Obstacle 4 (x, y, v_x, v_y)	(-7,18,1,0)	
Obstacle 5 (x, y, v_x, v_y)	(50,13,-1,0)	
Obstacle 6 (x, y, v_x, v_y)	(45,13,-1,0)	
Obstacle 7 (x, y, v_x, v_y)	(62,35,-1,0)	
Obstacle 8 (x, y, v_x, v_y)	(66,35,-1,0)	
k	3	9

4.2.1. Results

Figure 6 shows the results using Equation 9, Figure 7 shows the results using Equation 10, and Figure 8 shows the results of the potential method.

In Figure 6, the pathway was derived to follow obstacle 4 after it emerges in front of the movement direction of obstacle 6. In contrast, in Figure 7, a path was derived that passed between obstacles 1 and 2 and then behind obstacle 8. The results are shown in Figures 9 and 10. In Figure 8, the path was derived by moving after obstacles 5 and 6 passed and then passing behind obstacle 4. Figure 11 presents the results.

4.3. Experiment 2

This experiment was conducted to simulate a situation in which a vehicle proceeds straight on a road with two lanes in each direction (four lanes in total) at an intersection with multiple obstacles simultaneously

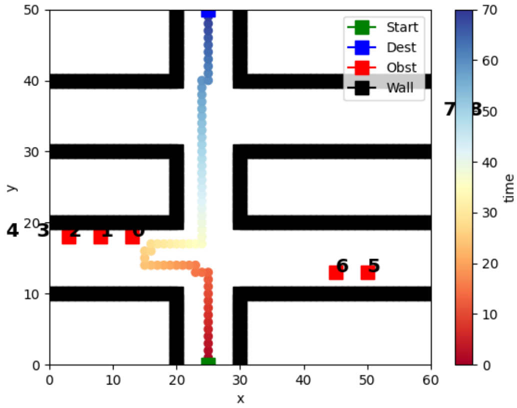

Figure 6: Experiment 1 Result: Without considering movement speed and direction

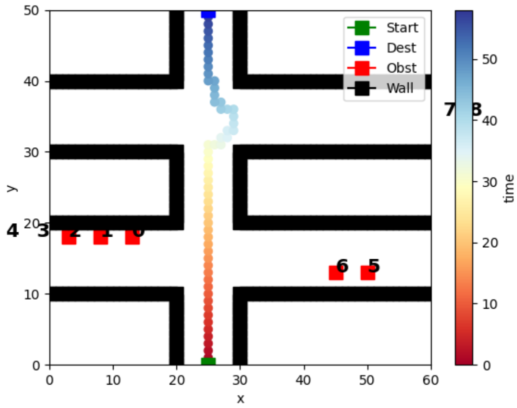

Figure 7: Experiment 1 Result: Considering movement speed and direction

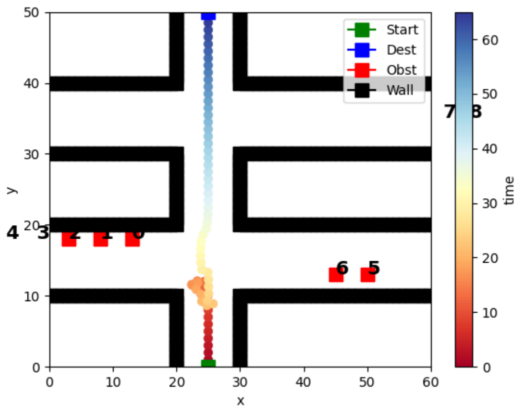

Figure 8: Experiment 1 Result: Potential method

crossing from the left and right. Figure 12 overviews the situation. Table 2 lists the parameters used in this experiment.

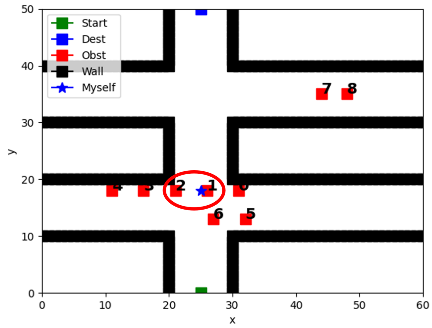

Figure 9: Vehicle position at $t = 18$ in Figure 7

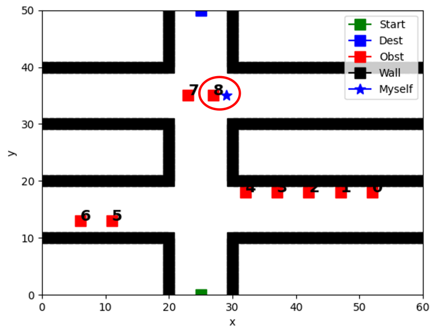

Figure 10: Vehicle position at $t = 39$ in Figure 7

Figure 11: Vehicle position at $t = 27$ in Figure 8

4.3.1. Results

The results using Equation 9 are shown in Figure 13, the results using Equation 10 are shown in Figure 14, and the results of the potential method are shown in Figure 15.

In Figure 13, the path was derived from the right side, passing between obstacles 5 and 7, then following obstacle 5, past obstacle 3, and then to the destination. In Figure 14, a path was derived that passed just behind obstacles 6 and 5 and between obstacles 1 and 3. The results are shown in Figures 16, 17, and 18. In Figure 15, we derived a path that follows obstacle 6 and then passes between obstacles 5 and 7. The results are shown in Figure 19.

4.4. Experiment 3

This experiment was conducted to simulate a situation in which a vehicle is turning right at an intersection and multiple oncoming vehicles are coming toward the vehicle. Figure 20 overviews the situation. Table 3 lists the parameters used in this experiment.

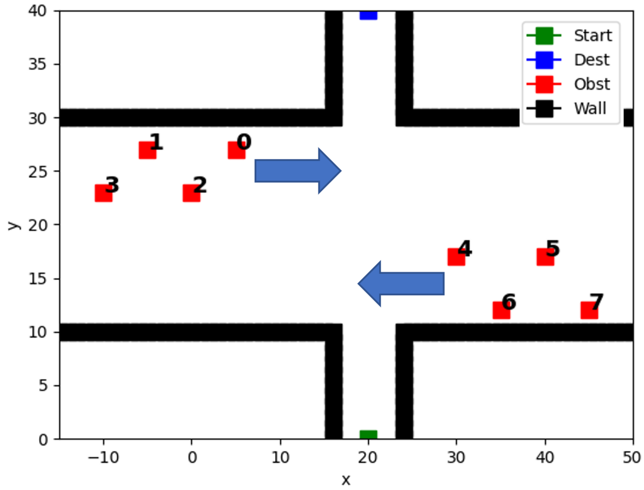

Figure 12: Experiment 2: Situation

Table 2: Experiment 2: Parameters

	Proposal Method	Potential method
Weight (Destination) w_d	0.01	
Weight (Obstacle) w_o	1000	
Weight (Wall) w_w	1	
Obstacle 0 (x, y, v_x, v_y)	(5,27,1,0)	
Obstacle 1 (x, y, v_x, v_y)	(-5,27,1,0)	
Obstacle 2 (x, y, v_x, v_y)	(0,23,1,0)	
Obstacle 3 (x, y, v_x, v_y)	(-10,23,1,0)	
Obstacle 4 (x, y, v_x, v_y)	(30,17,-1,0)	
Obstacle 5 (x, y, v_x, v_y)	(40,17,-1,0)	
Obstacle 6 (x, y, v_x, v_y)	(35,12,-1,0)	
Obstacle 7 (x, y, v_x, v_y)	(45,12,-1,0)	
k	5	7

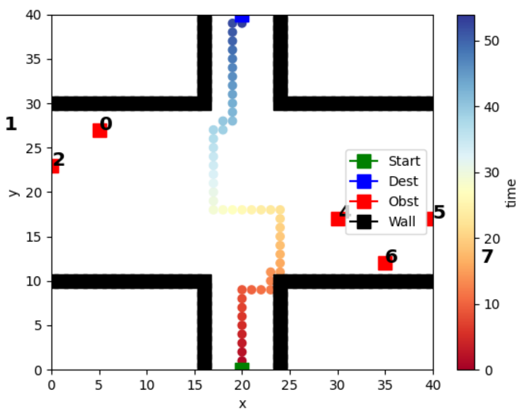

Figure 13: Experiment 2 Result: Without considering movement speed and direction

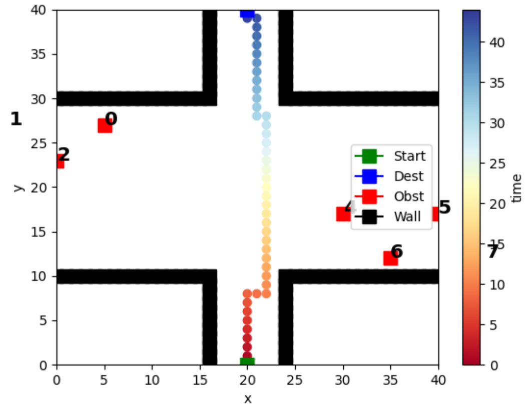

Figure 14: Experiment 2 Result: Considering movement speed and direction

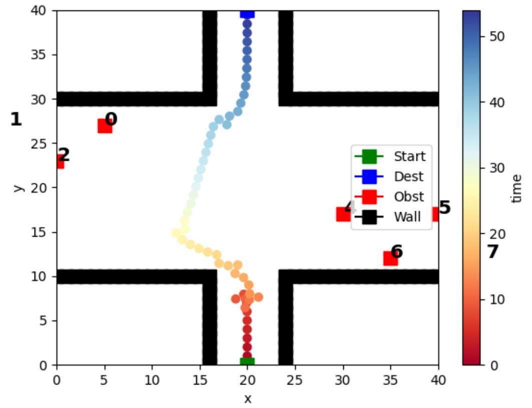

Figure 15: Experiment 2 Result: Potential method

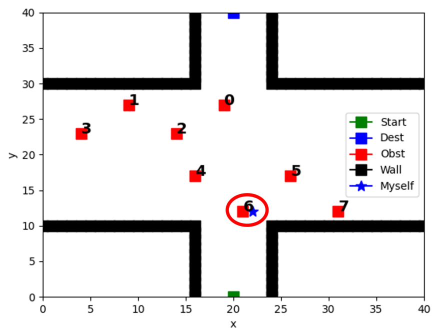

Figure 16: Vehicle position at $t = 14$ in Figure 14

4.4.1. Results

The results using Equation 9 are shown in Figure 21, the results using Equation 10 are shown in Figure 22, and the results of the potential method are shown in Figure 23.

In Figure 21, a path was derived in which the vehicle proceeds until it crosses obstacle 3 at the intersection, and then turns right. The result is shown in Figure 24. In Figure 22, a path was derived that passes immediately behind obstacle 3, rather than the path without consideration. In Figure 23, a path with a zigzag motion was derived.

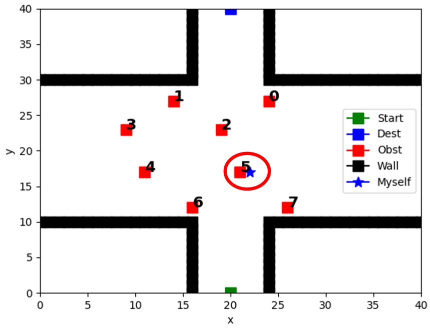

Figure 17: Vehicle position at $t = 19$ in Figure 14

Figure 18: Vehicle position at $t = 29$ in Figure 14

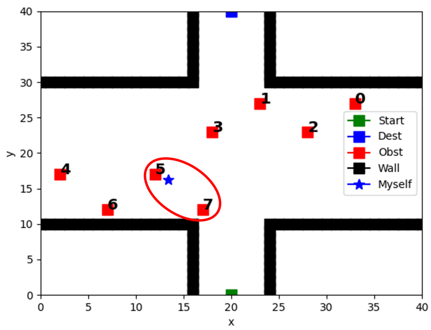

Figure 19: Vehicle position at $t = 28$ in Figure 15

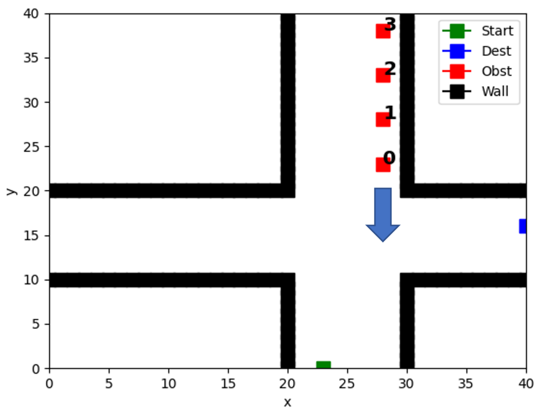

Figure 20: Experiment 3: Situation

Table 3: Experiment 3: Parameters

	Proposal Method	Potential method
Weight (Destination) w_d	0.01	
Weight (Obstacle) w_o	1000	
Weight (Wall) w_w	10	
Obstacle 0 (x, y, v_x, v_y)	(28,23,0,-1)	
Obstacle 1 (x, y, v_x, v_y)	(28,28,0,-1)	
Obstacle 2 (x, y, v_x, v_y)	(28,33,0,-1)	
Obstacle 3 (x, y, v_x, v_y)	(28,38,0,-1)	
k	7	9

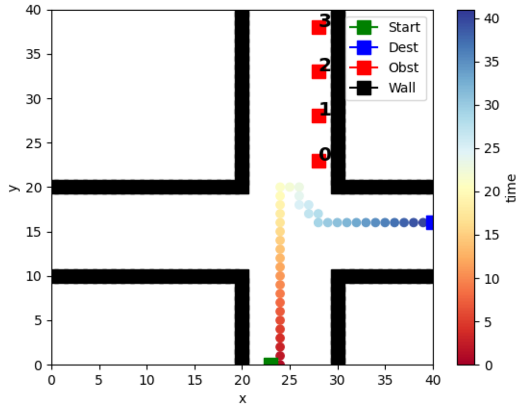

Figure 21: Experiment 3 Result: Without considering movement speed and direction

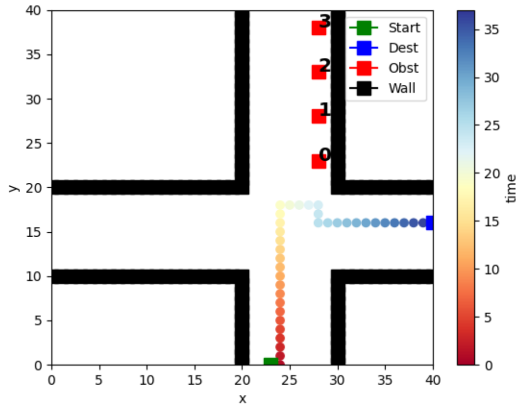

Figure 22: Experiment 3 Result: Considering movement speed and direction

5. Evaluation and Discussion

5.1. Evaluation of time required to reach the destination

Table 4 shows the time required to reach the destination for the two proposed methods and potential method in the three experiments.

Table 4 shows that the proposed method that considered speed and direction was faster in Experiments 1 and 2. This was because the potential value was smaller behind the direction in which the obstacle was

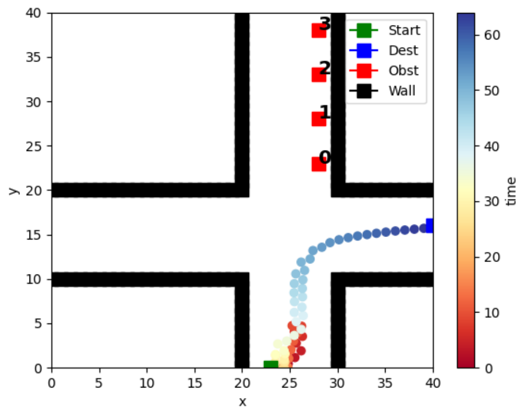

Figure 23: Experiment 3 Result: Potential method

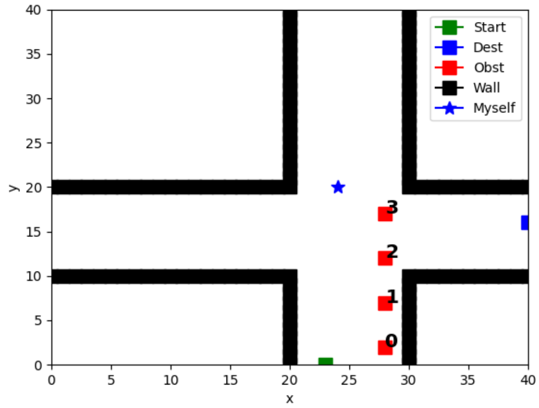

Figure 24: Vehicle position at $t = 21$ in Figure 21

Table 4: Time required to reach the destination

	Expt.1	Expt.2	Expt.3
Proposed method (w/o considering speed and direction)	70	54	41
Proposed method (considering speed and direction)	58	44	37
Potential method	65	54	64

moving such that the path was derived between vehicles. This result shows an advantage when multiple obstacles pass through a single intersection. In Experiment 3, the proposed method was faster than the potential method. This result shows that the proposed method is superior to the potential method when turning right at intersections with oncoming vehicles.

5.2. Evaluation by distance from obstacle

The minimum distances to obstacles and their averages for the two proposed methods and the potential method in the three experiments are shown in Table 5.

From Table 5, the proposed method can be confirmed to not consider speed and direction, having the greatest distance from obstacles and deriving a path that is less likely to cause collisions with obstacles. In contrast, the proposed method that considers speed and direction has the shortest distance from the obstacle and is considered to be more likely to cause a collision. Figure 25 shows the potential field of the proposed

Table 5: Minimum distance from obstacle and its average

	Expt.1	Expt.2	Expt.3	Average
Proposed method (w/o considering speed and direction)	3.606	2.236	4.000	3.281
Proposed method (considering speed and direction)	1.000	1.000	2.236	1.412
Potential method	1.771	1.596	3.011	2.126

method with speed consideration in Experiment 1 as it passes between vehicles. The orange circle is the vehicle, and the white area of the potential field is where the potential field diverges infinitely, indicating the current location of the wall or obstacle.

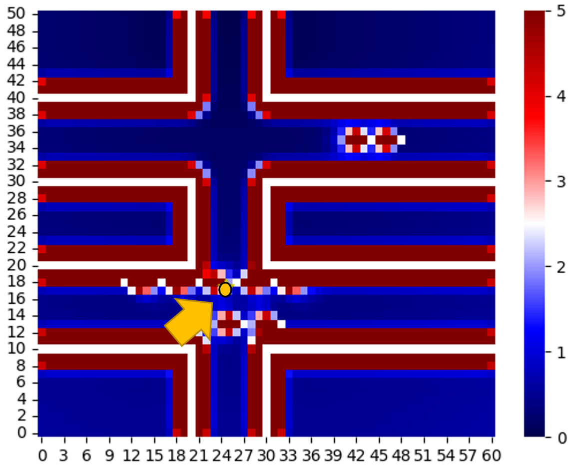

Figure 25: Potential field at $t = 18$ in Figure 7 (Experiment 1: Considering movement speed and direction)

From Figure 25, accidents are determined to be less likely to occur as a potential value because the vehicle is passing through a lower potential value behind an obstacle.

5.3. Difference between the paths derived by the proposed method and the potential method for right turns

In Figure 23, the potential method in Experiment 3 has a zigzagging motion. This is caused by the motion determination of the potential method. In the potential method, the direction of movement is determined by the gradient of the potential field. In Experiment 3, the vehicle tries to move in a straight line toward the destination. However, when it approaches a wall, it moves in the opposite direction of the wall, following the gradient generated by the wall's repulsive potential function. Simultaneously, the obstacle approaches and the vehicle moves backward once. Therefore, the vehicle is stuck in a situation where it cannot move in a traffic jam. Figure 26 shows this situation. Therefore, the potential method is not well suited for deriving a right-turn path.

In contrast, if a vehicle is oncoming, the proposed method determines that the oncoming lane is dangerous and derives a method to proceed through the intersection to turn right and avoid the oncoming vehicle. In addition, during traffic congestion, the proposed method derives a route that passes between obstacles, as shown in Figure 27. Therefore, the proposed method is useful for deriving a right-turn path.

5.4. Using the proposed method between the two types of methods

The proposed method hat considers speed and direction has higher potential values in the direction of movement and lower potential values near obstacles as the speed increases. Conversely, the slower the speed, the higher the potential value near the obstacle and the lower the potential value in the direction of movement, resulting in a potential field without considering speed and direction. Figure 28 shows this. Evidently, when

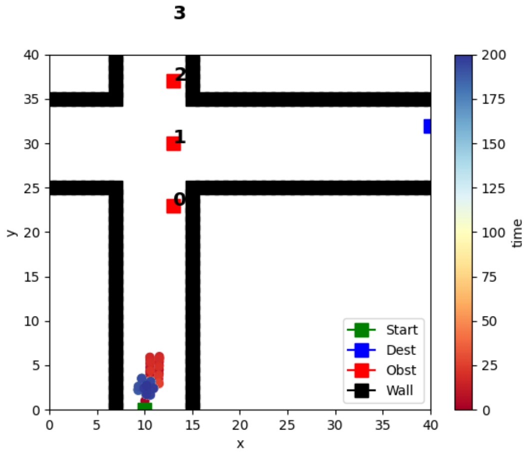

Figure 26: Potential methods in traffic congestion

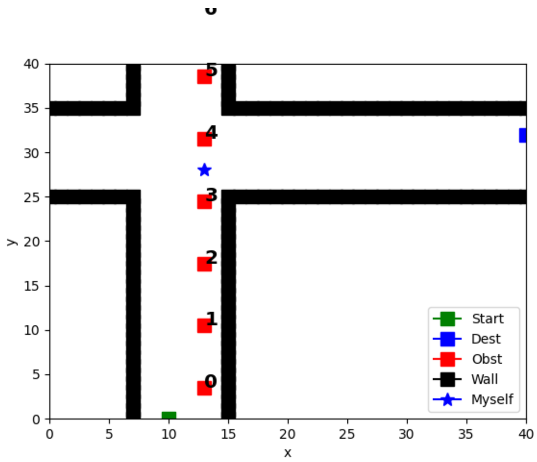

Figure 27: Proposed methods in traffic congestion

the speed of the obstacle is high, the proposed method, which considers speed, is more suitable because using a path that passes right behind the obstacle is safe, as shown in Figure 16. In contrast, if the speed of the obstacle is slow, the proposed method, which does not consider speed, is suitable for a safe path that can maintain distance from the obstacle.

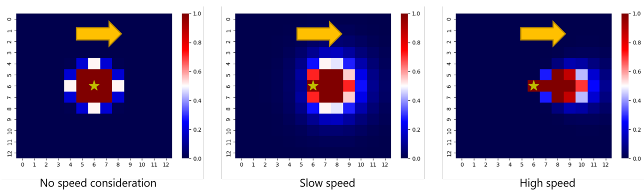

Figure 28: Potential field with speed

6. Conclusion

In this study, we proposed and evaluated a method for deriving routes by A* using potential values as costs. The results showed that, in some situations, the route derived by the proposed method was superior to the route derived by the existing potential method in terms of safety and time required to reach the destination. Our future work must improve the utility of the system. In this study, the movement of the vehicle only corresponds to four directions (up, down, left, and right). For automatic driving, determining the direction of movement in more detail is necessary, and smoother routes can be derived by expressing the movement in terms of angles. However, the amount of calculation in A* would be enormous; further work is required. In addition, this method assumes that the vehicle moves at a constant speed. If it becomes possible to derive a route that considers acceleration and deceleration, this method will be significantly important.

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