Strategic Creation and Placement of Landmarks for Robot Navigation in a Partially-known Environment

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***Abstract*—Navigation of autonomous robots in uncharted or uncertain, and constrained or hazardous environment is a common problem but integrated with multiple challenges. This paper considers a subsection of such an environment and essays a feasible yet innovative solution for accurate parking and obstacle avoidance of a car-like mobile robot. The new method is based on strategic creation and positioning of landmarks in a bounded workspace that will aid or guide the robot to safely navigate the workspace and finally park correctly inside of the designated parking bay. By autonomously controlling its translational velocity and the steering angle, the car-like robot navigates from one (newly fixed) landmark to another (newly fixed) and finally converges to a target with a pre-defined posture. Attaining accurate posture is very important in real-life situations which involve tasks such as loading or off-loading and deliveries in constrained spaces. The paper establishes practical posture stability of the system. The computer simulations verify the effectiveness of the proposed method and the proposed control inputs.**

Keywords— Landmark creation, Car-like robot, Parking, Posture, Obstacle avoidance

I. Introduction

Robotic motion planning and control problem has been an active research area for more than two decades now. Of many landmark problems, one problem that continues to garner intense attention among the researchers is generating a collision-free path for a robot or team of robots whilst accomplishing various tasks in known, partially unknown or fully unknown environments [1], [2], [3], [4], [5]. The literature contains many interesting situations and findings with the use of various robotic mechanical systems such as aerial and ground vehicles, swimming and flying robots, car-like, drones, tractor-trailer and mobile manipulators for applications such as transportation, companionship, save and rescue, pursuit-evasion, and explorations covering land, sea and space [6], [7], [8], [4], [9], [10], [11], [5], [12], [13]. While a number of techniques for autonomous vehicles appear in the literature, there is still much attention given to problems such as parking, lane changing/merging, cruise control, lifting, herding, avoidance of concave obstacles, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, attaining asymptotic stability in light of Brockett's theorem [14], to name a few, as these problems are difficult and challenging.

In the motion planning and control of nonholonomic robots, it is difficult to attain a desired final orientation of the robot at the target using continuous control inputs [3], [7]. To attain desired final orientations of nonholonomic robots, researchers have developed various methods such as forcing the robot to park inside a virtual parking bay constructed around the target [3], [7], [15], using a hybrid systems approach [16], designing a switched controller in the discrete time domain [17], using rapidly-exploring random tree (RRT) [18]. Following the work of Sharma *et al.*, in [7], [3], a practical desired final orientation of car-like robots can be achieved by forcing the vehicle to park parallel to the boundary lines inside a parking bay. However, the method itself is quite computationally intensive. Thus, one of the objectives of this paper is to develop an easy and simple algorithm to park a car-like robot correctly inside a virtual parking bay.

Another objective of this paper deals with the avoidance of concave obstacles. When a robot is attracted to its goal position while approaching a concave obstacle, there is a possibility that it may get trapped behind the obstacle when the shortest path to the goal position is required. Using the potential field method, when the robot moves near to a concave obstacle, it happens that at a particular position the attractive and repulsive forces are symmetric due to the obstacle surfaces, thus leading to a local minimum of the energy function [19]. Due to this local minimum, asymptotic point stability can not be attained.

To achieve the aforementioned objectives, we develop a new method of strategically placing artificial landmarks into the workspace for the robot to follow to its goal position. Artificial landmarks are objects or features that are added to a workspace for the sole purpose of robot navigation [20] and can be incorporated with extra information, such as, in the form of RFID, bar-codes and IR coding [20] for robots to easily communicate. We present a few relevant work from literature on the placements of landmarks. In [21], the authors discussed the optimized arrangement of artificial landmarks and presented a solution for building an accurate and reliable localization system based on combining artificial and natural landmarks. Salas *et.al.* in [22] presented an algorithm to compute the position of artificial visual landmarks in a mobile robot workspace. In [23], the authors investigated how artificial landmarks can be utilized to reduce the ambiguity in the environment so that the robustness of the localization process is increased. Beinhofer et.al in [24] considered the problem of optimally placing artificial landmarks for mobile robots that repeatedly have to carry out certain navigation tasks. Gao et.al in [25] also considered the problem of optimal landmarks placement in the warehouse so that the reliability of localization is improved. The main contribution of this paper is to develop an algorithm that strategically create and position landmarks in partially-known environment for the car-like nonholonomic robot to follow so that the mobile robot can avoid obstacles of any shape and size and then park correctly inside a parking bay with a desired final orientation.

The rest of the paper is organized as follows: In Section II the car-like vehicle model, target definition, the landmark definition, and the navigation procedure are given. Section III demonstrates the parking ability of the robot where the robot navigates through a set of landmarks so that a desired posture is achieved at the goal position. In Section IV, we discuss the placement of landmarks into the workspace so that the robot can avoid obstacles. The robot selects a point in the non-obstacle region as a landmark and uses it for navigation to safely reach the target. Section V gives a discussion on the contributions and future research possibilities along this line.

II. The Vehicle Model

This research considers a rear wheel driven car-like vehicle model, adopted from [3] and [7]. With reference to Figure 1, the coordinate point (x, y) denotes the center of mass of the vehicle, θ is the car's orientation with respect to the z_1-axis, ϕ is the steering angle with respect to car's longitudinal axis, while ε_1 and ε_2 are the safety parameters adopted from [3] and [7].

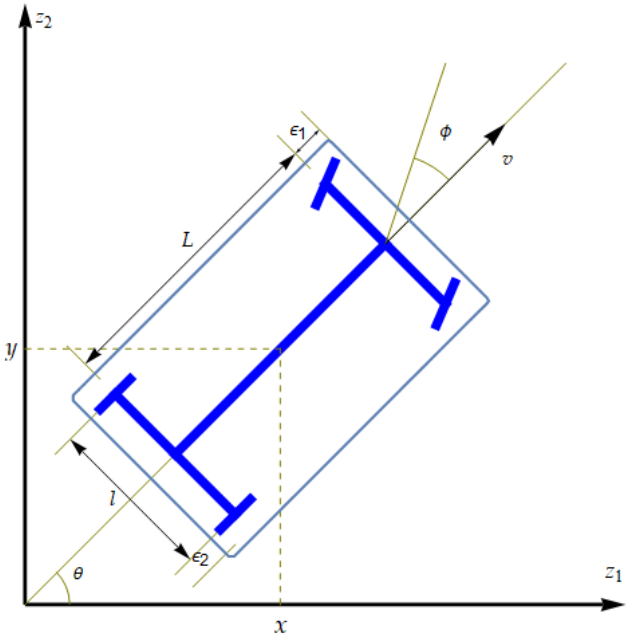

Fig. 1. Schematic representation of the car-like robot, adopted from [15].

Let L be the distance between the two axles and l the length of each axle, then the kinematic model of the car-like vehicle is given by [15]

$$\left.\begin{aligned} x' &= v\cos\theta - \frac{v}{2}\tan\phi\sin\theta \\ y' &= v\sin\theta + \frac{v}{2}\tan\phi\cos\theta \\ \theta' &= \frac{v}{L}\tan\phi \end{aligned}\right\} \quad (1)$$

where v is the vehicle's translational velocity. The vector notation $\mathbf{x} = (x, y) \in \mathbf{R}^2$ will be used to describe the position variables in (1). Moreover, v and ϕ are treated as nonlinear control inputs.

The car-like robot is required to safely move to a goal position via landmarks, we therefore affix a target for the robot. We define the goal position as:

Definition 1: The target of the car-like robot is a disk with center (p_1, p_2) and radius r_T. It is described as the set

$$T = \{(z_1, z_2) \in \mathbf{R}^2 : (z_1 - p_1)^2 + (z_2 - p_2)^2 \le r_T^2\}$$

Since our principal objective is based on placing and navigating through landmarks, we provide the following definition of landmarks:

Definition 2: The kth landmark with the rectangular position (lx_k, ly_k) in the z_1z_2-plane is given by

$$LM_k = \{(z_1, z_2) \in \mathbf{R}^2 : (z_1 - lx_k)^2 + (z_2 - ly_k)^2 = 0\}$$

for $k = 1, 2, \dots, r$.

Let $d_k(t) = ||(x(t) - lx_k, y(t) - ly_k)||$ for $k = 1, 2, \dots, r$ be the distance between the center, (x, y) of the car like robot and the kth landmark, LM_k at time $t \ge 0$ and define $(lx_{r+1}, ly_{r+1}) := (p_1, p_2)$. We further assume that $d_1 < d_2 < \dots < d_r$. When a set of landmarks is determined for the robot to navigate and finally reach to its target, the following control inputs are proposed.

$$\left.\begin{aligned} v(t) &= \alpha\|\mathbf{x}(t) - \mathbf{e}\| \prod_{k=1}^{r} \frac{\min\{1, d_k / d_{\max}\}}{1+\gamma} \\ \phi(t) &= \frac{2\phi_{\max}}{\pi}\tan^{-1}\left(\eta[ly^* - y)\cos\theta - (lx^* - x)\sin\theta]\right) \end{aligned}\right\} \quad (2)$$

where $\alpha > 0$, $\gamma > 0$, $\eta > 0$, $d_{\max} > 0$ are user-defined constants, $\phi_{\max} > 0$ is the maximum steering angle, $\mathbf{e} = (p_1, p_2)$. refers to the goal position, while $(lx^*, ly^*) \in \bigcup_{k=1}^{r} LM_k$ represents the landmark that would be selected from the robot to navigate through. The selection of (lx^*, ly^*) is given in Algorithm 1. Note that the term $\prod_{k=1}^{r} \frac{\min\{1, d_k / d_{\max}\} + \gamma}{1+\gamma}$ in $v(t)$ will ensure that the robot slows down as it enters the neighborhood of a landmark. This idea is inspired by nature where bees are known to slow down when approaching the narrowest section of a tunnel [26]. In addition, according to [27], robots need to slow down when a panel is being recognized so that it does not lose its sight. The neighborhood of the kth landmark is defined as the set

$\mathcal{N} = \{(z_1, z_2) \in \mathbf{R}^2 : (z_1 - lx_k)^2 + (z_2 - ly_k)^2 \le d_{max}^2\}$
for some predefined positive constant $d_{\max}$.

ALGORITHM 1: SELECTION OF (lx^*, ly^*).

```
if t = 0
    (lx*, ly*) = (lx1, ly1)
else
    if ||x(t) - e|| = 0
        (lx*, ly*) = (p1, p2)
    else
        for k = 1 to r
            if d_k = 0
                (lx*, ly*) = (lx_{k+1}, ly_{k+1})
            end
        end
    end
end
```

With the control inputs as defined in (2), we can claim the following:

1. At the center of the target $v(t) = 0$, otherwise $v(t) > 0$.

   Proof: Firstly, when $(x(t), y(t)) = \mathbf{e}$, we have $v(t) = 0$. Secondly, for $(x(t), y(t)) \neq e$, we see that $\alpha\|x(t) - \mathbf{e}\| > 0$ and $\prod_{k=1}^{r} \frac{\min\{1, d_k / d_{\max}\} + \gamma}{1+\gamma} > 0$. Hence $v(t) > 0$.

2. Let θ_f be the orientation of the vehicle at the target. Then $\mathbf{e}^* = (p_1, p_2, \theta_f)$ is an equilibrium point of system (1).

   Proof: Notice that when $(x, y, \theta) = (p_1, p_2, \theta_f)$, the translational velocity $v(t)$ vanishes to zero which implies that $x' = y' = \theta' = 0$. Thus $\mathbf{e}^*$ is an equilibrium point of system (1).

3. The controller, $\phi(t)$ is bounded as $-\phi_{\max} < \phi(t) < \phi_{\max}$.

   Proof: Note that $\tan^{-1}(.)$ is bounded as $|\tan^{-1}(.)| < \pi/2$. Hence $|\phi(t)| < \frac{2\phi_{\max}}{\pi} \cdot \frac{\pi}{2} = \phi_{\max}$ or equivalently $-\phi_{\max} < \phi(t) < \phi_{\max}$.

III. ROW PARKING OF A CAR-LIKE ROBOT

It is difficult and challenging to attain a desired final orientation of a nonholonomic robot using continuous control inputs. Sharma in [28] developed a suitable method to attain a desired final orientation by forcing the robot to park inside a virtual parking bay constructed around the target [28]. A similar idea was also applied in [15], where the desired final orientation of the vehicle was achieved by avoiding the lines of the virtual parking bay. However, the method itself is quite computationally intensive. In this section, we have developed an easy and simple algorithm to park the vehicle correctly inside a parking bay.

The method is based on the placement of landmarks in front of the parking bay. In order to guide the vehicle to its target and park correctly inside the parking slot, we place landmarks at regular intervals directly in front of the parking bay (see Figure 2). These landmarks, which should be collinear with the target, will help the vehicle to align itself before entering the parking slot. We further note that the landmarks considered in this paper are points on the z_1z_2-plane whose positions are known in advance. For the vehicle to converge to the target via the landmarks, we will use the controllers defined in equation (2) and Algorithm 1 will be used to determine (lx^*, ly^*). We verify the idea numerically via Simulation 1.

Simulation 1: To illustrate the effectiveness of our proposed methodology and the control inputs, we simulate a scenario where the car-like mobile robot has to maneuver from an initial to a final state and attain a practically reasonable posture inside the row structured parking bay. To assist the vehicle with the parking, we have placed three landmarks directly in front of the parking bay. Table I gives the values of the different parameters used in the simulations. Figures 2 and 3 show the convergence of the mobile robot to the desired state. In the final phase, the robot achieved a predefined final orientation.

TABLE I. VALUES OF THE DIFFERENT PARAMETERS USED IN THE SIMILATIONS

Initial and Final Configuration	
Initial position	(5, 5)
Initial orientation	0 rad.
Final position	Figure 2: (25, 46). Figure 3: (46, 40).
Final orientation	Figure 2: $\pi/2$ rad. Figure 3: 0 rad.
Position of Landmarks	
Figure 2	(25, 42), (25, 39), (25, 36).
Figure 3	(40, 40), (35, 40), (30, 40).
Vehicle Parameters	
Dimensions	$L = 2$ m, $l = 1$ m.
Safety parameters	$\varepsilon_1 = 0.2$ m, $\varepsilon_2 = 0.1$ m.
Other Parameters	
Workspace dimensions	$0 \le z_1 \le 50$, $0 \le z_2 \le 50$.
Constants	$\alpha = 0.2$, $\gamma = 0.01$, $\eta = 0.05$, $d_{\max} = 3$.

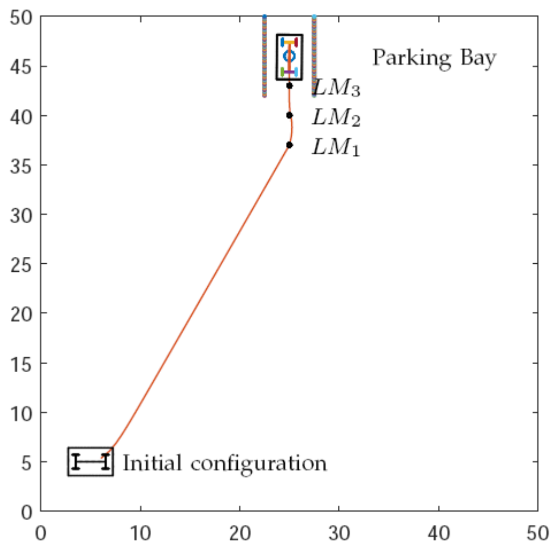

Fig. 2. Placement of landmarks to aid parking for a car-like robot.

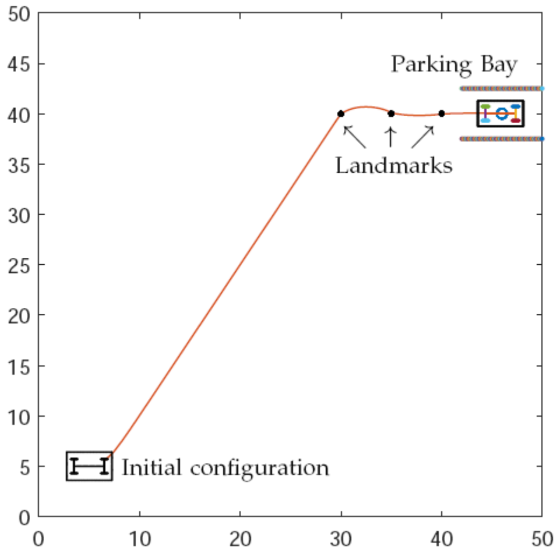

Fig. 3. Placement of landmarks to aid parking for a car-like robot.

IV. Strategic Placement of Landmarks for Obstacle Avoidance

We consider a *partially known* workspace that may be cluttered with fixed obstacles. The position of the target is known, however, the obstacles' positions, sizes and shapes are unknown. We assume that the car-like robot is equipped with sensors that can measure the distance from the robot to an edge of an obstacle and the direction of this edge relative to the robot's position. For the vehicle to safely steer pass an obstacle, we enclose the robot in a disk with center (x, y) and radius

$$r_V = \frac{1}{2}\sqrt{(L+\varepsilon_1)^2 + (l+\varepsilon_2)^2}\ .$$

For $(x, y) \neq (p_1, p_2)$, let ξ be the angular position of the target with the respect to the center of the vehicle, (x, y). The angle ξ is defined implicitly as

$$\tan\xi = \frac{p_2 - y}{p_1 - x}\ .$$

For the car-like robot to avoid obstacles along its path, we will follow the steps given in Algorithm 2. This algorithm finds a suitable coordinate point where landmarks can be placed for the robot to navigate to. This algorithm also ensures that these suitable points should not intersect with the obstacle region and is not too close to an obstacle, that is, not within a distance of r_V from the edge of an obstacle.

Algorithm 2: Landmark Creation for Obstacle Avoidance.

Step 1: Construct a reference axes with center $(x(0), y(0))$ (the reference point) and the two axes are parallel to the z_1 and z_2 axes.

Step 2: Suppose the visibility of the sensor from the reference point is up to a distance d. If no obstacle is 'seen' by the sensor at the polar coordinate points $(r, \xi \pm r_V/d)$, where $r < d$, then a landmark is created at the polar coordinate $(d - r_V, \xi)$ and the robot will maneuver to that landmark. If an obstacle is 'seen' by the sensor at a distance r from the reference point, then go to Step 3.

Step 3: Observe all the polar coordinate points $(r, \xi \pm i r_V/r)$, for $i = 1, 2, \ldots, \lceil \pi r/r_V \rceil$. If obstacles are 'seen' at all these points, then no feasible path to the target exist, so stop. Otherwise, go to Step 4.

Step 4: Select the point $(r, \xi \pm i r_V/r)$ which does not intersect with an obstacle and is closest to the (r, ξ) as a landmark point and the robot will maneuver to that landmark.

Step 5: When the robot reaches the landmark, then that landmark is updated as the new reference point. Repeat steps 2 to 4 until the robot reaches the target.

For the vehicle to maneuver to the landmark described in Step 4, we will use the control inputs defined in equation (2).

Simulation 2: In this example, the car-like robot has to maneuver from the initial position with rectangular position (5, 5) to its target at (46, 40). Using Algorithm 2, the respective landmarks as shown in Figure 4 are created. The first landmark is created at the polar coordinate $(d - r_V, \xi)$ = (15, 0.707), where no obstacles are 'seen' by the sensor at the polar coordinates $(r, \xi \pm r_V/d)$ for all $r < d$. When the robot reached the LM_1, then the edge of the obstacles were seen at a distance r = 13.7 from LM_1. Using the idea described in steps 3 and 4 of Algorithm 2, LM_2 was created at the polar coordinate (13.7,−0.127). Similarly, LM_3 and LM_4 were created at the polar coordinates (13.4, 0.464) and (15.0, 1.38), respectively.

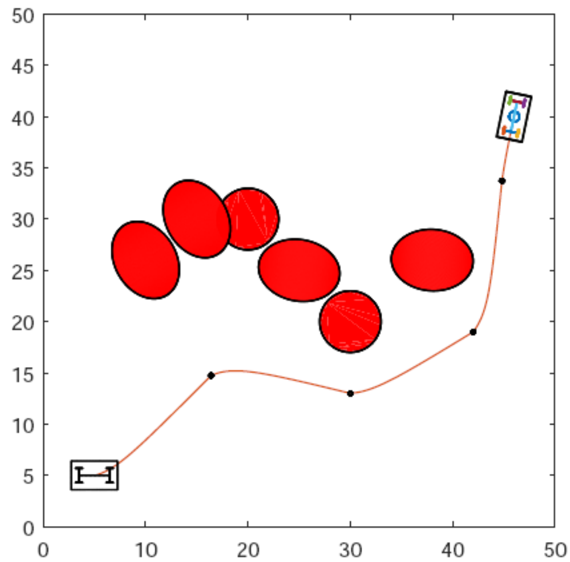

Fig. 4. Creation of landmarks for Obstacle Avoidance.

Simulation 3: We now consider a scenario where the robot's path is obstructed by concave obstacles. The respective landmarks, as shown in Figure 5, are created using Algorithm 2. These landmarks aid the car-like robot to navigate safely to its target. To achieves a predetermined posture, three landmarks were placed in front of the parking bay, which helped the robot to align itself before entering the parking bay.

Figure 6 shows the time evolution of the velocity profile along the trajectory of the robot. Looking at the velocity graph, we see that the car-like robot slowed down as it approached a landmark. However, it gained speed after leaving the landmark. Each local minimum on the velocity graph depicts that the robot was positioned at the center of each landmark at that instant. Finally, at the center of the target, the velocity is zero. Figure 7 shows the orientation of the vehicle. We see that $\theta(t) \to \pi/2$ as the vehicle converges to the target, hence aligning itself as it enters the parking bay.

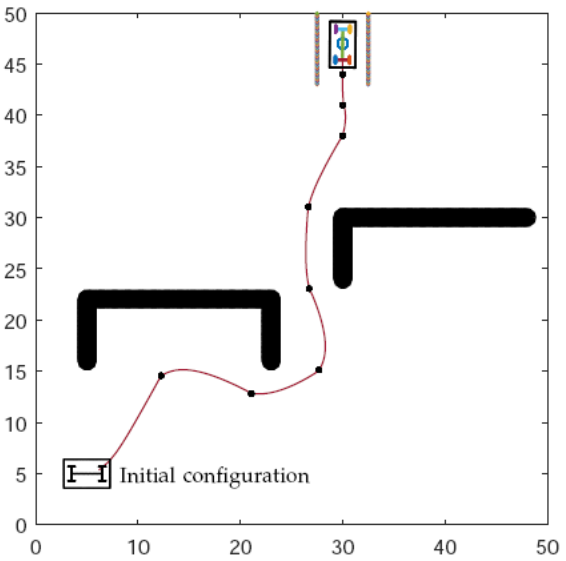

Fig. 5. Creation of landmarks for Obstacle Avoidance and Parking.

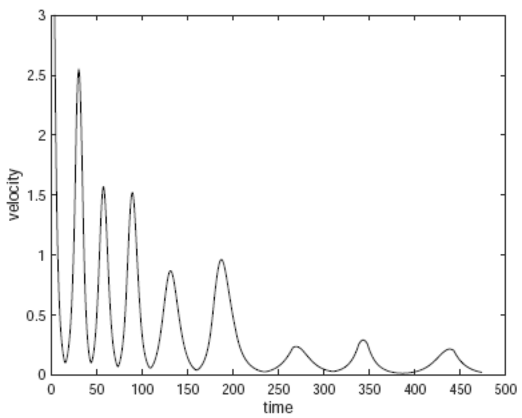

Fig. 6. Evolution of the velocity along the trajectory of the robot shown in Figure 5.

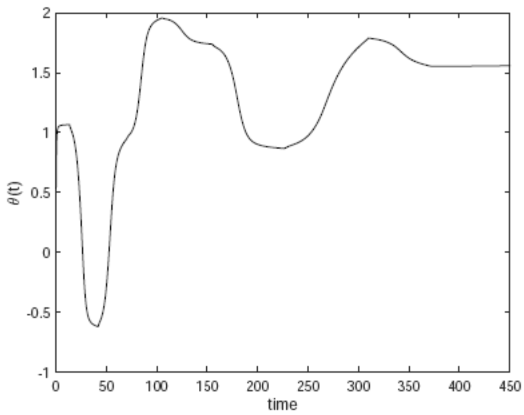

Fig. 7. Orientation of the robot for the trajectory shown in Figure 5.

V. CONCLUSION

In this paper, an algorithm based on creating and placing landmarks is presented to address the parking and obstacle avoidance ability of a car-like mobile robot. The robot is required to safely navigate through the created landmarks from an initial position to a goal position and finally park correctly inside a parking bay.

For parking, landmarks are placed at regular intervals directly in front of the parking bay. These landmarks, which should be collinear with the target, assist the vehicle to align itself before entering the parking slot and hence achieve a desired posture at the goal position. For obstacle avoidance, our algorithm determines a suitable position, not intersecting with the obstacle, where a landmark is placed for the robot to navigate through. The effectiveness of the proposed solution is verified through interesting and challenging computer simulations.

Future work along this line will consider automatic creation of landmarks through learning, considering multiple robots, three-dimensional robots, moving obstacles and fully unknown workspace.

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