Planning Control Commands to Assist in Car Maneuvers

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Abstract

Planning control commands of the steering angle and velocity for autonomous parking maneuvers is addressed. Our approach makes use of conformity between the control commands and resulting shape of the path. The path shape required for a parking maneuver is evaluated from the environmental model. The corresponding control commands are selected and parameterized to provide motion within the available space. The commands are executed by the car servo-systems which drive the vehicle into the parking place. The approach is implemented and tested on a CyCab automated vehicle. The results on a perpendicular parking maneuver are described, and the experiments illustrated by video.

1 Introduction

Steering a car in a constrained environment such as a parking lot requires much attention and driving experience. An assistance system for parallel parking was proposed in [1, 2, 3]. This system localizes a suitable place along a roadside, drives the vehicle to a convenient start position and orientation beside the parking place, monitors the environment and performs iterative sensor-based motions in order to move into the place. The present paper extends our previous work and focuses on obtaining the steering and velocity commands to attain the desired position and orientation of the vehicle relative to its environment.

The kinematic model of a car with front-wheel steering (non-holonomic system) is described by the following equation:

$$\dot{\mathbf{X}} = v\left(\cos\theta,\, \sin\theta,\, \frac{\tan\phi}{L}\right)^T, \qquad (1)$$

where $\dot{\mathbf{X}} = d\mathbf{X}/dt$, $\mathbf{X} = (x,\, y,\, \theta)^T$, x and y are the Cartesian coordinates of the midpoint of the rear wheel axle, θ is the orientation angle of the vehicle, v denotes the velocity of the midpoint of the rear wheel axle, ϕ is the steering angle, and L is the wheel base [4]. The steering angle $\phi(t)$ and velocity $v(t)$ are the control commands which drive the vehicle along a path $\mathbf{X}(t)$. The velocity at the rear wheel axle is: $v = v_f \cos\phi$, where v_f denotes the velocity of the midpoint of the front axle.

The model (1) is valid for a vehicle moving on flat ground with a pure rolling contact without slippage between the wheels and the ground. This purely kinematic model is adequate to describe low-speed motion. The constraints of velocity and acceleration are taken into account, in order to ensure that the planned motion is feasible for the servo-systems of the vehicle.

The conformity between the control commands and resulting path is expressed as a function

$$\mathbf{X} = \mathbf{\Gamma}\,(\phi,\, v), \qquad (2)$$

that allows us to compile a reference table where each generic path shape is associated with generic control profiles. For a given maneuver, the number of path shapes and corresponding control profiles is limited, e.g. a parallel parking maneuver can be composed of S-shaped paths. The generic control profiles are specified by such parameters as magnitude and duration which are computed according to the actual situation in the environment to ensure collision-free motion within the available space. Instead of computing a feasible path $\mathbf{X}$ leading the vehicle to the desired location, the feasible controls $(\phi,\, v)$ which approximately correspond to such a path are selected and parameterized to drive the vehicle to the desired position and orientation.

The advantages of this approach are: similarity to the actions of a human driver; capability to assist the driver in performing maneuvers; absence of a comprehensive path planner; and respecting the dynamic constraints of the steering and velocity servo-systems. The approach can be integrated as an option into existing systems.

This paper is organized as follows. The related works are discussed in section 2. Our approach to planning control commands is presented in section 3. The implementation and experimental results on autonomous parking maneuvers are described in section 4. The conclusions are given in section 5.

2 Related Works

A parking maneuver represents a particular case within a general problem of stabilization of a non-holonomic vehicle to a desired position [5], or within a problem of path tracking [6]. By Brockett's necessary stability conditions [7], the non-holonomic system is open-loop controllable, but it cannot be stabilized to a point by means of smooth time-invariant state feedback. Various feedback laws were proposed: time-varying [8], piece-wise continuous [9] and discontinuous [10]. Planning a feasible path and its tracking was considered in [4, 11, 12]. Steering the vehicle by means of sinusoidal functions was used in [13].

A combination of a linear feedback and non-linear feedforward control with artificial neural network technology was studied in [14]. The authors proposed a control architecture where the motion planning was performed off-line. The feasible parking trajectories are stored in a computer as parking programs. The necessary program is selected according to the situation by means of on-line approximation of the precomputed programs.

The smooth functions constructed from sinusoids were proposed in [1, 2] to provide the steering and velocity commands for a parallel parking maneuver. These commands are executed by the steering and velocity servo-systems of the vehicle. The approach was tested on an electric car, and the results are shown on video [3].

An optimal control law derived from the Pontryagin's principle was studied in [15]. The shortest parking trajectory consisting of two consecutive circular arcs was obtained. A collision-free parallel parking maneuver was evaluated with a 'bang-bang' steering command within a space of minimal length. The collision avoidance condition was derived from the geometry of the motion. The vehicle dynamics and tire slippage on the ground were neglected due to the low speed.

The fuzzy rules for parallel parking of a model car equipped with sensors and a microprocessor were derived in [16]. An approach to acquire the skills of a human driver by means of an artificial neural network and its further use in a fuzzy-hybrid control architecture was proposed in [17] where the controller operates with a video data. The experiments have shown that the velocity can vary substantially during a human-driven parking maneuver, i.e. it is easier for a driver to follow a consistent steering strategy than to keep at a constant speed [17].

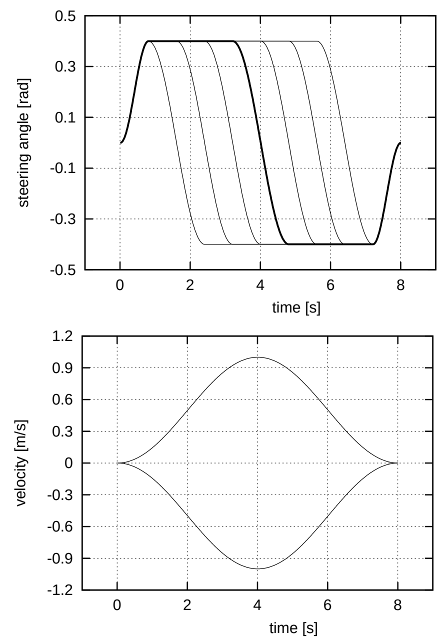
An extension of sensor-based navigation for a parallel parking maneuver was proposed in [18] where a navigation system GANESHA and its implementation on a Navlab vehicle were described. A combination of a neural network and processing of visual information was discussed in [19]. Training experiments were performed with 3D parking profiles extracted from a sequence of images. When a vacant parking place was detected, the learning was performed during the parking maneuver.

Various assisting devices for parking a car have been developed, and the capability of autonomous parallel parking was first reported for a Volkswagen Futura experimental vehicle [20]. A device mounted on the car to help the driver perform a parallel parking or perpendicular parking is described in [21]. This device comprises sensors to measure the distance that a car moves and monitor obstacles around the car, as well as a microcomputer that can generate various signals (in accordance with the driver's instructions and the data received from the sensors) and inform the driver how to drive the car (forward, stop, turn left or right, or reverse). The microcomputer may generate an output signal to control the steering mechanism, the transmission, the accelerator, and the brake system for backing the car into a parking space automatically.

While autonomous parallel parking is addressed in many publications, autonomous perpendicular parking (or parking in a garage) has received less attention. Our approach extends our parallel parking algorithm [1, 2, 3] to perpendicular parking.

3 Planning Control Commands

This section describes the generic profiles of the steering and velocity commands for parking maneuvers. While parallel parking can be performed with a symmetric steering command, an asymmetric steering profile provides arbitrary desired orientation. For example, a set of steering and velocity commands is shown in Fig. 1, and the resulting paths are depicted in Fig. 2 where the vehicle starts from the origin of the coordinate system. The symmetric steering command in Fig. 1a (bold line) results in the parallel parking maneuvers in Fig. 2 for the forward and backward motion; see the velocity profiles in Fig. 1b. Perpendicular parking can be achieved by means of an asymmetric steering command.



a

b

Figure 1: *An example of the steering and velocity commands: a – steering angle, b – velocity*

From driving experience it is known, that before the parking maneuver starts, the vehicle's position and orientation must be adjusted to the location of the parking

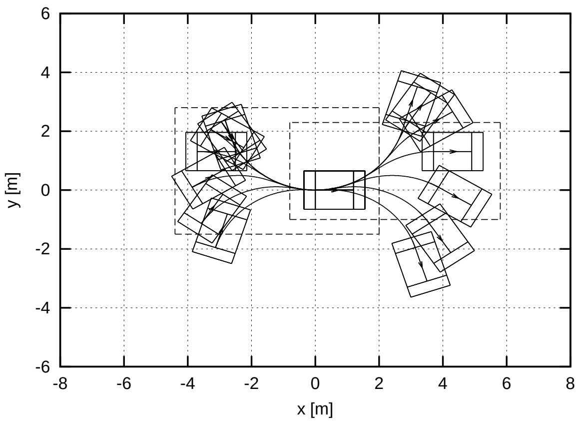


Figure 2: *A set of resulting paths*

place. A setup for perpendicular parking is shown in Fig. 3, where the distances D_f, D_s, D_w, d_f, d_v and d_w are computed from the sensor readings about the environment. In this scenario, the vehicle is almost peprendicular to the parking place, and the start position relative to the place is specified by the distance $D_f = D_f^\star$, where the adequate distance $D_f^\star$ is evaluated according to the experimentally obtained function $D_f^\star(d_v, d_w)$.

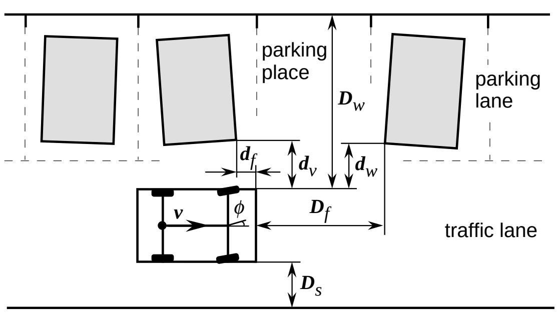


Figure 3: *Start location for perpendicular parking*

The perpendicular parking maneuver involves the following steps:

1. Forward motion aside and away from the parking place in order to reorient the vehicle (this places the vehicle across the traffic lane).
2. Backward motion toward the parking place in order to further reorient the vehicle (i.e. aligning with the parking place and entering the place).
3. Additional iterative motions are performed forwards and backwards as necessary in order to obtain the required orientation for moving into the parking place.
4. Straight motion backwards completes the perpendicular parking maneuver.

The generic velocity command $v(t)$ is similar for perpendicular and parallel parking meneuvers:

$$v(t) = \begin{cases} v_m\, k_v\, A_v(t), & 0 \le t < T_v, \\ v_m\, k_v, & T_v \le t < T_m - T_v, \\ v_m\, k_v\, B_v(t), & T_m - T_v \le t \le T_m, \end{cases} \tag{3}$$

where $v_m > 0$ is the maximal admissible velocity, $T_v > 0$ denotes the duration needed to accelerate the vehicle to a velocity v_m, a coefficient $k_v = \pm 1$ specifies the direction – forwards (+1) or backwards (–1), T_m denotes the estimated duration of motion during one step, and

$$A_v(t) = \frac{1}{2}\left(1 - \cos\frac{\pi\, t}{T_v}\right), \tag{4}$$

$$B_v(t) = \frac{1}{2}\left(1 - \cos\frac{\pi\,(T_m - t)}{T_v}\right). \tag{5}$$

The command (3) is applied during each step of the parking maneuver, see the example in Fig. 1b. For each pair of successive motions $(i,\, i+1)$, the coefficient k_v in (3) must satisfy the equation $k_{v,i+1} = -k_{v,i}$ that alternates between forward and backward directions.

Step 1. The generic steering command $\phi(t)$ is

$$\phi(t) = \begin{cases} \phi_m\, k_\phi\, A_1(t), & 0 \le t < T_\phi, \\ \phi_m\, k_\phi, & T_\phi \le t < T', \\ \phi_m\, k_\phi\, B_1(t), & T' \le t < T'', \\ -\phi_m\, k_\phi, & T'' \le t \le T_m, \end{cases} \tag{6}$$

where $\phi_m > 0$ is the maximal admissible steering angle, $k_\phi = \pm 1$ is a coefficient that specifies the side of the parking place relative to the direction of the vehicle (–1 for the right side and +1 for the left side), $T_\phi > 0$ denotes the duration needed to turn the steering wheels from a straight direction to ϕ_m, $T' = k_t\, T_m - T_\phi$, $T'' = k_t\, T_m + T_\phi$, $0 < k_t < 1$ is a variable coefficient, and

$$A_1(t) = \frac{1}{2}\left(1 - \cos\frac{\pi t}{T_\phi}\right), \tag{7}$$

$$B_1(t) = \cos\frac{\pi\,(t - T')}{2\, T_\phi}. \tag{8}$$

The values of ϕ_m, k_ϕ, k_t, v_m and T_m are computed according to sensor information about the environment and the estimated position of the vehicle. The duration of the motion T_m must satisfy the condition $T_m > T_m^\star$, where

$$T_m^\star = \max\left\{\frac{T_\phi}{1 - k_t},\ \frac{2\, T_\phi}{k_t},\ 2\, T_v\right\}. \tag{9}$$

Step 2. The generic steering command $\phi(t)$ is

$$\phi(t) = \begin{cases} -\phi_m\, k_\phi, & 0 \le t < T', \\ -\phi_m\, k_\phi\, A_2(t), & T' \le t < T'', \\ \phi_m\, k_\phi, & T'' \le t < T_m - T_\phi, \\ \phi_m\, k_\phi\, B_2(t), & T_m - T_\phi \le t \le T_m, \end{cases} \tag{10}$$

where

$$A_2(t) = \cos\frac{\pi(t - T')}{2\,T_\phi}, \quad (11)$$

$$B_2(t) = \frac{1}{2}\left(1 - \cos\frac{\pi(T_m - t)}{T_\phi}\right). \quad (12)$$

Step 3. The generic steering command $\phi(t)$ is

$$\phi(t) = \begin{cases} -\phi_m\, k_\phi\, A_3(t), & 0 \le t < T_\phi, \\ -\phi_m\, k_\phi, & T_\phi \le t < T', \\ -\phi_m\, k_\phi\, B_3(t), & T' \le t < T'', \\ \phi_m\, k_\phi, & T'' \le t < T_m - T_\phi, \\ \phi_m\, k_\phi\, C_3(t), & T_m - T_\phi \le t \le T_m, \end{cases} \quad (13)$$

where

$$A_3(t) = \frac{1}{2}\left(1 - \cos\frac{\pi t}{T_\phi}\right), \quad (14)$$

$$B_3(t) = \cos\frac{\pi(t - T')}{2\,T_\phi}, \quad (15)$$

$$C_3(t) = \frac{1}{2}\left(1 - \cos\frac{\pi(T_m - t)}{T_\phi}\right). \quad (16)$$

The generic profiles of the steering angle and velocity are parameterized, i.e. a search for values of ϕ_m, k_t, v_m and T_m is performed at each step by means of evaluating the model (1) while taking into account the geometric constraints of the environment and the actual position and orientation of the vehicle. The search results in such values of ϕ_m, k_t, v_m and T_m which provide the desired position and orientation, while the maximal possible ϕ_m and v_m still ensure that the vehicle moves within the available space.

The commands $\phi(t)$ and $v(t)$ are open-loop in the $(x,\, y,\, \theta)$-coordinates. They are executed by the steering and velocity servo-systems until the parked position and orientation are attained. The resulting accuracy of the motion depends on the accuracy of these servo-systems. Possible errors are compensated by subsequent motions.

4 Experiments

The method developed has been tested on a CyCab electric vehicle [22] shown in Fig. 4. The dimensions of the vehicle are: 1.90 m (length), 1.20 m (width) and 1.65 m (height). The weight of the CyCab is 350 kg, its maximal velocity is 25 km/h, and the maximal load is 250 kg (two people and luggage). The motion autonomy is two hours (provided by four lead seal batteries). The SICK laser scanner is mounted on the front part of the vehicle, as seen in Fig. 4. The CyCab vehicle can either be manually driven by a joystick, or it can move autonomously. Its onboard controller with a Motorola 555 processor runs under Linux. The method was implemented in C++ language.

Our experimental setup in a parking lot environment is shown in Fig. 5. The parking maneuver is performed while monitoring the environment and avoiding collisions with obstacles, e.g. a pedestrian in the way of the vehicle. The

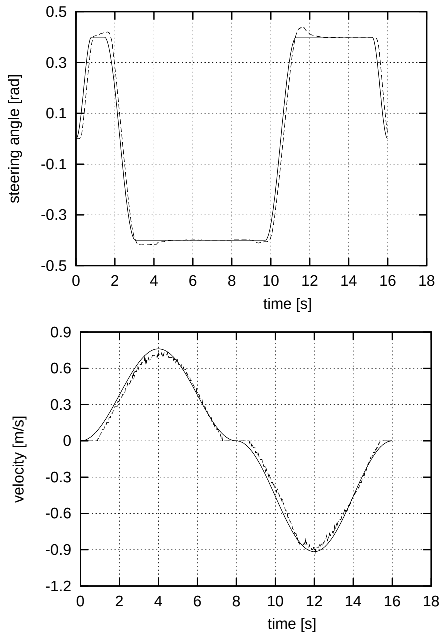
Figure 4: *A CyCab vehicle*

CyCab moves along the traffic lane until it attains a suitable starting location beside the parking place (the place is between two other CyCab vehicles shown in Fig. 5). Then, the control commands $\phi(t)$ and $v(t)$ are planned and executed to perform a perpendicular parking maneuver.

Figure 5: *Environmental setup for perpendicular parking*

An example of the control commands is shown in Fig. 6, and the corresponding motion of the vehicle is depicted in Fig. 7 where the displacement of the vehicle's corners is shown by dotted lines. The width of the traffic lane is sufficient for the vehicle to attain the orientation of 45° relative to the traffic lane in the first step of the maneuver. In the second step the vehicle reaches a position and orientation suitable for moving into the parking place, i.e. the third step in this case is not necessary.

The motion accuracy depends on the accuracy of the servo-systems which execute the planned commands, as shown in Fig. 6. The tracking errors of the servo-systems result in a discrepancy between the planned and actual motion, as seen in Fig. 7. At the end of each step, the resulting error of position and orientation is estimated from the sensor information, and the subsequent control commands are planned according to the actual position and orientation of the vehicle.



a

b

Figure 6: An example of the steering and velocity commands (solid line) and their execution by the servo-systems (dashed line): a – steering angle, b – velocity

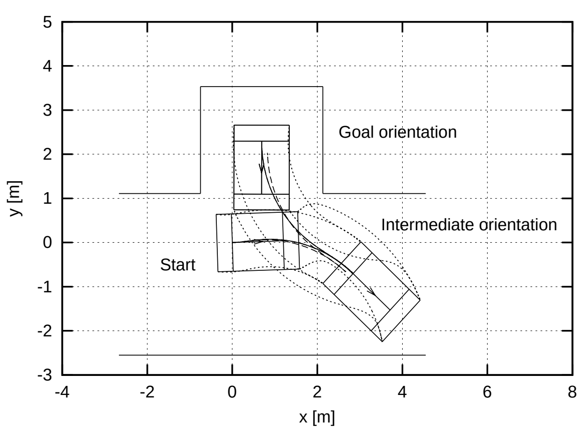
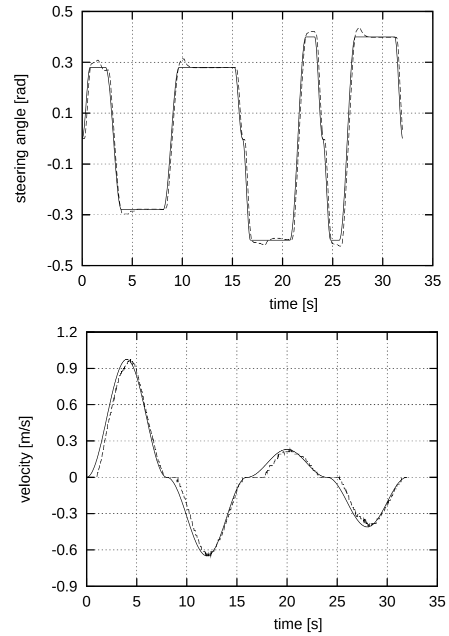


Figure 7: An example of a perpendicular parking maneuver: estimated path (solid line) and actual path (dashed line)



a

b

Figure 8: Steering and velocity commands (solid line) and their execution by the servo-systems (dashed line) in the case of lateral constraint: a – steering angle, b – velocity

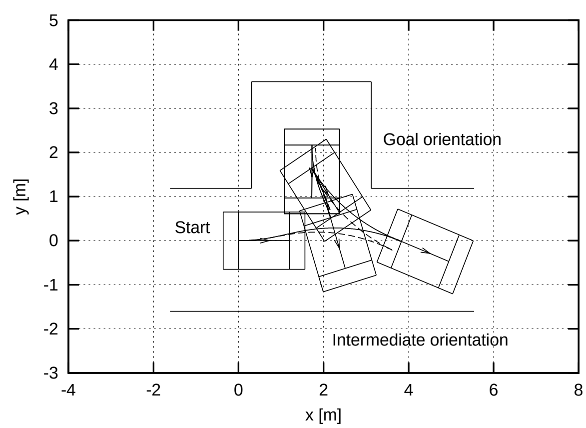


Figure 9: An example of a perpendicular parking maneuver in the case of lateral constraint: estimated path (solid line) and actual path (dashed line)

Perpendicular parking in the case of a lateral constraint (e.g. in a narrow street) is shown in Fig. 8 and Fig. 9. The search for values of ϕ_m, k_t, v_m and T_m takes into account the actual geometric constraints of the environment. The displacement of the car frame is simulated in order to ensure that the subsequent motion is performed without collisions. Comparing this with Fig. 6 and Fig. 7, the lateral constraint results in the additional iterations (the third step is needed for the vehicle to attain the proper orientation and position for moving into the parking place).

5 Conclusion

The approach to autonomously perform low-speed maneuvers in a constrained traffic environment was presented. The approach was described using an example of perpendicular parking (or garage parking) maneuver. The method was implemented on a CyCab automated vehicle, and the experimental results obtained were discussed. They are also illustrated on a video which may be downloaded at http://celultra.riken.go.jp/~paromt/dev.html.

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