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STEERING AND VELOCITY COMMANDS FOR PARKING ASSISTANCE

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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. They are executed by the car servo-systems which drive the vehicle into the parking place. The approach is tested on a CyCab automated vehicle. The experimental results on a perpendicular parking maneuver are described, and the experiments illustrated by video.

KEY WORDS

Mobile robot, driver assistance, parking maneuver

1 Introduction

A parking maneuver represents a particular case within a problem of stabilizing a non-holonomic vehicle to a desired position [1, 2], or within a problem of planning a feasible path to the position and subsequent tracking this path [3, 4, 5]. For the “feedback” approaches, accurate localization of the vehicle must be provided during the motion. The “feedback” and “planning” approaches require accurate kinematic and dynamic models of the vehicle and its environment. However, within these models some of the vehicle’s parameters are uncertain (e.g. radius of tires, mass of the vehicle) or unknown (e.g. disturbance forces). The “planning” approaches must result in a feasible reference path. If the planned path differs from a feasible one because of unmodelled dynamics or inaccuracies within the models, the vehicle is unable to follow it accurately.

While uncertainties and inaccuracies exist and they are unavoidable, a combination of “feedback” and “planning” is proposed to provide a robust operation for autonomous parking. The motion control procedure involves a Localization-Planning-Execution cycle which is repeated until a specified location of the vehicle relative to its environment is reached [6, 7, 8]. The present paper extends our previous work on parallel parking and focuses on planning the steering and velocity commands which drive the vehicle to the desired position and orientation.

The existing conformity between the control commands and resulting shape of the path 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 planning a feasible path to the desired location and subsequent tracking this path, the feasible steering and velocity commands 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 kinematic and dynamic constraints of the steering and velocity servo-systems. The approach can be integrated as an option into existing systems.

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 [3]. 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. Taking into account the kinematic and dynamic constraints ensures that the reference steering angle $\phi(t)$ and velocity $v(t)$ are feasible for the vehicle.

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 combination of a linear feedback and non-linear feedforward control with artificial neural network technology was proposed in [9]. The motion planning is 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.

An optimal control law derived from the Pontryagin's principle was studied in [10]. 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 [11]. 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 [12] 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 [12].

An extension of sensor-based navigation for a parallel parking maneuver was proposed in [13] 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 [14]. 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 have been developed, and the capability of autonomous parallel parking was first reported for a Volkswagen Futura experimental vehicle [15]. A device mounted on the car to help the driver perform a parallel or perpendicular parking maneuver is described in [16]. It 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 numerous publications, perpendicular parking (or parking in a garage) has received less attention. The present paper extends our parallel parking algorithm [6, 7, 8] to perpendicular parking.

3 Planning Control Commands

While parallel parking can be performed with a symmetric steering command, see [6, 7, 8], 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 curve) results in the parallel parking maneuvers in Fig. 2 (dashed rectangles) 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.

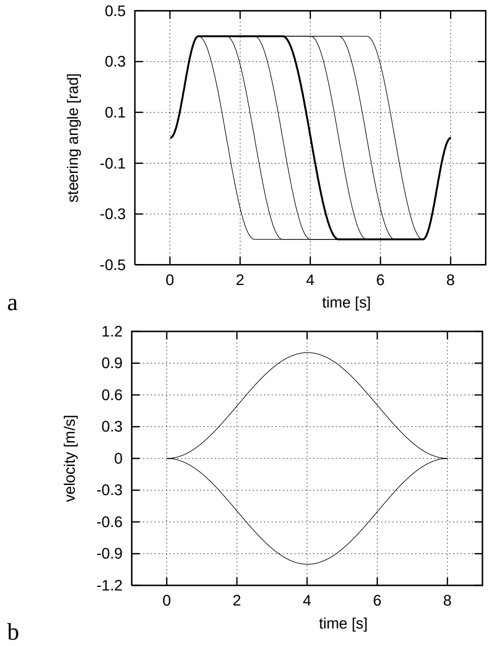

Figure 1. An example of the steering and velocity commands: a – steering angle, b – velocity.

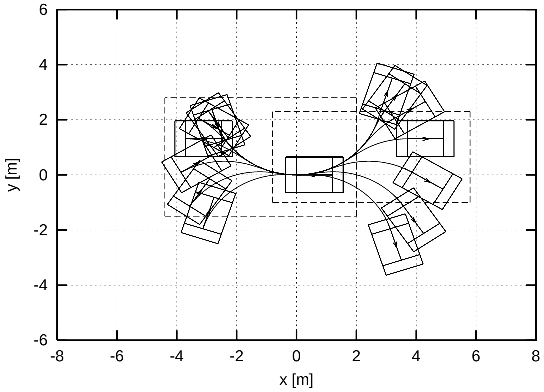

Figure 2. A set of resulting paths of the vehicle.

The parking maneuver is composed of low-speed forwards-and-backwards motions with coordinated control of the steering angle and velocity. 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 $D_f^\star\,(d_v,\, d_w)$.

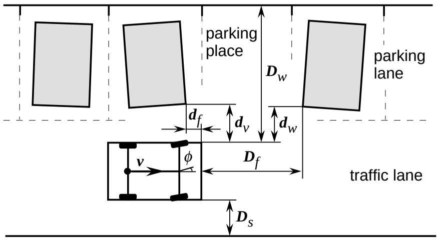

Figure 3. Start location for perpendicular parking.

The reference steering angle and velocity are smooth functions constructed from sinusoids. The generic velocity command $v(t)$ is similar for perpendicular and parallel parking maneuvers:

$$v(t) = \begin{cases} v_m\,k_v\,A_v(t), & 0 \le t < T_v, \\ v_m\,k_v, & T_v \le t < T_m - T_v, \\ v_m\,k_v\,B_v(t), & T_m - T_v \le t \le T_m, \end{cases} \tag{2}$$

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

$$A_v(t) = \frac{1}{2}\left(1 - \cos\frac{\pi\,t}{T_v}\right), \tag{3}$$

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

The command (2) 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 (2) must satisfy the equation $k_{v,i+1} = -k_{v,i}$ that alternates between forward and backward directions. The steering command is specific for each step of the perpendicular parking maneuver which involves four steps.

Step 1: forward motion aside and away from the parking place in order to re-orient the vehicle which moves from S_1 to S_2 in Fig. 4. The generic steering command $\phi(t)$ is

$$\phi(t) = \begin{cases} \phi_m\,k_\phi\,A_1(t), & 0 \le t < T_\phi, \\ \phi_m\,k_\phi, & T_\phi \le t < T', \\ \phi_m\,k_\phi\,B_1(t), & T' \le t < T'', \\ -\phi_m\,k_\phi, & T'' \le t \le T_m, \end{cases} \tag{5}$$

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

$$A_1(t) = \frac{1}{2}\left(1 - \cos\frac{\pi t}{T_\phi}\right), \tag{6}$$

$$B_1(t) = \cos\frac{\pi\,(t - T')}{2\,T_\phi}. \tag{7}$$

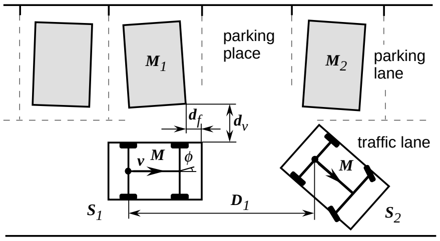

Figure 4. The vehicle moves from S_1 to S_2.

The values of $\phi_m,\ k_\phi,\ k_t,\ v_m$ 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

$$T_m^\star = \mathbf{max}\left\{\frac{T_\phi}{1 - k_t},\ \frac{2\,T_\phi}{k_t},\ 2\,T_v\right\}. \tag{8}$$

Step 2: backward motion toward the parking place in order to further re-orient the vehicle and attain a location S_5 in Fig. 5. The generic steering command $\phi(t)$ is

$$\phi(t) = \begin{cases} -\phi_m\,k_\phi, & 0 \le t < T', \\ -\phi_m\,k_\phi\,A_2(t), & T' \le t < T'', \\ \phi_m\,k_\phi, & T'' \le t < T_m - T_\phi, \\ \phi_m\,k_\phi\,B_2(t), & T_m - T_\phi \le t \le T_m, \end{cases} \tag{9}$$

where

$$A_2(t) = \cos\frac{\pi(t - T')}{2\,T_\phi}, \tag{10}$$

$$B_2(t) = \frac{1}{2}\left(1 - \cos\frac{\pi(T_m - t)}{T_\phi}\right). \tag{11}$$

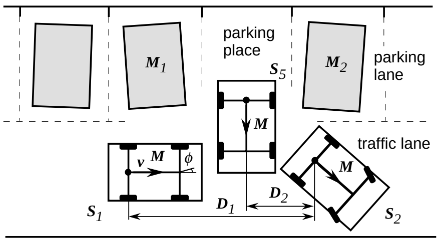

Figure 5. The vehicle in a location S_5 is aligned and centered relative to the parking place.

Step 3: if the position and orientation S_5 in Fig. 5 was not attained, the vehicle is in an intermediate location S_3 as shown in Fig. 6. This step aims to attain a location S_5 shown in Fig. 7 by means of repetitive motions, e.g. forwards from S_3 to S_4 and backwards from S_4 to S_5.

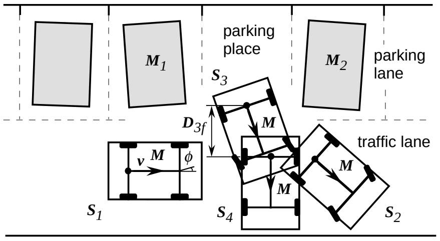

Figure 6. The vehicle moves from S_3 to S_4.

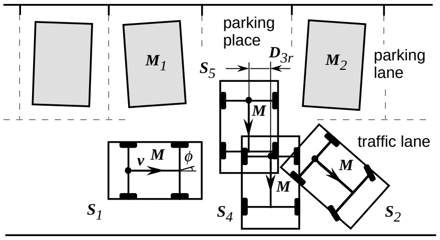

Figure 7. The vehicle moves from S_4 to S_5.

The generic steering command $\phi(t)$ is:

$$\phi(t) = \begin{cases} -\phi_m\, k_\phi\, A_3(t), & 0 \le t < T_\phi, \\ -\phi_m\, k_\phi, & T_\phi \le t < T', \\ -\phi_m\, k_\phi\, B_3(t), & T' \le t < T'', \\ \phi_m\, k_\phi, & T'' \le t < T_m - T_\phi, \\ \phi_m\, k_\phi\, C_3(t), & T_m - T_\phi \le t \le T_m, \end{cases} \tag{12}$$

where

$$A_3(t) = \frac{1}{2}\left(1 - \cos\frac{\pi t}{T_\phi}\right), \tag{13}$$

$$B_3(t) = \cos\frac{\pi(t - T')}{2\,T_\phi}, \tag{14}$$

$$C_3(t) = \frac{1}{2}\left(1 - \cos\frac{\pi(T_m - t)}{T_\phi}\right). \tag{15}$$

Step 4: straight motion backwards from S_5 in Fig. 7 completes the perpendicular parking maneuver.

The generic profiles of the steering angle $\phi(t)$ and velocity $v(t)$ 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 asymmetry of the steering command is associated with the coefficient k_t.

The feasibility of the commands $\phi(t)$ and $v(t)$ is provided by means of taking into account the dynamic constraints of the steering and velocity servo-systems when searching for values of ϕ_m, k_t, v_m and T_m. These constraints affect the durations T_v and T_ϕ. When the command (2) is applied, the lower bound of T_v is $T_v^\star = 0.5\,\pi\, v_m/\dot{v}_m$, where $\dot{v}_m$ denotes the maximal admissible acceleration. The duration T_ϕ needed to turn the steering wheels from a straight direction to ϕ_m is lower-bounded by $T_\phi^\star = \pi\, \mathbf{max}\left\{\frac{\phi_m}{2\dot{\phi}_m},\, \sqrt{\frac{\phi_m}{2\ddot{\phi}_m}}\right\}$, where $\dot{\phi}_m$ and $\ddot{\phi}_m$ are the maximal admissible steering rate and acceleration respectively.

The search results in such values of ϕ_m, k_t, v_m and T_m of the commands $\phi(t)$ and $v(t)$ which provide attaining the desired position and orientation, while the maximal possible values of ϕ_m and v_m still ensure that the vehicle moves within the available space.

The localization-planning-execution cycle with the commands $\phi(t)$ and $v(t)$ is performed until the desired position and orientation are attained. Note that the commands $\phi(t)$ and $v(t)$ are open-loop in the $(x,\, y,\, \theta)$-coordinates, and the resulting accuracy of the motion depends on the accuracy of the steering and velocity servo-systems. Possible errors are compensated by subsequent motions.

4 Experiments

The method developed has been tested on a CyCab electric vehicle [17] shown in Fig. 8. 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. 8. The CyCab vehicle can either be manually driven by a joystick, or it can move autonomously. Its on-board controller with a Motorola 555 processor runs under Linux. The method was implemented in C++ language.

Figure 8. A CyCab vehicle.

Autonomous parking involves a controlled sequence of motions, in order to localize a sufficient parking place, obtain a convenient start location for the vehicle beside the place, and perform a maneuver to move into the parking place. During the localization mode the vehicle moves slowly along the traffic lane. The range data processing allows to build a local map of the environment at the sides of the vehicle. Vacant place is detected and its borders are localized. The orientation of the place is calculated and dimensions are compared with those of the vehicle. The decision on suitability of the place for parking is made.

Our experimental setup in a parking lot environment is shown in Fig. 9. 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 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 in Fig. 9). Then, the control commands $\phi(t)$ and $v(t)$ are planned and executed to perform a perpendicular parking maneuver.

Figure 9. Environmental setup for perpendicular parking.

An example of the control commands is shown in Fig. 10, and the corresponding motion of the vehicle is depicted in Fig. 11 where the displacement of the vehicle's corners is shown by dotted curves. 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 required.

Perpendicular parking in the case of a lateral constraint (e.g. a narrow street) is shown in Fig. 12 and Fig. 13. 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. 10 and Fig. 11, 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).

The motion accuracy depends on the accuracy of the servo-systems which execute the planned commands, as shown in Fig. 10 and Fig. 12. The tracking errors result in a discrepancy between the planned and actual motion, as seen in Fig. 11 and Fig. 13. At the end of each step, the resulting error of position and orientation is estimated from the sensor data, and the subsequent control commands are planned according to the actual location of the vehicle.

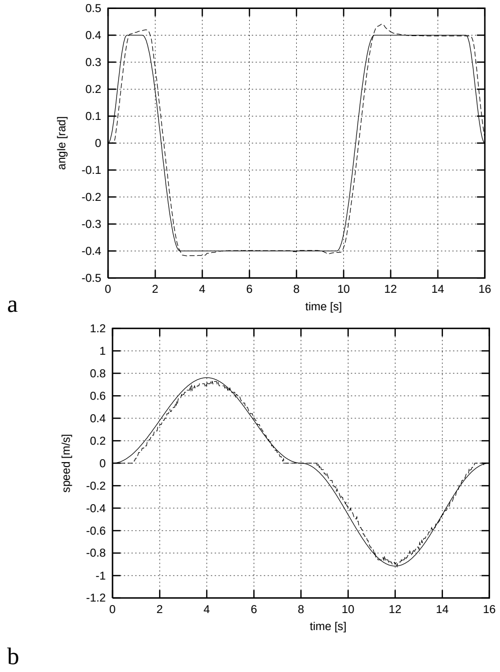

Figure 10. An example of the steering and velocity commands (solid curve) and their execution by the servo-systems (dashed curve): a – steering angle, b – velocity.

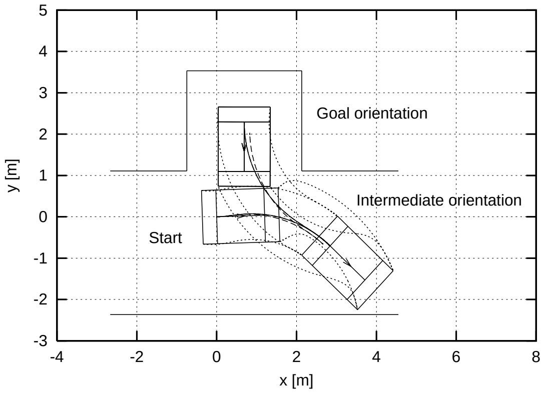

Figure 11. An example of a perpendicular parking maneuver: estimated path (solid curve) and actual path (dashed curve).

5 Conclusion

The approach to autonomously perform low-speed maneuvers in a constrained traffic environment was presented. It makes use of conformity between the control commands and resulting path of the non-holonomic vehicle. The generic steering and velocity commands were considered

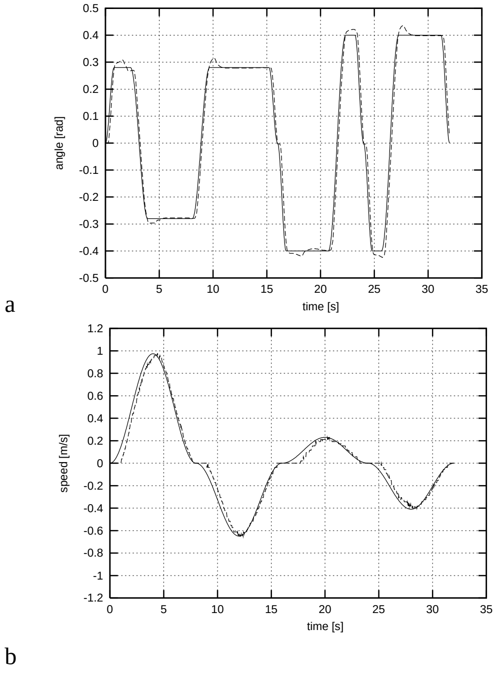

Figure 12. Steering and velocity commands (solid curve) and their execution by servo-systems (dashed curve) in the case of lateral constraint: a – steering angle, b – velocity.

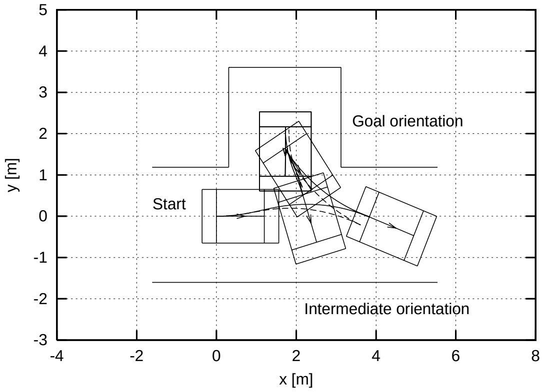

Figure 13. An example of a perpendicular parking maneuver in the case of lateral constraint: estimated path (solid curve) and actual path (dashed curve).

using an example of perpendicular parking maneuver. The experiments were performed on a CyCab vehicle. The obtained results proved the effectiveness of our approach. The autonomous perpendicular and parallel parking maneuvers developed are illustrated on video which may be downloaded at http://celultra.riken.jp/~paromt/dev.html.

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Note. This paper is an extended version of [18].

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