ITDP-Robot: Design of An Intelligent Transport Dispatch Parking Robot

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Abstract

In this paper, a novel electric autonomous parking robot prototype was proposed, which aims to address the parking hassle caused by the imbalance between the vehicle ownership and the amount of the parking spaces. The mechanical structure was elaborately designed to allow the parking robot to adapt to vehicles with different wheelbases and tracks. The electrical structure was constructed with the aim of X-by-wire and distributed component-based control concept. To be capable of autonomous driving, the parking robot software system based on ROS was designed with the capability of environment perception, self-localization and path planning. Furthermore, a simulation environment based on Gazebo was built in order to simplify the development of the parking robot's autonomous driving algorithms and validate those algorithms' robustness. Though this parking robot is under the prototype stage, the dispatch strategy and the convenience for parking were also considered. Compared with the state-of-art parking robot, this parking robot is not only capable of working indoor parking lots but also the complex outdoor environments.
Keywords: *parking robot, mechatronic design, autonomous driving system, simulation and application*

1. Introduction

According to global vehicle ownership and vehicle production statistics, the vehicle ownership is steadily increasing. Hao et al. (2011) proposed a hybrid model of China's vehicle ownership, by using this model, they projected that China's vehicle population would reach 184.8, 363.8 and 606.7 million by 2020, 2030 and 2050 respectively. With the increase in vehicle ownership, parking has become an increasingly severe social issue especially in China, due to the shortage of parking spaces and the "information island" effect. In most instances, searching for a suitable parking space demands time consumption. Furthermore, a long search for an available parking space in a highly congested scenario might induce exhaustion, tension or even traffic accidents. Hence, to alleviate this problem, Jaurkar et al. (2016), Kotb et al. (2017), Latif et al. (2018) and Zhu (2018) developed and implemented intelligent parking guidance systems to provide the drivers with information about the availability of parking spaces.

In the past few years, with the rapid development of artificial intelligence (AI), the research and development of autonomous driving vehicles have made great progress. Besides, X-by-wire chassis is also undergoing a rapid development, as Eder et al. (2010), Sens (2013), Zong et al. (2013), Ni et al. (2018) shown, the next generation of automobiles will increasingly incorporate electronic control units (ECUs) and X-by-wire chassis in novel automotive control applications. Especially, steer-by-wire has many potential applications due to its superior flexibility, as Luo et al. (2017) and Zhang et al. (2017) shown, four-wheel steering and four-wheel drive (4WS4WD) electric vehicle (EV) is of higher maneuverability and flexibility which is prerequisite for valet parking and self-driving. In this social context, intelligent parking technology has become a research hotspot, competitive focus and application breakthrough point in the field of autonomous driving. As Schwesinger et al. (2016), Banzhaf et al. (2017), Kang et al. (2017) and Huang et al. (2018) shown, the realization of automated valet parking (AVP) enables the vehicle to drive to a parking spot and park itself, which allows passengers to leave the car in a drop-off zone. And It is believed that AVP system has great potential to mitigate the parking headache for the future smart city. However, due to the prohibitive cost of sensors and technical maturity, most ordinary vehicles cannot be equipped with this functionality. Besides, to realize the automatic parking for the cars equipped with these facilities, parking lots must be upgraded to meet the demand of automatic parking technology. But it's inevitable that there are some different requirements among the different automatic parking technology solutions. Therefore, to adapt to different technical specifications, the renovation and transformation to the traditional parking lots are too challenging.

To address these difficulties, as He et al. (2016) previously shown, the fully automatic parking lot equipped with automatic parking robot is designed creatively. With the assistance of autonomous parking robots, the parking process can be tremendously simplified, which makes the autonomous parking available for the traditional vehicles. The customer does not need to park by himself/herself anymore. They only need to park the car at a transfer station and then submit a parking request to the parking lot system, after that, a parking robot will carry the vehicle to a suitable parking space assigned by the dispatch system. And the pick-up process is nearly the same as the parking process. To reduce the unnecessary waiting time at the transfer station, the customer can even make a reservation of the picking up process. There is no doubt that the development of automatic parking lots can significantly improve parking safety and convenience. Furthermore, the automatic parking lot can dramatically improve the utilization efficiency of space, which means the automatic parking lots can accommodate much more vehicles than the traditional parking lots. Hence, it is reasonable for us to believe that this field of technology is of great prospect.

Within the scope of this paper, the next section briefly describes some relevant state of the art parking robots and followed by a detailed illustration of the mechanical design of our parking robot in section III. After that, in section IV the parking robot's electrical design is presented, and section V illustrates the design of the autonomous driving system. Section VI describes the simulation results of the parking robot in a specific virtual parking lot. Then in section VII, we introduce the application about our parking robot. The conclusion in the last Section ends this work.

2. State of The Art

Meanwhile, quite a few companies are offering or at least announcing innovative parking robot or concepts. For instance, as the Web-1 presents, the Yee Fung company in Shenzhen, China, developed the latest generation of AGV parking robot -- GETA, which has a payload of 2.6 tons and a maximum speed of 1.5 m/s. It can store and retrieve almost all passenger vehicles. The average cost of time is less than 120 seconds. Besides, as the Web-2 presents, the SERVA Transport Company, Germany, whose latest generation of RAY™ parking robots, has a maximum transport load of 3 tons and a maximum travel speed of 3 m/s. This Robot is also capable of handling almost all passenger vehicles.

Figure 1. Tongji autonomous parking robot prototype "ITDP-Robot".

However, still, these robots are only able to be applied in indoor parking lots, outdoor parking lots are too complicated to be handled due to the complex environments. Our contribution to this trend is the setup of a novel electric autonomous parking robot, characterized by comprising two lateral and a transverse stretch and folding apparatuses, with the aim of adapting to the wheelbase and tread of different vehicles. The parking robot is designed to carry vehicles from one position to a given spot without human intervention, with the capability of environment perception, self-localization and path planning, and can be competent for the outdoor parking lots. The prototype of our autonomous parking robot is shown in Figure 1.

In what follows, the task to build our autonomous parking robot prototype based on four-wheel steering with the capability of adapting to the complex outdoor environments was described in detail.

3. Mechanical Design

The mechanical system of the parking robot consists of the following parts: body, traction units, steering drive unit, stretch and folding unit and elevating unit. Among them, the traction units provide the driving power of this parking robot and control the traveling direction; the steering drive unit can improve the steering performance; stretch and folding unit allows the parking robot to adapt to vehicles with different wheelbases and tracks; elevating unit is used for holding the wheel and lifting the vehicle. With the help of these units, our parking robot can lift and transport vehicles of different sizes.

3.1 Body

The body is the basis of the entire mechanical structure, and all units will be mounted on the body to achieve its function. The body of the vehicle is welded by steel pipes, and fine mechanical simulations are performed to ensure its strength and rigidity. As Figure 1 shows, the body of the parking robot consists of four parts connected by stretch and folding unit: front-left part, front-right part, rear-left part and rear-right part. The traction units are mounted on the front two parts and the steering drive unit on the rear two parts. In addition to this, an extra universal wheel is mounted on each part to improve the mechanical properties and elevating unit is also installed on each part to lift the vehicle.

3.2 Traction Drive Unit

The traction drive unit illustrated in Figure 2, is based on a permanent magnet synchronous motor which is mounted horizontally. Allow for the heavy weight of the parking robot, the polyurethane wheels are applied, of which the maximum load is 1800kg. The traction motor and a traction gearbox with a gear ratio of 1:29.3 are integrated and coupled with the wheel. After the reduction of the traction gearbox, the nominal wheel torque is up to 225Nm and can guarantee that a certain gradient can be overcome. Besides, a rotary encoder (E40H10-1024-3-T-5, Autonics) that has a resolution of 1024 p/r provides the prerequisites for the realization of the closed loop speed control of the traction motor.

Figure 2. Integration of Traction and Steering Unit.

3.3 Steering Drive Unit

The steering drive unit was divided into two different parts. The front steering drive unit is integrated with the traction motor and polyurethane wheels perpendicularly. Actuated by a steering drive controller, the steering motor generates a torque of 1.5 Nm and a power of 400 W. The steering motor couples with the gear under the flange which can act as a reduction gear box and as a result the wheel can change the direction of the parking robot even under a heavy load that is up to 3000kg. To control the steering angle precisely, there is also a rotary encoder (E40H10-1024-3-T-5, Autonics) coupled with the shaft of the steering motor, with which the steering angle is closed-loop controlled.

Compared with the front one, the structure of the rear steering drive unit is much simpler. And a horizontally mounted permanent magnet synchronous motor can generate sufficient steering torque with a gearbox. This special gearbox can record the absolute steering angle of the rear wheels even though the power is switched off suddenly, which guarantees security after an unexpected halt caused by emergencies.

3.4 Stretch and Folding Unit

With the revolution of stepper motors can both of the lateral and longitudinal stretch and folding units move precisely to adjust according to the variant track and wheelbase of different cars. Lead screws with right and left-hand thread are adopted in the unit and the lead of the thread is carefully selected to ensure that the lead screw has self-locking characteristics so that no additional mechanical locking means are required. Linear rails are also used so that the unit can stretch or fold in a specific direction and bear the load during lifting and carrying vehicles. Lead screws and linear rails are assembled in three square tube steel welded frames which are bolted to two parts of the body, and they can move relative to each other in a specific direction to achieve the lateral and transverse stretch and folding. The strength and stiffness of lead screws, lead screws nuts, linear rails, and the frame are carefully checked to ensure that the frame does not fail even when lifting 2.5-ton cars.

3.5 Elevating Unit

The elevating unit is designed to clamp the wheel and lift and lay down the car slowly and steadily. For the clamping function, the worm gear mechanism is used because of its self-locking characteristics so that no additional locking mechanism is required and a stepper motor is applied to drive the arms to clamp the tires of the vehicle. In order to lift and lay down the vehicle, a servo motor and a gearbox are integrated and coupled with a ball screw which can convert the rotational motion to linear motion and the max load of each elevating unit is 10000N. On each elevating unit, there are three limit switches to guarantee the security when the car is being lifted at a maximum speed of 1 cm/s.

4. Electrical DESIGN

In this section, the electrical design of our autonomous parking robot is detailed illustrated, with the aim of X-by-wire and distributed component-based control concept.

4.1 Electrical Architecture

As we can see in Figure 3, with the aim of the convenience for components extension the electrical architecture is layered and includes distributed components. The basic electrical architecture consists of three essential components, i.e., Jetson TX2, VCU (Vehicle Control Unit), and EPEC (EPEC 3724 Control Unit). Jetson TX2, VCU and EPEC can establish half-duplex communication via CAN bus. VCU send commands to the traction drive controller, front and rear steering drive controllers, and elevating drive controllers, of which the communication protocol is customized CAN or CANopen. In reverse, the listed components can also send data to VCU. EPEC controls stretch and folding unit and receives the data sent by RC receiver with pulse via cables.

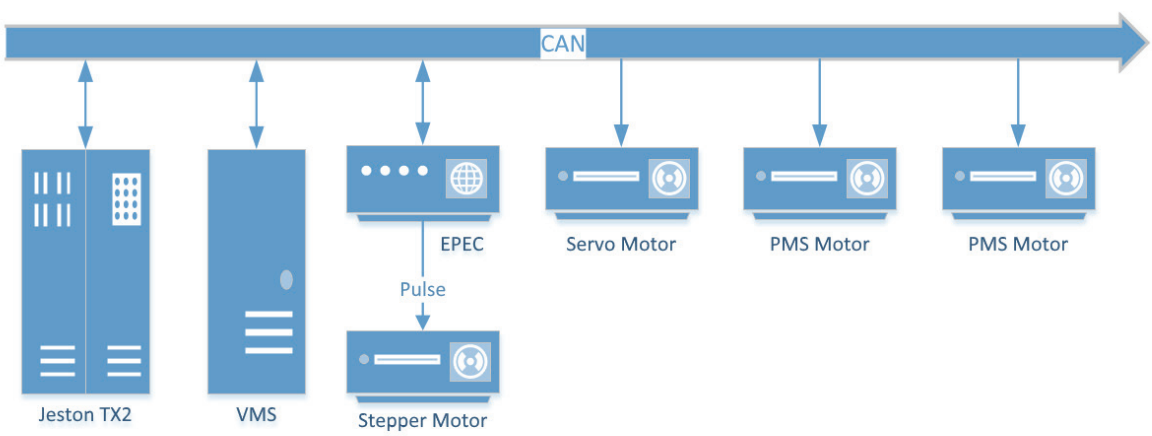

Figure 3. Electrical Architecture of "ITDP-Robot."

4.2 Power Supply Unit

The power supply unit of the vehicle is made up of 4 lead acid batteries, each of the batteries is with 12VDC. In Figure 3 the power distribution is shown. Traction motors demand 48VDC input voltage in order to actuate the traction motors that reach a maximum power of 2200W. The steer drive unit and the drive controllers in elevating and stretch unit all need 48VDC input voltage. Furthermore, a DC-DC converter transfer the voltage from 48V to 12V and as a result it can supply power for EPEC and Jetson TX2. The other components, such as sensors and limit switches are also supplied by this power unit with some other converters when necessary.

5. AutoNomous Driving Design

In the following, insights were given into issues concerning the autonomous driving design of our autonomous parking robot. With the aim of being competent for autonomous driving, the parking robot was designed with the capability of environment perception, self-localization and path planning. Furthermore, to achieve the target of carrying vehicles from one position to a given spot without human intervention, as a unique capability, the parking robot is also necessary to have the ability to detect and align the customer's vehicle accurately. The hardware and software design of the parking robots' autonomous driving system are illustrated in detail in following subsections.

5.1 Hardware Architecture

Figure 4 presents the overall hardware architecture of “ITDP-Robot”. We use two NVidia Jetson TX2 to build up our core computation platform, where the two devices communicate with each other over Ethernet through a switch. The first device receives signals from the robot's vehicle control unit (VCU) and EPEC 3724 control unit(EPEC) dedicated for remote control(RC). Also, it handles real-time data from camera sensors and conducts vision detection using deep learning technique. Joint self-localization with both GNSS and Velodyne LiDARs relies on the second device, which collects all laser point cloud from all LiDARs, performing tasks like map fusion, obstacle detection and target vehicle recognition. As for the sensors, the parking robot is equipped with nine single-beam Rplidar sensors. Six of them are aimed for the detection of the customer's vehicle when the parking robot is assigned to carry the vehicle to the parking lot, and the other three are equipped to detect obstacles during the operation. The vision system is composed of four monocular cameras, which are responsible for the detection and identification of derivable areas, traffic signals, and lane markers. The two Velodyne VLP-16 scanners mounted on the front edge are designated to detect and identify obstacles and play the most important roles in self-localization and mapping.

All the sensors mentioned above are carefully calibrated and unified to one global coordinate frame, the defined parking robot coordinate frame centered at the front axle, which has been proved to be helpful for vehicle maneuvers.

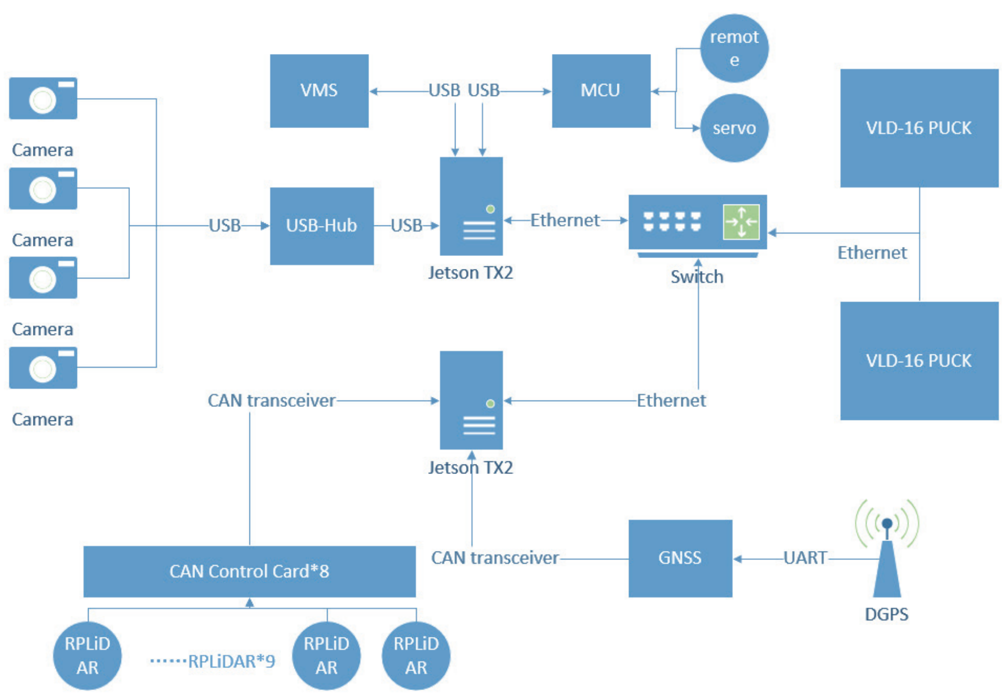

Figure 4. The autonomous driving system’s hardware architecture of “ITDP-Robot.”

5.2 Software Architecture

The software system of “ITDP-Robot” is implemented based on ROS and its overall architecture is illustrated in Figure 5. Each transparent rectangle represents a meta package in ROS, while every inner blue rectangle means a ROS package or a ROS node. Messages transmitted between ROS packages are shown as arrows in Figure 5. With the purpose of making every function non-interfering, the system is uncoupled in 5 independent units: Environment Perception Unit, Self-Localization Unit, Map Fusion Unit, Dispatch and Path Planning Unit and Motion Control Unit.

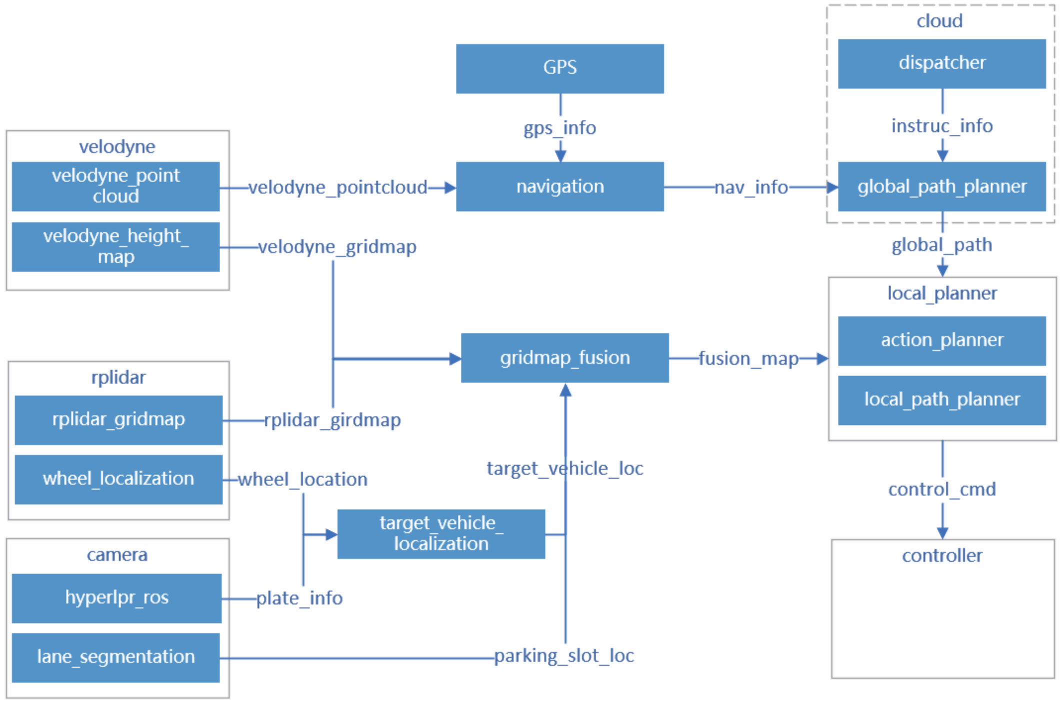

Figure 5. The autonomous driving system's software architecture of "ITDP-Robot."

5.2.1 Environment Perception Unit

The Environment Perception Unit consists of "velodyne", "rplidar" and "camera" meta packages, for receiving and processing data from 16 beams LiDAR, single beam LiDAR and camera sensors respectively. Velodyne contains 2 ROS packages, publishing point cloud messages and grid map messages (the point cloud projected to a 2D plane and filtered by height). Regarding rplidar, besides the grid map, the wheel location messages are also published, using the wheel localization method based on the L-shape feature. In the camera module, both car plate messages and parking slot messages are generated by deep learning object detection and semantic segmentation models. All of these messages are then subscribed by Self-Localization Unit and Map Fusion Unit.

5.3 Self-Localization Unit

The Self-Localization Unit only aims to publish global localization information messages to Dispatch and Path Planning Unit. In order to improve robustness and adaptation ability, LiDAR-dominated NDT-matching is adopted instead of GPS-dominated localization method. The general pipeline of self-localization is described as follow. Firstly, a high definition 3D point cloud map of the working area is built in advance. Then once the robot drives into the working area, an NDT (Normal Distributions Transform) algorithm will launch to get the localization information, by matching the point cloud message with the point cloud map and computing the transform matrix. Finally, an EKF (Extended Kalman Filter) is applied to fuse the localization result of NDT and GPS, and then outputs the final result.

5.4 Map Fusion Unit

The function of this unit is to generate a Fusion Map utilizing the message from Environment Perception Unit. For efficient message transmitting and specific message defining, the Fusion Map message consists of 3 layers: grid map layer, target vehicle location layer and parking slot location layer. Each layer is stored independent but can be transmitted together as a general fusion grid map.

5.5 Dispatch and Path Planning Unit

The Dispatch Unit is deployed on the cloud, subscribing the global localization message and publishing the global path for the robot. More details are mentioned in Section VII. As for Path Planning Unit, local path is planned according to the fusion grid map published by Map Fusion Unit. Every local decision also depends on Path Planning Unit such as lifting or laying down the target vehicle.

5.6 Motion Control Unit

With the aim of high maneuverability and flexibility, the mechanical structure and electrical structure were designed based on the X-by-wire theory. Therefore, a motion control unit was introduced to provide the interfaces between the software system and the hardware system. The motion control unit was constructed based on the closed-loop proportion integration derivative (PID) control theory. With this unit, the parking robot can response for the expected motion rapidly and smoothly.

6. Simulation

Allow for that the autonomous driving software architecture was constructed on ROS. To simplify the development of the parking robot's autonomous driving algorithms and validate the robustness, we have built a simulation environment on a robot simulator Gazebo, which has a robust physics engine, high-quality graphics, and convenient programmatic and graphical interfaces.

Figure 6 shows the simulation environment built in Gazebo, which is constructed based on a ratio of 1:1 to the real scenes. A close to real representation parking robot presented in Figure 6 was constructed with SolidWorks. Also, all sensors mentioned in section 5.1 were carefully configured in the simulation environment to provide sensors data as consistent as possible with the real sensors data. It is worth to mention that all the kinematic parameters were specified according to the real circumstance, and a specific script was composed to test the kinematic performance of our parking robot. Also, in this simulation scenario, the car's pick-up process with the ITDP-Robot was validated, Figure 7 presents the simulation result.

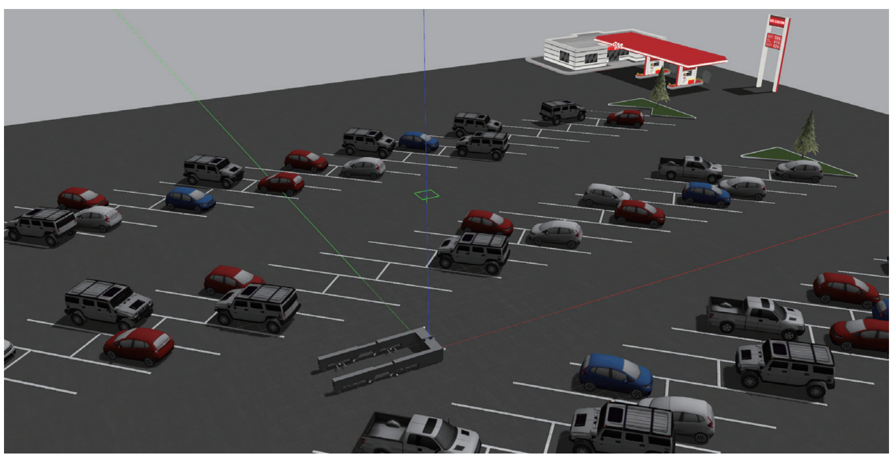

Figure 6 Simulation environment built in Gazebo.

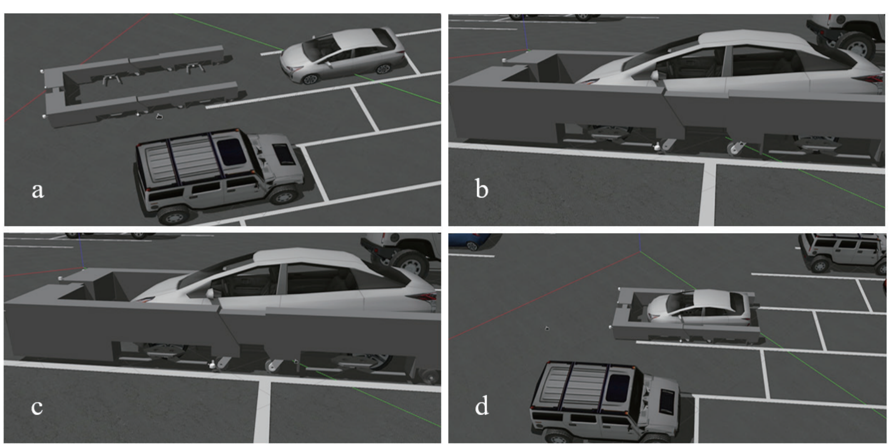

Figure 7 The simulation for the car pick-up process with the "ITDP-Robot."

7. Application

In this section, the dispatch strategies and more parking and pick-up process details were presented. With intelligent and robust dispatch strategies, the automatic parking lot system can reasonably and efficiently dispatch the optimum parking robot to execute the parking and pick-up operation.

7.1 Dispatch Strategies

In order to complete the parking and pick-up task at the fastest speed and with minimum cost, we propose a multi-objective optimization method. We introduce 0-1 decision variables, comprehensively use the operating cost and time cost of the entire parking lot as the objective function, and based on the actual work completion logic to formulate the constraints according. Furthermore, in order to adapt to different scenarios and different tasks, the dynamic task generation strategies were introduced.

Allow for that the above scheduling problem belongs to the NP-hard problem, with the traditional algorithm to obtain the optimized dispatch strategy might consume plenty of computational time, especially as the amount of the scheduling tasks increases. To satisfy the demand of real-time scheduling, we innovatively introduced a hybrid parallel genetic algorithm, utilizing the simulated annealing algorithm to improve the accuracy and executing parallel computation on GPU to reduce the computational time.

7.2 Parking and Pick-up Process

Outside the parking lot, some capacious transfer stations were constructed. When the user wants to park the car, he does not need to consume time and energy to search for an available parking space anymore, only needs to stop the car at a transfer station and submit a parking request to the server. Then the parking process for the user was finished, and a parking robot will take the vehicle to a suitable parking space assigned by the dispatch system. The vehicle's information will automatically upload to the cloud server. When the user wants to pick up the car, he only needs to submit a pick-up request to the server, and then the server will assign a parking robot to take the car from the parking lots to the transfer station.

Considering that even if there are intelligent and robust dispatch strategies, due to the pick-up operation time, the customer will still have to waste some waiting time during the pick-up process. To improve the experience, a smart-phones' app was developed from scratch to help the customer to manage the car. With the assistance of this app, the customer can submit a reservation request to the server at any time. When it is time for picking up, the server will send a notice to inform the customer to confirm the pick-up request. If the customer confirms the request, the server will assign a parking robot to take the car to a suitable transfer station and feedback the transfer station's location to the app. As a result, when the customer arrives at the transfer station, the car is already there in a driving direction, and the customer will not waste time to wait for the pick-up process anymore.

Conclusions

In this paper, with the aim of addressing the parking hassle caused by the imbalance between vehicle ownership and the number of parking spaces, we proposed a novel electric autonomous parking robot prototype. Because of the elaborately designed mechanical structure, the parking robot can adapt to cars with different wheelbases and tracks. And this parking robot can be competent for both the indoor and outdoor scenes with the assistance of the autonomous driving system based on ROS. Also with the assistance of the developed dispatch system, the automatic parking lot system will dispatch the optimum parking robot to execute the parking and pick-up operation. Since the whole system is still under the prototype stage, for further future work, we will conduct more experiments to examine the algorithms' robust and optimize the robot's mechanical structure.

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