ESTRO: Design and Development of Intelligent Autonomous Vehicle for Shuttle Service in the ETRI

Jaemin Byun, Ki-In Na, Myungchan Noh, Joochan Sohn and Sunghoon Kim

Abstract— **ESTRO(ETRI Smart Transport RObot) project aims at the development of autonomous vehicle to transport goods and people without the help of driver in the well-structured area such as campus. The autonomous vehicle, ESTRO has been designed and implemented by modifying electronic vehicle. In addition, the cost of sensors and the complexity of system are minimized on the purposed of a commercial autonomous driving system in urban traffic environment. This paper proposes the design of H/W and S/W architecture for the autonomous vehicle and describes the method of environmental perception and navigation. The implemented system has been tested in ETRI campus.**

I. INTRODUCTION

Through the technologies of autonomous driving have developed, it is possible to drive safely and conveniently in complex environment with dynamic objects such as vehicles and pedestrians.

Recently, autonomous vehicle has a lot of problems on the legal and technological issue for commercialization, so most of main technologies have been just applied for ADAS (Advanced Driver Assistance System) products until now. The Google driverless cars have officially licensed in Nevada, these vehicles are being tested around real traffic environment on the state [1]. The Stadtpilot project' autonomous vehicle (Leonie) has shown to the ability of driving autonomously in real traffic environment of Braschchweig, Germany [2]. However, in the Republic of Korea, there is no legal framework which enables autonomous driving on public roads.

Therefore, ESTRO project aims at autonomous driving with low-speed in the well-structured section such campus and area where the specialized traffic regulations are applied. ESTRO system has developed as a robotic vehicle for transporting supplies and carrying people to final destination without driver's support. The ESTRO can perform the call service that user can call the autonomous vehicle to user's requested place with mobile devices using wireless communication.

A. Relative Works

Important events for the autonomous vehicle research are DARPA Grand Challenges and Urban Challenge. The Grand Challenges in 2004 and 2005 were held in the Mojave Desert, America. The objective of Grand Challenges was to create the first fully autonomous ground vehicle capable of completing a substantial off-road course within a limited time. There was no winner at the first Grand Challenge, but five vehicles successfully completed the race at the second Grand Challenge. The Urban Challenge in 2007 took place for further advanced vehicle requirements to include autonomous operation in the urban environment. In this competition, the six teams were successfully finished the given course. Mainly, the vehicles of Stanford University and Carnegie Mellon University are well operated in both the second Grand Challenge and the Urban Challenge. Both Junior of Stanford University and Boss of Carnegie Mellon University had Applanix POS-LV220/420, Velodyne HDL-64 3D LIDAR, IBEO Alasca XT LIDAR, RADAR and cameras. These vehicles mainly perceived surrounding information with LIDAR and continuously detected its position with GPS/INS equipment [3], [4]. This configuration for the autonomous vehicle has become common after these competitions. Furthermore, the autonomous vehicle has been researched much actively.

Europe countries and America are actively researching and developing the autonomous vehicle. INRIA, France has been developing the robust electric autonomous vehicle, the Cybercar using 2D LRF-based SLAM and V2V/V2I communication [5]. In 2010, VisLab ran the VisLab Intercontinental Autonomous Challenge, a 15,000km test of autonomous vehicles from Parma, Italy to Shanghai, China [6]. Moreover, Autonomous Labs of Freie University, Germany has been developing the autonomous vehicles with 3D LIDAR and cameras [7]. This team also has succeeded the test autonomous driving in Berlin's street and highways in 2011. MuCar-3 with the 3D LIDAR is being developed by university of the Bundeswehr Munich, Germany [8], [9]. This project mainly is focused on the LIDAR-based 3D object perception. Google have been developing fully autonomous vehicle, Google Driverless Car, equipped with cameras inside the car, a 3D LIDAR on top of the vehicle, RADAR on the front of the vehicle and a position sensor attached to one of the rear wheels that helps locate the car's position on the map. This project is currently famous in autonomous vehicle research and is being led by Google engineer, Sebastian Thrun who is also director of the Stanford Artificial Intelligence Laboratory which developed both Stanley and Junior [10], [3].

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B. *Outline*

Section II describes the platform and the software architecture of the developed autonomous vehicle, ESTRO. In section III, the method for environmental perception will be described such as on-road marker detection with cameras, curb and obstacle detection with LRFs, and localization with GPS, odometer and on-road marker. Moreover, local map, the integration form of multiple sensory data will be also introduced. In section IV, the behavior planning, the path planning and its control will be introduced. Experimental scenarios such as normal road, intersection and parking lot will be demonstrated and discussed in section V. Finally, Section VI closes with conclusions.

II. VEHICLE PLATFORM & SOFTWARE ARCHITECTURE

A. *Vehicle Platform*

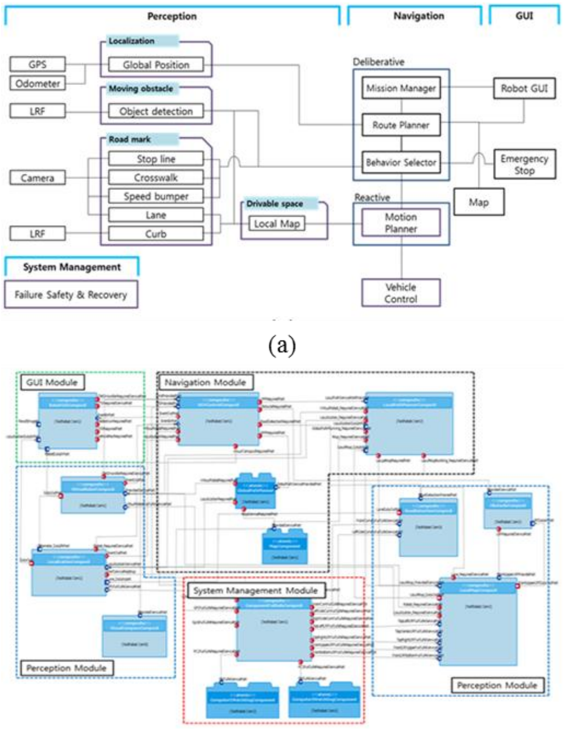
ESTRO has been being developed since 2008 at ETRI. The objective of this autonomous vehicle is the unmanned shuttle system which can autonomously transfer human and load to everywhere in ETRI. It includes two LRFs; one is equipped on the top of the vehicle for extracting curb and the other is equipped at the front of the vehicle for detecting obstacles. Three CCD cameras are also used for detecting on-road markers such as lane, crosswalk, speed bump, and stop line. The GPS on the vehicle and the odometer at rear wheel were arranged for localization. Touch screen monitor and speakers are set for communication with users as shown in Fig. 1.

Figure 1. ESTRO hardware configuration

B. *Software Architecture*

The software architecture for the autonomous vehicle system has to be designed efficiently because the autonomous system is too complex and huge to operate in real-time and to understand its structure easily. ESTRO also has various types of devices and various components have to be separately executed at the same time. Therefore, the software architecture for ESTRO has also efficiently designed as shown in Fig. 2.a. The designed software architecture for ESTRO has four module; perception module, navigation module, GUI module, and system monitoring module.

Perception module perceives environmental information such as on-road markers, curb, obstacles, and current position with cameras, LRFs, GPS, and odometer. It also builds the local map, which various types of sensor data were integrated into. Navigation module gets environmental information in the form of the local map from perception module and performs both behavior planning and path planning. In addition, it can also generate the directional commands to control the autonomous vehicle continuously for following the planned path. GUI module shows the current condition of the ESTRO periodically and transfers user commands to the vehicle operation system. The system monitoring module always monitors faults of the operating components and keeps them running safely. The designed software architecture for ESTRO is developed using OPRoS (Open Platform for Robotic Service) components [11]. According to the functions of component, components are distributed into each module and components in module consist of atomic components or composite components consisting of atomic components as Fig. 2.b.



(a)

(b)

Figure 2. Software architecture of ESTRO; it consists of perception module, navigation module, GUI module and system monitoring module

III. ENVIRONMENTAL PERCEPTION

For the environmental perception, ESTRO has various types of sensors such as three cameras, two LRFs, odometer, and GPS. The surrounding information on the road such as curb, obstacle, on-road markers and position are detected from each sensor component. All the acquired data from sensor components are integrated and displayed in the form of the local map, which is the occupancy grid map including surrounding information for navigation as shown in Fig. 3.

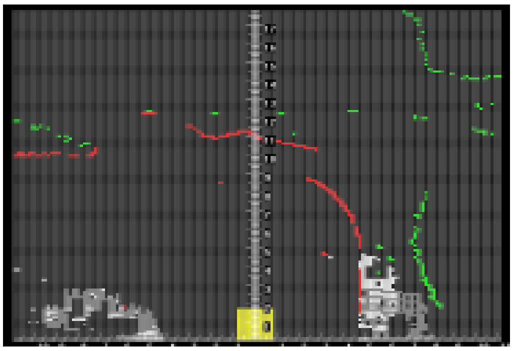


Figure 3. The generated local map

A. *Road Recognition and Obstacle Detection*

Before collecting sensor data from cameras and LRFs equipped on ESTRO, intrinsic and extrinsic calibrations are performed with a planar checkerboard pattern [12]. After solving for constraints between the views of a planar checkerboard calibration pattern from cameras and LRFs, their coordinate systems are calibrated to the same vehicle coordinate system.

For on-road markers detection, a raw colored image is converted into a gray scale image at first. Adaptive rectangular ROI (Region of Interest) extraction and noise filtering is also performed. Next, edge extraction through sobel approach and line fitting through Hough transformation method are achieved to get characteristics of the extracted lane. Speed bumper, crosswalk and stop line are also detected in the similar way to lane detection as shown in Fig. 4 [13].

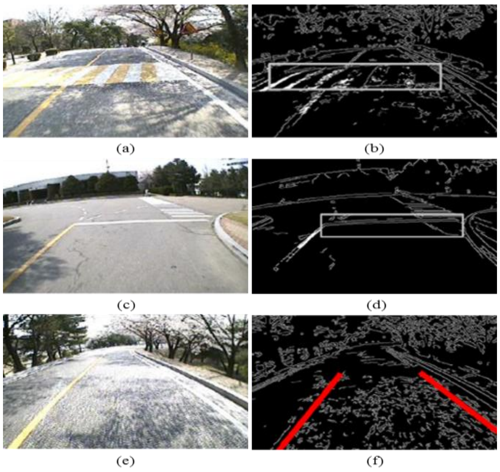


Figure 4. On-road markers extraction; (a) original image of normal road, (b) extraction for speed bumper, (c) original image of stop line, (d) extraction for stop line, (e) orginal image of lane, (f) extraction for lane

The LRF on the top of the vehicle is used for detecting curb, which is the raised edge of a pavement or sidewalk. Firstly, curb shape is geometrically recognized and its position is also derived with LRF data. Secondly, the position of curb is estimated and is also tracked using particle filter approach [14].

Obstacles on road are detected by the LRF at the front of the vehicle, which is arranged in the parallel with ground as shown in Fig. 1. All the detected obstacles are segmented and its size and distance are also estimated [15]

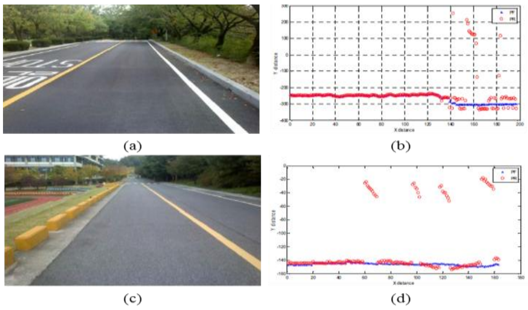


Figure 5. Curb extraction; (a) image of continuous curb, (b) extraction for continuous curb, (c) image of discontinuous curbs, and (d) extraction for discontinuous curbs.

B. *Localization*

Firstly, the current position of ESTRO is continuously calculated using GPS and odometer. This derived position value contains some error. However, ESTRO is assumed to be operated at well-known roads such as ETRI campus where on-road marker information such as lane and stop line is already stored in the map. Therefore, both the lateral and the longitudinal distance error in the position calculated by GPS and odometer can be compensated using on-road marker with Extended Kalman Filter as shown in Fig. 6. Besides, for reducing the sensors error such as drift error and jumping position of GPS, Mahalanobis distance approach is also applied. As a result, the accuracy of the estimated position is better than normal EKF localization [16], [17].

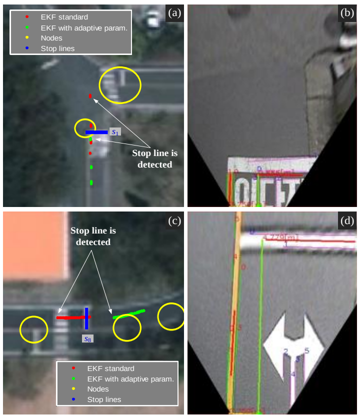


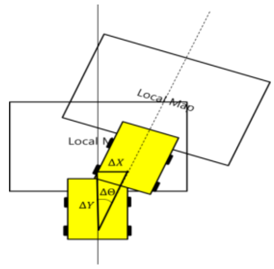
Figure 6. Comparison of two position estimates (EKF with and without adaptive parameter) near the stop line. (a) and (c) are the robot positions when the robot is detecting the stop lines. (b) and (d) are the bird-view images of mono-camera when the robot is detecting the stop line.

C. *Local Map Building*

For integrating multiple data from various sensors, local map is applied. On-road markers such as lane, speed bump, crosswalk, and stop line from cameras are described as typical representative values. For example, lane can be represented by its starting point and slope. In addition, crosswalk and speed bump are represented its distance and size. After transmitting these transformed data to the local map building component, they are integrated into the local map altogether. The detected curb and obstacle information are also described as relative position and size by LRF component and are also displayed in local map.

The local map has to be continuously updated, because the vehicle is moving. To update the previous local map, both relative pose and position change of the vehicle has to be periodically measured such as rotation angle and translation value. The transformed previous local map is integrated to current local map which include only current sensory data as shown in Fig. 7. In other words, local map contains both previous and current surrounding information at the same time.

In the local map, the position of the vehicle is fixed at bottom and middle of the map as shown in Fig. 3. The derived current position from localization component is matched with the fixed vehicle position in local map. In addition, the other positions of local map also are derived based on this position connectivity relatively.



$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} \cos(\Delta\theta) & -\sin(\Delta\theta) & \Delta X \\ \sin(\Delta\theta) & \cos(\Delta\theta) & \Delta Y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix}$$

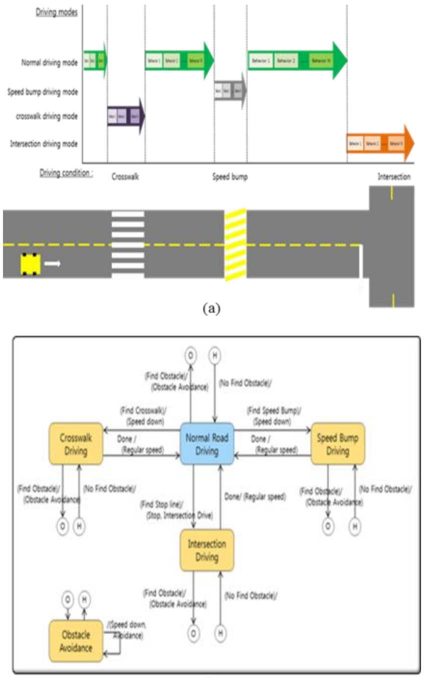
Figure 7. Local map transformation and update

IV. PLANNING AND CONTROL

A. *Behavior Planning*

ESTRO can select proper behaviors corresponding to the changes of road environment for driving safely and efficiently. Most of real road environments are composed of normal road which has well-painted lane, intersection, speed bump, cross walk, etc. According to road environment, the vehicle should choose its proper driving mode. For example, the basic behavior mode, normal driving mode, is to keep the certain distance between the vehicle and well-painted lane on the road environment.

Moreover, the vehicle also performs obstacle avoidance by reducing the speed of the vehicle and avoiding obstacles when they suddenly appear in front of vehicle. Suitable states have to be selected according to input information and it also transits to another suitable state through proper surrounding information shown in the Fig. 8.a. The state transition diagram is designed by analyzing the pattern of driver’s behavior.



(a)

(b)

Figure 8. Behavioral planning; (a) Scenario of the driving control system depending on driving condition, driving mode and behaviors, and (b) Diagram of driving condition transfer

B. *Path Planning and Control*

To reach the desired destination by autonomous driving, it is essential to include both the global and the local path planning. Therefore, the ESTRO system is largely separated into two steps of path planning. First step is global path planning which generates routes to pass and to reach for final destination. The global path planer performs path planning with the topological map information includes in the road connection relation and physical distance among neighbor nodes. Furthermore, the optimal path is generated by minimizing cost function which means the total traveling distance based on Dijkstra algorithm. The results of it are information on list of the node included in road property and the relation among nodes, while it traveling from start point to final destination. Next step is local path planning which performs periodically according to change of environment, it is decided the way by the result of above introduced behavior planning where the vehicles drives on the normal road or free form road such as intersection and parking lot area.

The implemented local path generator is based on three degree of Bezier curve [18]. The planned path could be smooth enough for ESTRO which is car-like model to track and to follow it. The important step for deciding the shape of Bezier curve is to pick up control points. By considering of processing time and complexity, the ESTRO system is based on three degree of Bezier curve as shown in Fig. 9.

For the three degree of Bezier curve, the four points have to be decided as control points in the normal case. The first point means the current position of the vehicle and last point means the position of next node which is decide by global path planning. A lot of candidate paths are generated at the same time by changing the position of rest two points on the center line of the current road. To get an optimal path among a lot of generated paths, every path is evaluated with three criteria such as kinematics constraint, obstacle collision, degree of smoothness. Finally, the optimal path can be selected, which has low cost.

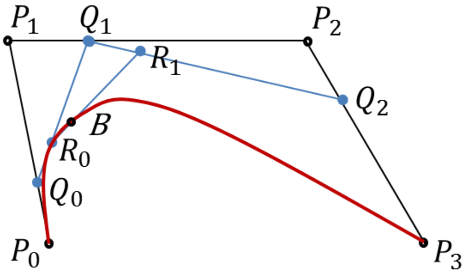


Figure 9. Beizir curve of degree 3 at t=0.5.

In the case of free-from road such as intersection and parking lot, the path planning module generates Bezier curve from the start configuration, $q_s = (x_s, y_s, \theta_s)$ to the target configuration $q_t = (x_t, y_t, \theta_t)$. The feasible paths can be generated by changing the second control point P_1 and the third control point P_2 as shown in Fig. 9. The first control point P_o and the fourth point P_3 are located at the start and the target node. For considering the various positions of the second control point, they are propagated the constant along the line with θ_s slope. The third control point is accomplished with the same procedure. Therefore, the different paths for a target state can be generated. As a result, the optimal path can be determined among candidate paths by evaluating and comparing cost of paths. To follow accurately the generated optimal path above, the pure pursuit method is applied. The pure pursuit method generates steering angle and velocity of vehicle [19]. The important factor of this method is a look-ahead distance. The look-ahead distance can be decided based on prior knowledge of the road on the map. With this method, the lateral tracking error of ESTRO in the test site is fewer than 50cm.

V. EXPERIMENT AND RESULT

To show the performance of the developed autonomous vehicle, ESTRO, the real driving test was performed on 7 km road environment of ETRI including many possible traffic situations and various types of roads such as well-structured road, intersection, parking lot, etc. as shown in Fig. 10. In this test site, ESTRO conducted various types of driving including lane keeping, speed control, obstacle avoiding, intersection driving, etc. as shown in Fig. 11.

Figure 10. The map of ETRI campus(more than 7 km real road environment)

Figure 11. (a) ESTRO stopped in front of stop line for compensation on the intersection, and (b) ESTRO stopped when the pedestrian crossed the road.

A. Normal Road

Most of roads in the test site are well-structured road which has both lanes and curbs on one side or on both sides as Fig. 12. However, most of them are surrounded by trees and buildings, so it is not easy to get high accuracy position with the equipped low-cost GPS (over RMS 2m on average). Furthermore, it is impossible to drive autonomously depending on only localization information. Thus, the vehicle has to compensate position derived by GPS and odometer with pre-saved road information in the digital map such as lane, stop line, etc.

The mid-point of current road is calculated by recognized curb and lanes and pre-saved road information such as the road width, the number of lanes, etc. The vehicle can drive by following the calculated midpoint. Speed of the vehicle is about 10 ~ 20 km/h. Average tracking error which is difference with mid-point of road is less than 30cm.

Figure 12. Well-structured noraml road which has lanes and curbs

B. Intersection

Autonomous driving highly depends on the accuracy of location in the area of intersection without lanes as show in Fig. 13. Therefore, before the vehicle enters the intersection, position was compensated by left and right side lane and stop line information to improve the position accuracy. For this compensation, the vehicle has to stop for a short period when the distance between the front of vehicle and stop line is within 1m. The vehicle went forward if there are not obstacles such as pedestrians and vehicles are on the generated route. When obstacles appear, the vehicle stopped and started again to follow the planned path on intersection after obstacles disappeared.

Figure 13. The exmpale of intersection area in our test site

Fig. 11 panels: (a) (b)

C. Parking Lot Area

As shown in Fig. 14, the driving in parking lot is based on the extraction of traversable area with the local map. The vehicle generates the virtual path to the next node on the traversable area of local map and generate steering angle for tracking the generated path. In parking lot, obstacle detection is important because the parked vehicle can be suddenly moved and pedestrian can appear.

Figure 14. The exmpale of parking lot area in our test site

VI. CONCLUSION

This paper explained about ESTRO project which aims at the development of autonomous vehicle to transport goods and people without the help of driver in the well-structured area such as campus. At the first, H/W configuration and S/W architecture of ESTRO were introduced. The methods for road recognition, obstacle detection, localization, and local map building for environmental perception were described. In addition, the methods for behavior planning, path planning, and control also were explained for planning and control. For demonstration of the developed vehicle, real driving test in ETRI campus was performed at normal road, intersection and parking lot.

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