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Outdoor Navigation of a Mobile Robot Using Differential GPS and Curb Detection

Seung-Hun Kim , Chi-Won Roh , Sung-Chul Kang and Min-Yong Park

Abstract— **This paper demonstrates a reliable navigation of a mobile robot in outdoor environment. We fuse differential GPS and odometry data using the framework of extended Kalman filter to localize a mobile robot. And also, we propose an algorithm to detect curbs through the laser range finder. An important feature of road environment is the existence of curbs. The mobile robot builds the map of the curbs of roads and the map is used for tracking and localization. The navigation system for the mobile robot consists of a mobile robot and a control station. The mobile robot sends the image data from a camera to the control station. The control station receives and displays the image data and the teleoperator commands the mobile robot based on the image data. Since the image data does not contain enough data for reliable navigation, a hybrid strategy for reliable mobile robot in outdoor environment is suggested. When the mobile robot is faced with unexpected obstacles or the situation that, if it follows the command, it can happen to collide, it sends a warning message to the teleoperator and changes the mode from teleoperated to autonomous to avoid the obstacles by itself. After avoiding the obstacles or the collision situation, the mode of the mobile robot is returned to teleoperated mode. We have been able to confirm that the appropriate change of navigation mode can help the teleoperator perform reliable navigation in outdoor environment through experiments in the road.**

I. INTRODUCTION

OUR goal is to develop an autonomous mobile robot which can patrol Korea Institute of Science and Technology (KIST). In the last decades there have been remarkable developments in localization and mapping algorithm of navigation system for indoor/outdoor mobile robots. In indoor cases, personal service robots perform the missions of guiding tourists in museum, cleaning room and nursing the elderly [1]. In outdoor cases, mobile robots have been used for the purpose of patrol, reconnaissance, surveillance and exploring planets, etc [2].

The indoor environment has a variety of features such as walls, doors and furniture that can be used for mapping and navigation of a mobile robot. In contrast to the indoor cases, it is hard to find any specific features in outdoor environment without some artificial landmarks [3]. Fortunately, the existence of curbs on roadways is very useful to build a map and localization in outdoor environment. The detected curb information could be used for not only map building and localization but also navigating safely [4].

Many kinds of navigation algorithm of a mobile robot have been proposed. Most of the algorithms, however, are developed for autonomous navigation. Therefore, navigation algorithms for the teleoperated mobile robot that is usually used in hazardous and disaster field are necessary. A hybrid strategy for a reliable mobile robot consists of a mobile robot and a control station. The mobile robot sends image data to the control station. The control station receives and displays the image data and then the teleoperator commands the mobile robot based on the image data. However, the image data would not be sufficient for reliable teleoperation, because the camera positioned on the mobile robot could not see all obstacles surrounding the mobile robot and the teleoperator could send an erroneous velocity command. For the purpose of reliable outdoor navigation, the mobile robots should be able to navigate with commanded translational and rotational velocities, perceive static and varying environments and avoid dynamic obstacles.

In this paper, we propose the localization algorithm of a mobile robot using differential GPS and the outdoor environment map building algorithm using curbs detection [5], [6]. And also, we present a hybrid strategy for a reliable mobile robot in outdoor environment. Depending on the size of obstacles, the distance between the robot and curbs obtained using a laser range finder, the velocity and the braking distance of the robot, the modes of the robot alternate between autonomous and teleoperated modes.

II. MOBILE ROBOT SYSTEM

A. Mobile Robot Platform

We construct the navigation system on an ATRV-mini from RWI Inc. It is a four-wheeled robot designed for outdoor use and comes equipped with odometry. We choose this robot, because it can climb up and down over speed bumps and slopes. We add a laser range finder to detect obstacles and build a map of the environment. For global localization, we add a DGPS receiver. A camera that can pan, tilt, zoom-in and zoom-out, is installed to send the image data to the control station.

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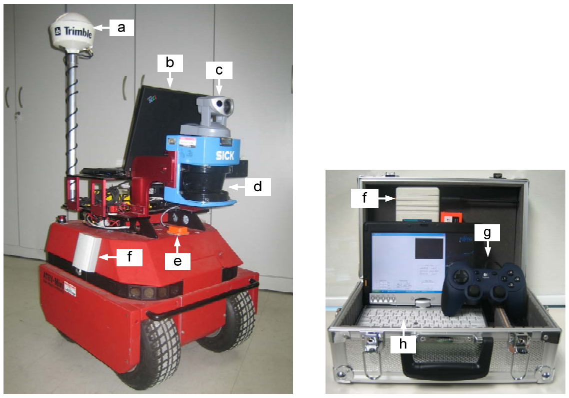


Fig. 1. Mobile robot system (a) DGPS antenna (b) PC (c) Pan-tilt image Camera (d) LMS200 laser range finder (e) MTi Attitude/heading sensor (f) Wireless LAN bridges (g) Joypad (h) Control station

B. *Odometry*

Odometry is the process of estimating the position of a mobile robot by advancing from a known position using wheel's rotational velocity, angular velocity and distance traveled. In order to determine the position of the robot using the odometry, we integrate the rotational velocity of wheel, v_k and the angular velocity of the robot, ω_k. One handicap of numerical integration is that the error in the odometry accumulates over time because of inaccuracies in the model, limited precision of encoders and unobservable factors such as wheel slippages. We deal with the problem of error's accumulation by fusing the information from a DGPS and an attitude/heading sensor as described in section III.

The following equation is the nominal model of system dynamics:

$$x_{k+1} = f(x_k, u_k, k) + w_k \text{, where} \tag{1}$$

$$f(x_k, u_k, k) = x_k + T_s \begin{pmatrix} -v_{rk} \sin\theta_{rk} \\ v_{rk} \cos\theta_{rk} \\ \omega_{rk} \end{pmatrix}.$$

$x_k = [x_{rk}, y_{rk}, \theta_{rk}]^T$, superscript T means transpose, is the state vector that represents the position and the orientation of the robot as shown in Fig. 2. $f(\cdot)$ is nonlinear function of the robot that relates the state at time k to the state at time k+1. Here, T_s is sampling time. The control inputs applied to the robot are $u_k = [v_{rk}, \omega_{rk}]^T$, where v_{rk} is the translational velocity and ω_{rk} is the rotational velocity of the robot. We assume the process noise in the dynamics model to be a zero-mean Gaussian white noise, i.e., $w_k \sim N(0, Q_k)$, where Q_k is the covariance matrix of x_{rk}, y_{rk} and θ_{rk} as the following:

$$Q_t = \begin{pmatrix} \sigma^2_{x_{rk}} & 0 & 0 \\ 0 & \sigma^2_{y_{rk}} & 0 \\ 0 & 0 & \sigma^2_{\theta_{rk}} \end{pmatrix}. \tag{2}$$

The initial state x_0 is determined by calculating the relative position of the robot with respect to the known point using a DGPS.

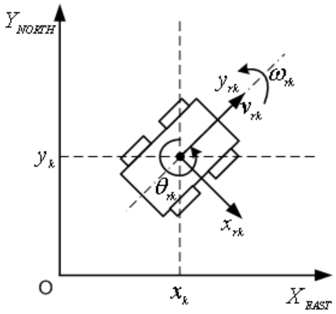


Fig. 2. The coordinate of the mobile robot

C. *Differential GPS (DGPS)*

The DSM 132 receiver outputs NMEA (National Marine Electronic Association) messages for GPS position data transfer between electronics equipment. We can obtain latitude and longitude with respect to WGS-84 geographic coordinate system by the GGA (GPS Fix Data) message that contains the time, position and fix related data. The DSM 132 receiver sends the latitude and longitude to the robot at every 1 second.

The errors causing degradation in accuracy are resulted from atmospheric conditions, multipath errors and interference of electronic devices or GPS. The multipath errors are caused due to signals reflected by nearby objects. DGPS removes most of the errors caused by atmospheric conditions. The errors are further reduced by the advanced design of the DSM 132 receiver, and we obtain the positional accuracy within 1 meter of error's variance.

The orientation obtained from a DGPS is highly unreliable. Therefore we adapt an MTi, a heading sensor, to the robot. Its internal low-power signal processor provides drift-free 3D earth-magnetic field data. Its angular resolution is 0.05° and static error of heading is less than 1°. The MTi sends the orientation to the robot at every 100 milliseconds.

The measurement model equation is

$$z_k = h(x_k, k) + v_k \text{, where} \tag{3}$$

$$h(x_k, k) = \begin{pmatrix} x_{mk} \\ y_{mk} \\ \theta_{mk} \end{pmatrix}.$$

$z_k = [x_{mk}, y_{mk}, \theta_{mk}]^T$ is the measurement. The position x_{mk}, y_{mk} and orientation θ_{mk} are obtained from the DGPS and the heading sensor, respectively. We assume that the measurement noise v_k to be a zero-mean Gaussian white noise, i.e., $v_k \sim (0, R_k)$, where R_k is the covariance matrix of x_{mk}, y_{mk} and θ_{mk} as the following:

$$R_k = \begin{pmatrix} \sigma^2{}_{x_{mk}} & 0 & 0 \\ 0 & \sigma^2{}_{y_{mk}} & 0 \\ 0 & 0 & \sigma^2{}_{\theta_{mk}} \end{pmatrix}. \qquad (4)$$

III. LOCALIZATION

We propose a localization method that fuses the DGPS and odometry data using the extended Kalman filter [7], [8]. Extended Kalman filtering is a well known method for estimating the position and angle of a differentially driven mobile robot. In the 2D outdoor robot localization problem, the states of the robot are its position and orientation $(x_{rk}, y_{rk}, \theta_{rk})$. The robot's states evolve according to nonlinear stochastic difference equations.

We linearize the system dynamics and measurement equations (Eq. (1) and (3)) and apply an EKF algorithm for localization.

Prediction step

$\hat{x}_k^- = f(\hat{x}_{k-1}, u_k, k-1)$: predicted state

$P_k^- = F_{k-1} P_{k-1} F_{k-1}^T + Q_{k-1}$: predicted covariance of the state

$$F_{k-1} = \left.\frac{\partial f(x_k, u_k, k-1)}{\partial x_k}\right|_{x_k = \hat{x}_{k-1}^-} = \begin{pmatrix} 1 & 0 & -\cos\hat{\theta}_{k-1} \\ 0 & 1 & -\sin\hat{\theta}_{k-1} \\ 0 & 0 & 1 \end{pmatrix}$$

F_{k-1} is Jacobian matrix of the nonlinear function of the mobile robot. Q_k (Eq. (2)) is the covariance matrix of process noise, w_k, as shown in the previous section.

Update step

$K_k = P_k^- H_k^T (H_k P_k^- H_k^T + R_k)^{-1}$: optimal Kalman gain

$\hat{x}_k = \hat{x}_k^- + K_k \{z_k - h(\hat{x}_k^-, k)\}$: estimate of the state

$P_k = [I - K_k H_k] P_k^-$: updated covariance of the state

$$H_k = \left.\frac{\partial h(x_k, k)}{\partial x_k}\right|_{x_k = \hat{x}_k^-} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

H_k is Jacobian matrix of $h(\cdot)$ in the measurement equation. R_k (Eq. (4)), the covariance matrix of v_k, is the most important factor to determine the effectiveness of the EKF and it is affected by nearby buildings and trees because v_k is the error of the measured position by a DGPS.

IV. CURB DETECTION

The outdoor mobile robot requires ability to navigate in a dynamic, uninstrumented and potentially dangerous environment due to curbs and obstacles. Using the laser range finder, it can measure the distance from the obstacles and calculate the distance between obstacles. These data obtained from the laser range finder can be used in environment mapping and obstacle avoidance.

An important feature of road environment is the existence of curbs. The curbs could be used in mobile robot navigation. We propose an algorithm to detect curbs through the laser range finder, which is positioned on the mobile robot and looking down the road with a small tilt angle as shown in Fig. 3. The mobile robot builds the map of the curbs of roads and the map is used for tracking and localization. (n, x_L, y_L) is obtained by the laser range finder, where n represents n-th data and x_L, y_L are the distance data in the laser range finder's coordinate. We use the curb edges on the both sides of the mobile robot for mapping and tracking.

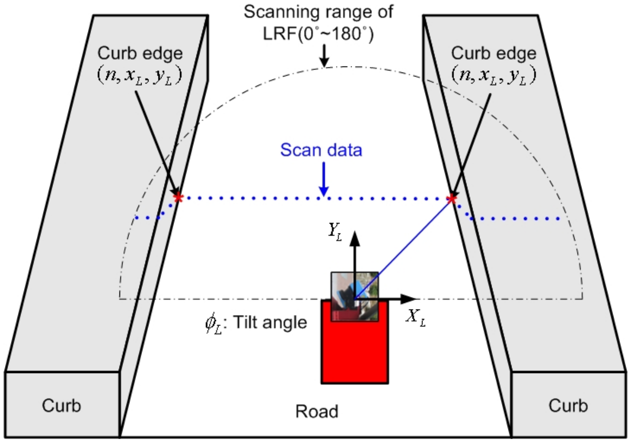


Fig. 3. Curb detection on the road using a laser range finder with tilt angle

1) *Extracting the longest straight line*

The laser range finder senses the surface of roads due to the small angle between the laser range finder and the mobile robot. Therefore, the longest straight line of the raw data from laser range finder is the surface of roads and the curbs locates the edges of the road. We extract the longest straight line using Hough Transform [9]. In Hough transform, each line is represented by two parameters, commonly called ρ and θ, which represent the length and angle from the origin of a normal to the line. Using this parameterization, an equation of the line can be written as:

$$\rho = x_n \cos\theta + y_n \sin\theta, \qquad (5)$$

(x_n, y_n) is the n-th measurement data, where n is 1 to 361 and $\theta \in [0, 2\pi)$. The dominant ρ and θ are obtained by Hough Transform, called ρ_d and θ_d as shown in Fig. 4.

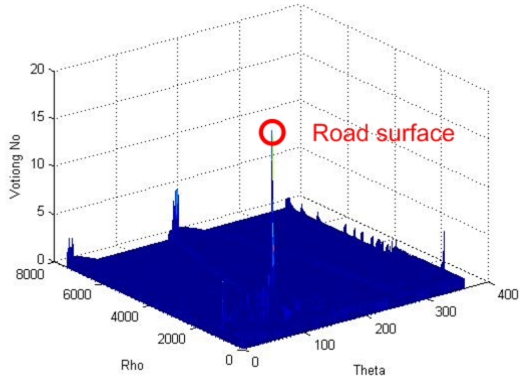


Fig. 4. The dominant ρ and θ found by Hough Transform

The red line in Fig. 5 shows the longest straight line represented by ρ_d and θ_d.

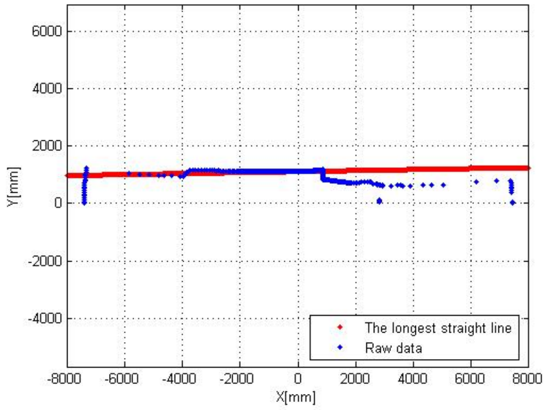


Fig. 5. The raw data and the points around the longest line

2) *Fitting the points around the straight line*

It is needed to fit the raw data points corresponding to the straight line for identifying the road surface and the curbs. We can know the road surface and curbs exist on the boundary of the straight line from Fig. 5. To obtain the boundary points of the line, we first calculate ρ by Eq. (5) for each raw scan data with θ_d. And then, choose the points satisfying the following Eq. (6). The blue points of Fig. 6 show the fitting points with $\Delta\rho$ of 100mm.

$$\rho_d - \Delta\rho \le \rho \le \rho_d + \Delta\rho \tag{6}$$

3) *Extracting the curb edge points*

The scan data of a flat road surface has two specific characteristics. One is that the scan data of road surface is on the straight line and the interval between adjacent two points is small. The other is that the slope of the straight line is parallel to the direction X_L of a laser range finder.

When the distance between adjacent two points is continuously within d and the slope between them is less than σ, the two points are considered as being on the straight line (Eq. (7)). The end points (red stars in Fig. 6) of the straight line are the road edges and also the start points of the curbs. Therefore the curb edge points could be obtained by finding the end points of the straight line.

$$\sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2} \le d \text{ and}$$
$$\left| \tan^{-1}\left(\frac{y_i - y_{i+1}}{x_i - x_{i+1}} \right) \right| \le \sigma \tag{7}$$

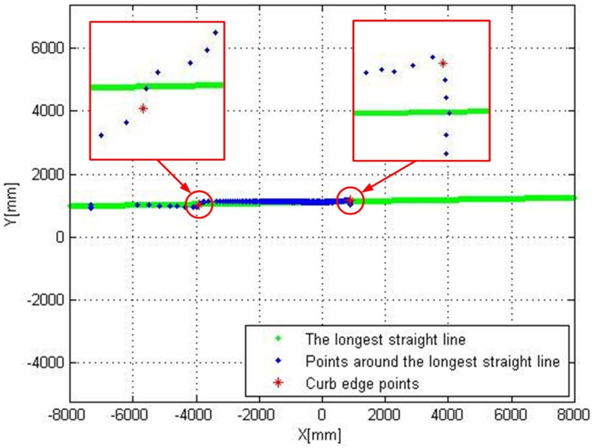


Fig. 6. The extracted curb edge points

V. HYBRID NAVIGATION STRATEGY

We propose a hybrid strategy for reliable navigation of a mobile robot. When the robot which is controlled by the teleoperator in teleoperation mode faces with unexpected obstacles or situations when a collision is expected, it changes the operation mode in four steps:

1) the mobile robot sends a warning message to the teleoperator,
2) it changes from teleoperation mode to autonomous mode,
3) it automatically performs path planning and avoids the obstacles, and
4) after avoiding the obstacles or the collision situation, it returns to teleoperation mode and then the teleoperator controls the mobile robot again.

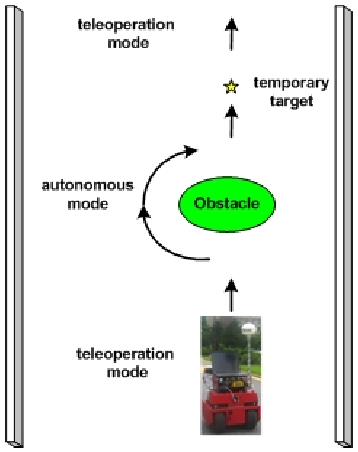


Fig. 7. Hybrid navigation strategy

We have developed an algorithm to make a decision of mode change considering the size of obstacles, the distance between the curbs of roads, the navigation velocity and the braking distance of the robot. When the robot suddenly meets unexpected obstacles, it calculates the distance between the curbs on the opposite sides of the road, distances between the robot and the obstacles, and then determines whether to move or stop. If the width of the road is too narrow to avoid the obstacle, the robot stops and sends the alarm message to the teleoperator. In this case, the robot waits until the obstacles disappear so that it can keep going along the way. On the other hand, if the width of the road is sufficiently large to avoid the obstacles, it changes the operation mode from teleoperation to autonomous mode and avoids the obstacles itself.

VI. EXPERIMENTS

A. *EKF-Based Navigation Experiments*

We have performed a number of experiments to verify the performance of EKF-based navigation. The robot was driven by the teleoperator along a road in KIST with maximum velocity of 0.8m/s. Fig. 8 shows the robot approaching to a turning point. Fig. 9 shows the robot's route started at (0,0) and ended at (-30,-3). Odometry has basically several error sources of inaccuracies in the model, wheel misalignment and wheel slippages, etc. We can identify these effects from the odometry route that has error bound of tens of meters. This odometry data alone is not used for localization or navigation. The frequency of overall the robot's routine was 5Hz and odometry data was obtained at 5Hz. The DGPS and heading sensor data were sent every 1 second. The difference of sampling times makes that EKF prediction routine is performed every 200ms until the updated DGPS position data and heading sensor data are received. If new data from the DGPS receiver and the heading sensor are received, the EKF update routine is executed. We can identify this trend from Fig. 10. The data obtained from EKF prediction routine would be used for autonomous navigation.

Fig. 8. The mobile robot driving along the road

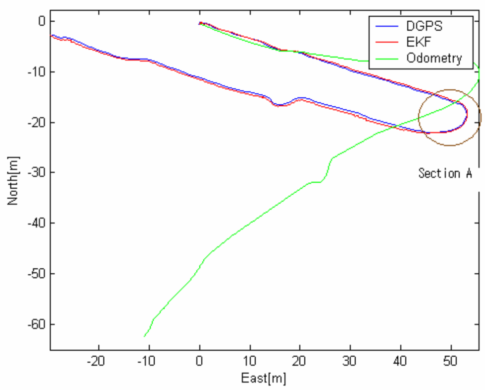


Fig. 9. The mobile robot's route: start point (East:0, North:0)

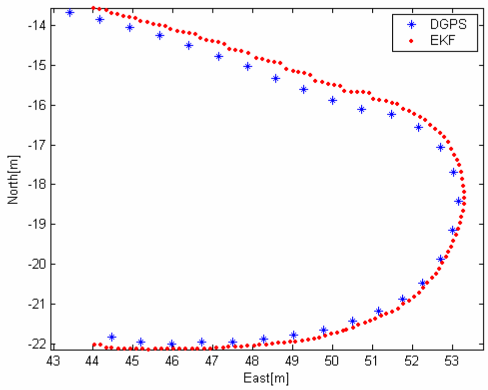
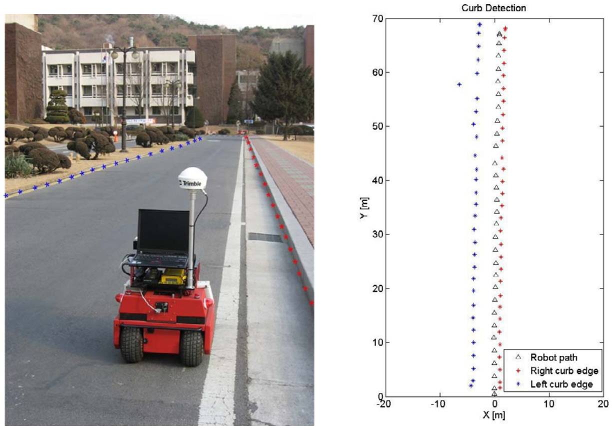


Fig. 10. Magnified route of Section A of Fig. 9

B. *Curb Detection Experiments*

We have experimented to identify the performance of the proposed curb detection algorithm. The mobile robot was driven along a road with the distance (600mm) between the mobile robot and curbs in KIST. The tilt angle (ϕ_L in Fig. 3) between the mobile robot and the laser range finder is 25°. We selected the values d and σ as 50mm and $\pi/4$ in Eq. (7). The red, blue stars and the black triangles in Fig. 11 show the detected curbs and the robot path, respectively. Even though the mobile robot moves zigzag, the detected curb path is smooth. The average error of the curb points is 20mm.



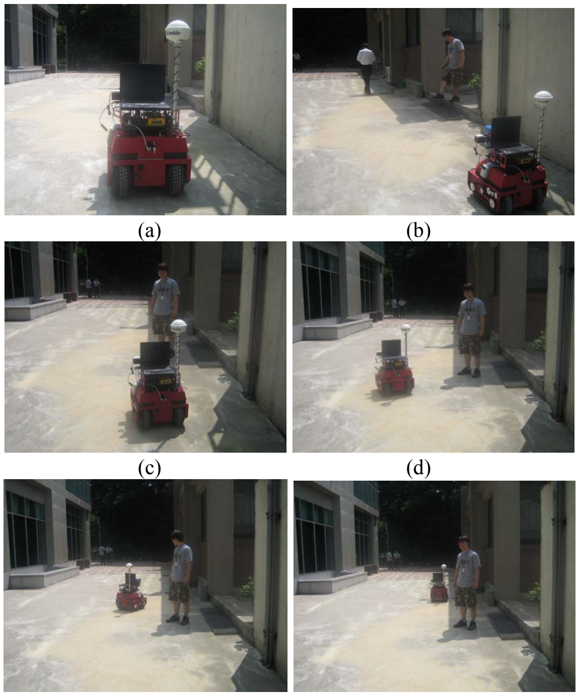
(a) (b)

Fig. 11. Curb detection experiment (a) The mobile robot tracking the curbs (b) Robot path and detected curbs

C. Hybrid Navigation Experiments

To test the proposed hybrid navigation algorithm, some experiments have been performed. The laser range finder is used for building local environment map with ICP algorithm [10]. The robot was driven in the teleoperation mode with approximately commanded velocity of 0.5m/s. After a while, one person appears in front of the robot. If the distance between the mobile and the person is less than 2m and the operator commands going on, the robot performs reactive obstacle avoidance procedure. The experiment procedures are shown at Fig. 12 and Fig. 13. The robot determines whether it can avoid the person or not based on the environment map. If there is a space to avoid, it continues the proposed obstacle avoidance routine. After avoiding the person and there is no obstacle, it waits the command from the teleoperator. This experiments shows that the proposed algorithm help the teleoperator drive reliably in case of his/her not noticing the unforeseen obstacles.

The teleoperator generally drives the robot based on the image data received from the mobile robot. In some cases, the teleoperator cannot notice the curbs and the robot collides with them without the proposed strategy. With the proposed hybrid strategy, the robot can avoid the collision and help the teleoperator perform more reliable navigation.



(a) (b)

(c) (d)

(e) (f)

Fig. 12. Hybrid navigation experiment: (a) driving in the teleoperated mode (b) appearance of a unnoticed person (c) detection of the person and driving within 2m (d) changing the mode to autonomous navigation and avoiding the person (e) avoiding the person and driving to the temporary target (f) changing mode and waiting the command from the operator after reaching the temporary target

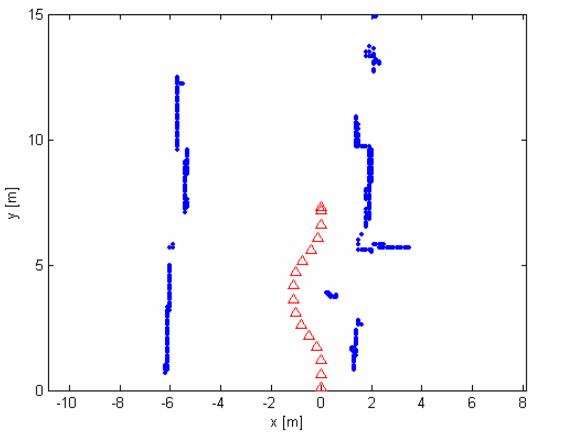


Fig. 13. Environment map built during the hybrid navigation (red triangle: trajectory of the robot)

VII. CONCLUSION

We find out the position of the mobile robot using a framework of EKF based on differential GPS and odometry. And also, we obtain the information of the road where the mobile robot might be moved using curb detection.

We propose a hybrid strategy of autonomous and teleoperation modes for reliable mobile robot navigation. Depending on the outdoor environments, the mobile robot changes the navigation mode, between teleoperation and autonomous mode. We have been able to confirm that the proposed hybrid navigation algorithm helps the teleoperator to perform reliable navigation in outdoor environment through experiments in the road.

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