Design of the 3D perceptive system based on laser scanner for a mobile robot

Zi-xing Cai[1], *Jin-xia Yu*[1,2], *Zhuo-hua Duan*[1,3], *Xiao-bing Zou*[1]

1 College of Information Science & Engineering
Central South University
Changsha Hunan, 410083, China

2 College of Computer Science & Technology
Henan Polytechnic University
Jiaozuo Henan, 454003, China

3 Department of Computer Science
Shaoguan University
Shaoguan Guangdong, 512003, China

Summary
It is necessary for autonomous navigation of mobile robot to have the ability of terrain mapping and analysis for 3D environment. This paper designs a 3D perceptive system for a mobile robot based on a 2D laser scanner LMS291 mounting on a high precision rotating table with horizontal and pitch rotation. Based on the measurement principle of LMS291, its ranging accuracy in different condition is tested and analyzed. A terrain mapping method is proposed and an elevation map is built for the purpose of terrain analysis. By analyzing the cause of system error and sensor noise, a dynamic adaptive filter is presented to realize the real-time and dynamic filter. In addition, the smoothing filter based on the Gaussian distribution is introduced to reduce the scanning gap. In order to classify the free area and obstacle area, terrain flatness analysis by the elevation map is implemented. Experiment results demonstrate that the system for 3D perception is effective and it can provide the support for mobile robot navigation.

Key words:
Mobile robot, laser scanner, elevation map, terrain flatness analysis, dynamic adaptive filter

1. Introduction

Intelligent mobile robot is a robotic system having the capability of sensing the environment and its state for realizing the autonomous navigation to the destination in order to fulfill certain tasks [1]. Autonomous navigation requires that a mobile robot have the ability of terrain mapping and analysis for 3D environment in which obstacles detection is a key problem.

Sensors suitable for obstacles detection are stereo vision, microwave radar, ultrasonic sensor and laser measurement system and so on [2-5]. Stereo vision can easily be affected by the illumination, resolution, focus adjustment and attention point selection, etc. Thus, its computation is complex and the information is distorted seriously when it is used to detect the distance of obstacles [6], while laser measurement system can validly solve the above difficult problems of acquiring the depth information according to vision technique [7,8]. Laser measurement system includes simple range sensor using laser scanner, 2D laser scanner [9-12] that scans in one plane, 3D laser scanner [7,8,13] that scans and “nods,” thus producing a range image of an area. A 3D laser scanner would be the best choice for terrain mapping due to different obstacles in 3D environment. However, 3D laser scanners are inhibitively expensive for most mobile robot applications. A cost-effective alternative for 3D mapping is to mount a 2D laser scanner that is aimed forward and downward on the front of end of a mobile robot [14].

This paper designs and realizes a 3D perceptual system for a mobile robot based on a 2D laser scanner LMS291. In order to sense the actual state of 3D environment, LMS291 is mounted on a high precision rotating table. Based on the measurement principle of LMS291, its ranging accuracy is tested and analyzed. Then according to a terrain mapping method, mobile robot builds the elevation map. After analyzing system error and noise disturbance of LMS291, this paper designs the dynamic adaptive filter for the real-time scanning data to realize reliable obstacles detection and the smoothing filter based on Gaussian distribution to reduce the scanning gap. In order to classify the free area and obstacle area in navigation, terrain flatness analysis by the elevation map is implemented so as to guide mobile robot to avoid obstacles. With experiments, it proves that this system has better flexibility for mobile robot to sense 3D environment and can provide the support for mobile robot navigation in unstructured environment.

2. Measurement Principle and Performance Analysis of Laser Scanner

2.1 Measurement Principle of Laser Scanner

LMS291 made by Sick Corporation is a laser scanner that can provide 2D scanning field (180º). It is based on a time-of-fight (TOF) measurement principle (Laser Radar) as depicted in figure1 [14,15]. A pulsed laser beam is emitted and reflected from the object surface. The reflection is registered

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by the scanner's receiver. The time between transmission and reception of the laser beam is used to measure the distance between the scanner and the object.

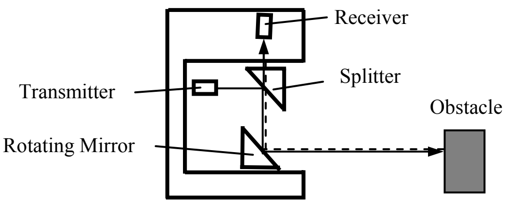


Fig. 1 Measurement principle of laser radar

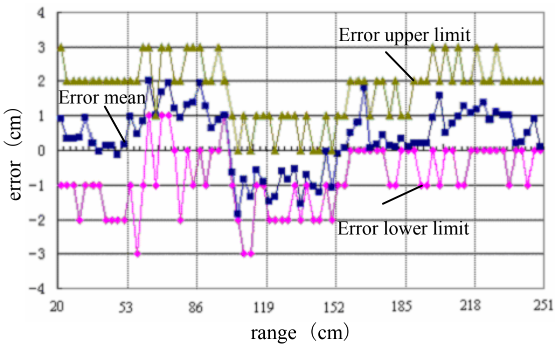
2.2 Tests and Analyses of Ranging Accuracy

The following tests are run to estimate ranging accuracy of laser scanner LMS291.

(1) Alignment of ranging data

In order to verify the measurement accuracy of LMS291, we aligned the range from 20 to 248 cm. with the test platform in figure 2(a) and moved the target every 3 cm at which the target is measured 100 times. It can get 7700 measurement data as shown in figure 2(b) in which error mean of each measured point and the upper limit and the lower limit of error of all measurement data are painted. This test discovered that maximum deviation of the object with fixed reflectivity (dust color carton) is between 3 and 33 cm. In addition, standard deviation of measuring error is 0.94 cm in this test.

(a) Aligned experiment for range measurement of laser scanner



(b) Distribution curve of range error measured by laser scanner

Fig. 2 Deviation curve of range measured by laser scanner

(2) Statistical characteristics analysis with different surface

Aimed at the properties of objects' surface such as reflectivity, gray, chroma, roughness and curvature, we implement the test with 12 different object organized in five groups at fixed range (100cm) where the object is measured 1000 times. Test results are shown in table 1 and it discovered that the discrepancy of standard deviation among different object is within the range of ±10 mm and the influence of properties of objects' surface is trivial.

Table 1: Experiments of various objects' surface properties

Object		***Mean*** $\bar{d}$ (cm)	***Standard Variation*** σ (cm)
1.Reflectivity	Aluminum Board	101.05	0.30
	Board	100.17	0.76
2.Gray	White Paper	100.07	0.26
	Black Paper	100.30	0.35
3.Chroma	Red Paper	100.52	0.34
	Green Paper	100.21	0.31
	Blue Paper	100.49	0.32
4.Roughness	120# Sand Paper	100.37	0.83
	360# Sand Paper	100.57	0.63
	400# Sand Paper	100.58	0.61
5.Curvature	Stainless Steel Bucket(11cm dia.)	100.09	0.84
	Stainless Steel Bucket(23cm dia.)	100.10	0.83

(3) Effect of Angular Resolution

Angular resolution of LMS291 is selectable at 1º, 0.5º or 0.25º. In order to investigate the effect of angular resolution, the rotating table is used and its resolution γ_h is set to 0.01º. In figure 3, an object is placed in front of LMS291 about 1.5m and a uniform background is done at the back of this object about 0.8m. The rotating table drives LMS291 to rotate in clockwise direction or not. Ranging data is recorded 100 times every 0.01º. This test discovered the sensitive angle occurring mixed pixel disturbance is 0.19º, which provide the support for the error model of LMS291.

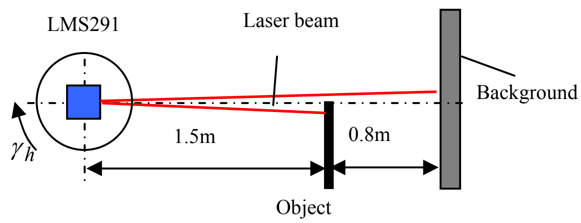


Fig. 3 Test of angular resolution of LMS291

(4) Statistical characteristics analysis at different range

The spacing of light impulse is emanative with increasing measurement range. Using the aluminum board as measurement object, its standard deviation changes from $\sigma = 0.85$ to $\sigma = 1.78$ cm in the range of 2.5m~60m. Dividing the standard deviation into several groups is shown in table 2 in which $\sigma_{\bar{d}}$ is standard deviation of the same object repeating to measure for many times and σ_d is the 3 times of $\sigma_{\bar{d}}$ as system error of different object. So, $\sigma_{\bar{d}}$ can be used to estimate the measurement error of stationary object and σ_d to estimate the measurement error at some times.

Table 2: Standard deviation at different range

d (cm)	$d \le 500$	$500 < d \le 1000$	$1000 < d \le 2000$	$2000 < d \le 4000$	$d > 4000$
$\sigma_{\bar{d}}$ (cm)	1.0	1.2	1.35	1.7	1.8
σ_d (cm)	3.0	3.6	4.05	5.1	5.4

3. Design of the 3D Perceptive System Based on Laser Scanner

3.1 System Architecture

The 3D perceptive system is composed of a 2D laser scanner LMS291 and a high precision rotating table with the horizontal and pitch rotation so as to detect 3D environments. The heading of robot is consisted by the rotating table that can rotate in the horizontal and pitch direction respectively. Controls on the heading of robot and on the locomotion of the bodywork are separated in order to gain more flexibility. The heading of robot can rotate from –150 to 150 degrees in horizontal direction and from –50 to 15 degrees in pitch direction (see figure 4). The rotating table is driven by the 24 Volt DC stepping motor of which step angle is 1.8 degrees, locomotion control uses PCL 839 control card and the driver works in 10 subdivision mode. The reduction ratio is 180 which means the motor rotates a circle the rotating table 180 circles, and a pulse drives 0.18º rotation of the platform which means the rotating table rotates 0.001 degree a pulse. In fact, the repetitive positioning accuracy of the rotating table is 0.01 degree due to the gap of mechanical transmission. The maximum velocity of rotating table is 16 degrees per second in horizontal direction and 8 degrees per second in pitch direction.

Industrial personal computer (IPC) is adopted to realize the distribution control and 4 sets IPC system can be installed in a computer bus board. Each IPC system includes one CPU slot, two PCI expansion slot and one ISA expansion slot. There are 3 sets of IPC system in control system of mobile robot used to control the robot locomotion (IPC0), to deal with the vision information (IPC2) and to realize the controls on laser scanner and the rotating table (IPC1) respectively. A high-speed communication interface card installed in PCI expansion slot communicates with laser scanner LMS291 by RS422 protocol and a locomotion card PCL839 installed in ISA expansion slot controls the rotation of the rotating table in horizontal and pitch direction. Laser scanner can be set two work modes. One is continuous scan and the other is instruction trigger. When continuously scanning, more detecting data can be obtained, but this may cause the data overflow in buffer area. Furthermore, the data from laser scanner is too difficult to synchronize with state parameters of robot, which causes the inaccuracy of data matching. Hence, a periodical query is raised for the scan results. After ending the scan and getting the measurement data, a new scan is started up immediately. LMS291 would get 361 measurement data throughout the 180º scanning field with 0.5º resolution. Each measurement data has two bytes and the length of data package including start bit and parity bit is 732 bytes. With 500kbps communication rate, the transmission delay time is 13ms and the scan time of LMS291 is 26.67ms. Thus we use 40ms to undergo the scan of LMS291and deal with the data.

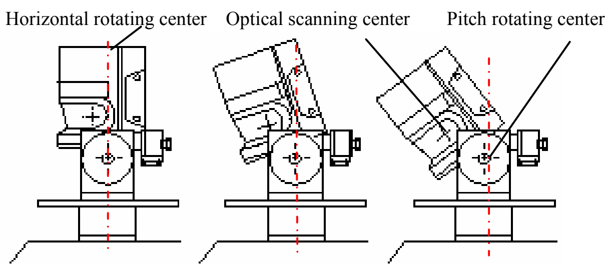


Fig. 4 Sketch map of laser scanner and rotating table

3.2 Terrain Mapping

Mobile robot measures and represents the 3D terrain based on laser scanner, which can not only sense the operating environment but also provide a strong support for terrain analysis, obstacle detecting and path planning.

There are two steps to represent the 3D terrain by the measurement information of LMS291. One is that the measurement information is reflected to O_r coordinate system using robot as reference center and its bodywork plane as reference plane on the assumption that the bodywork plane is stationary (see figure 5). Providing the scanning center of LMS291 on the rotating table is O_2, the rotating table rotates around the y_1 axis of O_1 coordinate system at the γ_P pitch. The horizontal rotation of rotating table equals the rotation around the z_r axis of the locomotion center of robot O_r coordinate system at the γ_h angle. O_1 translates d_0 along the z_r axis of O_r coordinate system and O_2 translates d_1 along the z_1 axis then d_2 along the x_1 axis of O_1 coordination system.

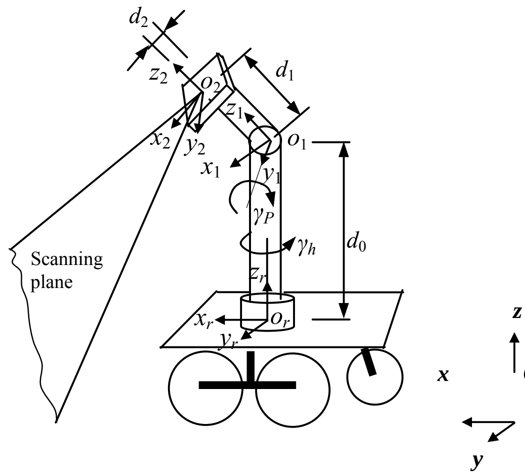


Fig. 5 Coordinates transformation from the laser measurement system to the robot reference plane

The scanning plane of LMS291 is the radiate fanning-shape area whose circle center is O_2 and scale from –90 to 90 degrees in the x_2-y_2 scanning plane. The 2D array ($\rho_{i,j}$, $\lambda_{i,j}$) in polar coordinate system is used to present the measurement data where $\rho_{i,j}$ is the measuring distance and $\lambda_{i,j}$ the polar angle (x_2 is the polar axis). The suffix i denotes the moment measured by the operation cycle in the main program. At the i-th moment, the data package scanned by LMS291 is sent and it includes 361 measurement data. The suffix j denotes the number of measured point in a data package. The measured value ($\rho_{i,j}$, $\lambda_{i,j}$) in x_2-y_2 scanning plane can be translated into the vector pattern in x_2-y_2-z_2 reference frame by the following formula.

$$u|_{O_2} = (\rho_{i,j}\cos\lambda_{i,j}, \rho_{i,j}\sin\lambda_{i,j}, 0, 1)^{T} . \tag{1}$$

At the i-th moment, the state of rotating table is $\{\gamma_P , \gamma_h\}$. The vector $u|_{O_2}$ in x_2-y_2-z_2 reference frame can be translated into the terrain elevation in O_r coordinate system. The translation transformation is presented by Tran() and the rotation transformation around some coordinate axis is presented by Rot(). In the following transformation matrix, s denotes sine function sin() and c denotes cosine function cos().

$$u|_{O_r} = T_r \cdot u|_{O_2} \tag{2}$$

Where,

$$T_r = \mathrm{Trans}(0,0,d_0)\ \mathrm{Rot}(z_r,\gamma_h)\ \mathrm{Rot}(y_1,\gamma_P)\ \mathrm{Trans}(d_2,0,d_1)$$
$$= \begin{bmatrix} c\gamma_h c\gamma_p & -s\gamma_h & c\gamma_h s\gamma_p & d_2 c\gamma_p c\gamma_h + d_1 s\gamma_p c\gamma_h \\ s\gamma_h c\gamma_p & c\gamma_h & s\gamma_h s\gamma_p & d_2 c\gamma_p s\gamma_h + d_1 s\gamma_p s\gamma_h \\ -s\gamma_p & 0 & c\gamma_p & -d_2 s\gamma_p + d_1 c\gamma_p + d_0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The result reflected from scanning data to robot plane is:

$$\begin{cases} x_{r|i,j} = \rho_{i,j}(c\lambda_{i,j} c\gamma_p c\gamma_h - s\lambda_{i,j} s\gamma_h) + d_2 c\gamma_p c\gamma_h + d_1 s\gamma_p c\gamma_h \\ y_{r|i,j} = \rho_{i,j}(c\lambda_{i,j} c\gamma_p s\gamma_h + s\lambda_{i,j} c\gamma_h) + d_2 c\gamma_p s\gamma_h + d_1 s\gamma_p s\gamma_h \\ z_{r|i,j} = -\rho_{i,j} c\lambda_{i,j} s\gamma_p - d_2 s\gamma_p + d_1 c\gamma_p + d_0 \end{cases} \tag{3}$$

The measuring error in height direction is the following:

$$\Delta z_{r|i,j} = \frac{\partial z_{r|i,j}}{\partial \rho_{i,j}}\Delta\rho_{i,j} + \frac{\partial z_{r|i,j}}{\partial \lambda_{i,j}}\Delta\lambda_{i,j} + \frac{\partial z_{r|i,j}}{\partial \gamma_P}\Delta\gamma_P \tag{4}$$
$$= -c\lambda_{i,j} s\gamma_P \Delta\rho_{i,j} - \rho_{i,j} s\gamma_P s\lambda_{i,j}\Delta\lambda_{i,j} - (\rho_{i,j} c\lambda_{i,j} c\gamma_P + d_2 c\gamma_P + d_1 s\gamma_P)\Delta\gamma_P$$

In order to estimate the error value, the following formula can be got by formula 4. Here,

$$\Delta z_{r|i,j} = \frac{\sqrt{2}}{2}\Delta\rho_{i,j} + \frac{\sqrt{2}}{2}\times 3.48\times 10^{-3} + \frac{\sqrt{2}}{2}\times 1.74\times 10^{-4}(\rho_{i,j} + d_2 + d_1) \tag{5}$$

Where, rotating error of rotating table $|\Delta\gamma_P|_{\max} \le 0.01^\circ = 1.74\times 10^{-4}$, system error of object $\Delta\rho_{i,j} = \pm 3$ (cm) aimed at the target reflectivity changing from 10 to 10,000%, angular error of LMS291 $\Delta\lambda_{i,j} = 0.19^\circ = 3.48\times 10^{-3}(rad)$, d_1 equals to 2.5cm and d_2 equals to 7.5cm. When $\gamma_P = -45^\circ$, $|\Delta z_{r|i,j}| \le 2.2$ (cm) can be calculated by formula 5. Assumed that the terrain traversability of robot is 10cm, it must distinguish the variation in terrain about 5cm to insure the safe operation of robot. Therefore, this system can meet the performance requirement of 5cm terrain variation.

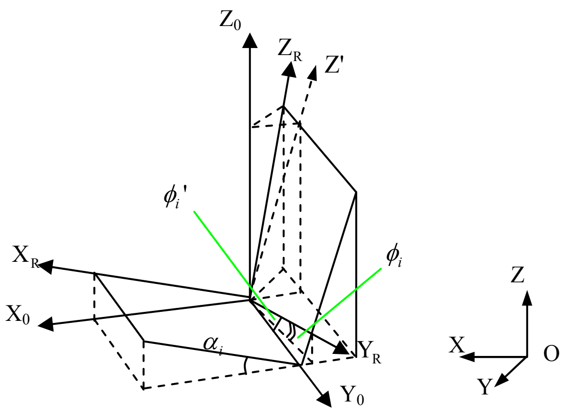


Fig. 6 Coordinate transformation from the robot reference plane to the world coordinate system

The second step is to reflect the measurement information into the world coordinate system according to the coordinates transformation of robot in 3D terrain. In this condition, the posture of robot can be presented by the state of reference centre of robot platform (x_i, y_i, z_i, θ_i, α_i, ϕ_i) where θ_i denotes the heading, α_i the pitch, and ϕ_i the roll respectively. The heading of robot is obtained from the output of fibre optic gyros, and the pitch and roll of robot are obtained from the output of tile sensor mounted on bodywork platform that make an angle of the reference horizontal plane. Then, the measured points are reflected into the world coordinate system. The equal coordinates transformation mode is adopted: the robot coordinate is translated into (x_i, y_i, z_i) firstly, then rotates θ_i angles (the heading) around the new z axis, α_i angles (the pitch) around the new y axis, and ϕ_i' angles (the roll) around the new x axis in turn. The mapping from the robot reference plane to the global coordinate system is shown as follows.

$$u|_O = {}^{O}_{O_r}T \cdot u|_{O_r} \quad (6)$$

Where,

$$
\begin{aligned}
{}^{O}_{O_r}T &= \mathrm{Trans}(x_i, y_i, z_i)\mathrm{Rot}(z_{new}, \theta_i)\mathrm{Rot}(y_{new}, -\alpha_i)\mathrm{Rot}(x'_i, \phi'_i) \\
&= \begin{bmatrix} c\theta_i c\alpha_i & -c\theta_i s\alpha_i s\phi'_i - s\theta_i c\phi'_i & -c\theta_i s\alpha_i c\phi_i' + s\theta_i s\phi'_i & x_i \\ s\theta_i c\alpha_i & -s\theta_i s\alpha_i s\phi_i' + c\theta_i c\phi'_i & -s\theta_i s\alpha_i c\phi_i' - c\theta_i s\phi_i' & y_i \\ s\alpha_i & c\alpha_i s\phi_i' & c\alpha_i c\phi_i' & z_i \\ 0 & 0 & 0 & 1 \end{bmatrix}
\end{aligned}
$$

Here, we define the uplifted direction as the positive direction, which is contrary to the rotation direction made by right hand rule, so it should rotate $-\alpha_i$ angles around the new y axis. ϕ_i' is the roll considering the rotation compensation as shown in figure 6. The transformation formula is expressed as follows.

$$\phi_i' = \arcsin \frac{\sin \phi_i}{\cos \alpha_i} \quad (7)$$

At last, a 2-D array $A[m][n]$ is used to record the terrain elevation where m, n denotes the corresponding grid coordinate in projection plane respectively. The grid with 3cm resolution is adopted in horizontal plane and with 2cm resolution in height direction.

$$m = (\mathrm{int})\frac{x_{o|i,j}}{3},\ n = (\mathrm{int})\frac{y_{o|i,j}}{3},\ A[m][n] = (\mathrm{int})\frac{z_{o|i,j}}{2} \quad (8)$$

4. Error Analysis and Filter Design

4.1 Error Analysis in 3D Terrain Mapping

In the 3D terrain figure transformed by measurement information of LMS291, there exist the following problems:

(1) Communication disturbance
There may exist the error code for LMS291 in communication with the computer system. Here, cyclic redundancy check (CRC) code is embedded in the information from LMS291 to recognize the error data packets.

(2) Noisy disturbance from environment
In the environmental lightness, there may exist some frequency near to the laser scanner, which would produce the disturbance. The features of noisy disturbance are random and discrete. It often took on the pulse noise in terrain elevation map.

(3) Data packets losing
There may occasionally lose data packets thus we can get infinite values (greater than or equal to 8192) if the measuring range is exceeded, or the reflectivity is too small, or the angle of incidence is too big.

(4) Areas obstructing
There may exist the blind area for LMS291 scan due to the obstacles obstructing. Because the environment in the blind area is difficult to be expressed, we assumes that the height of the blind area is relative to the height of 0 value in the wheel-terrain contact plane of robot.

(5) Scanning gap
There may exist the scanning gap for LMS291 with 0.5º resolution if the detecting range is rather far or the robot move forward or rotate at some speed when the LMS291

scans the environment at the 25Hz frequency. We also make the above assumption. If so, there may show the sunk drawback of object surface figure.

(6) Mixed pixel disturbance
LMS291 is based on a time-of-fight (TOF) measurement principle. When a laser spot is located at the very edge of an object, the measuring range is that of a combination of the foreground and the background objects, i.e., the range falls in between the distances to the foreground and background objects. This condition is called "mixed pixels". The mixed pixel disturbance is obviously produced in our experiment. The standard deviation of measurement data caused by mixed pixel in the polar angle direction is rather large.

4.2 Design of Dynamic Adaptive Filter (DAF)

The filter and smooth of the environmental elevation information from LMS291 is similar to the process of gray level images in some extent. The common image processing filter can be applied to the process of elevation map. However the traditional processing techniques such as smoothing filter, Gaussian filter, median filter are imperfect for all images, which may make images blurred because of the unconditional application. Certainty assisted spatial filter (CAS) is adopted in reference 16, but CAS likes the other image processing filters which are off-line to deal with the elevation map. CAS cannot reduce the disturbance in on-line navigation and is limited to the mixed pixel disturbance. Therefore, the dynamic real-time filter needs to be designed to meet the requirement of mobile robots navigation.

By the analysis of the ranging data of the mobile robot in motion, it indicates that the measured values of laser scanner have the relativity at the neighbouring scan orientation in a measurement and is also at the adjacent sampling interval in the orientation direction of each polar coordinate. Hence, dynamic adaptive filter is designed to eliminate the noise disturbance in obstacles detection. The analysis window to the measurement data ($\rho_{i,j}$, $\lambda_{i,j}$) is built as follows:

$$\begin{matrix} \rho_{i-1,j-1}, & \rho_{i-1,j}, & \rho_{i-1,j+1} \\ \rho_{i,j-1}, & \rho_{i,j}, & \rho_{i,j+1} \\ \rho_{i+1,j-1}, & \rho_{i+1,j}, & \rho_{i+1,j+1} \end{matrix} \quad (9)$$

Where, the suffix i denotes the moment measured by the number of operation cycle in the main program, that is the number of scanning data packages. A data package includes 361 measurement data in 180 degrees scanning field and the sampling period is 40ms. The suffix j denotes the number of measured point in a data package. The internal rotating mirror of LMS291 turns at 4500 rpm (75rps), and the scan time is 13.3ms with 1 degree resolution. In our system, the ranging data is obtained by two scan with 0.5 degree resolution. So, the ranging data in formula 9 have the maximum correlation in time and space. The difference $\Delta\rho_{\min}$ between $\rho_{i,j}$ and its adjacent measured values can be calculated according to the following formula.

$$\Delta\rho_{\min} = \min\{|\ \rho_{t+i,s+i} - \rho_{i,j}\ |, \\ t,s = -1,0,1 \ \&\ t \neq 0, s = 0 \ \&\ t = 0, s \neq 0\} \quad (10)$$

When the environment is static and the robot is stationary, the rationality of $\Delta\rho_{\min}$ can be estimated according the standard deviation of different ranging scale by experiments. When they are both dynamic, the velocity of mobile robot and target should be considered. In such condition, the threshold value of $\Delta\rho_{\min}$ can be set as follows.

$$\delta(\rho,v) = \sigma(\rho) + \frac{1}{25}(|\,v_{goal}\,| + |\,v_{robot}\,|) \text{ (cm)} \quad (11)$$

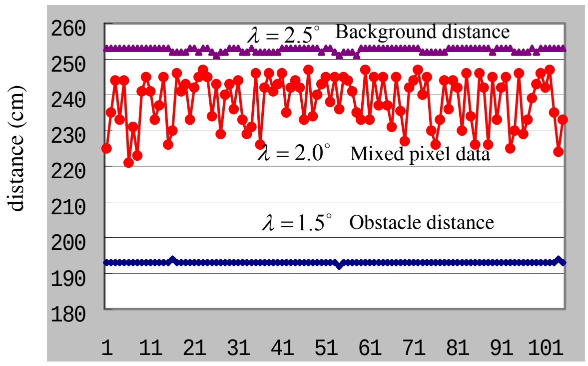
Where, $\sigma(\rho)$ can be estimated by the standard deviation of different range according to the environment condition or robot motion by table 2.

If $\Delta\rho_{\min} > \delta(\rho,v)$, then the measured value $\rho_{i,j}$ is regarded as the measurement noise and does not used to calculate the elevation map and detect obstacles. The dynamic target in operating environment is mainly the foot passenger, and their velocity is less than 100cm/s. When the robot moves at the speed of 25cm/s, the measured value $\rho_{i,j} = 400\text{cm}$, then $\delta(\rho,v) = 3 + \frac{1}{25}(|100| + |25|) = 8\text{cm}$.

In order to realize DAF, the measured value of laser scanner at the current moment is saved in storage buffer. After the measured values at the next moment are obtained, the analysis among the moment i-1, i, i+1 is implemented, which means that the delay about a sampling period will be brought. For mobile robot, this cannot cause too large effect because its velocity is not too high. DAF is used in the following experiments, and the results show it can validly filter the disturbance when the measured value of laser scanner is converted into the elevation information in the world coordinate system.

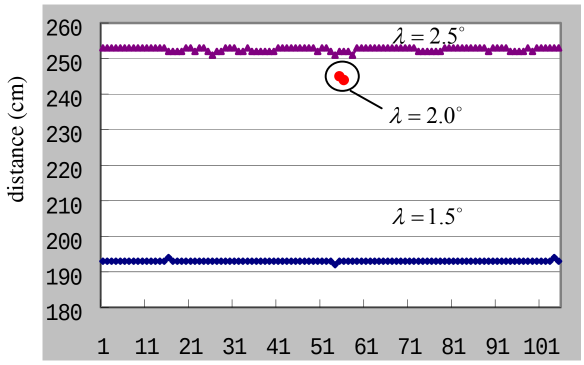
(1) Experiment for fixed target when robot is stationary.
First, we use DAF to filter ranging data for fixed target when robot is stationary. If robot is stationary and target is fixed that is $v_{goal} = 0$ and $v_{robot} = 0$, then $\delta(\rho,v) = 1\,\text{cm}$. Aimed at mixed pixel disturbance (see figure 7(a)), DAF is used to deal with the ranging data. It can be seen the

filter effect is obvious when $\lambda = 2.0^\circ$ in figure 7(b) where the mixed pixel disturbance can be rejected about 98%.



time (1:40ms)

(a) Ranging data with mixed pixel disturbance



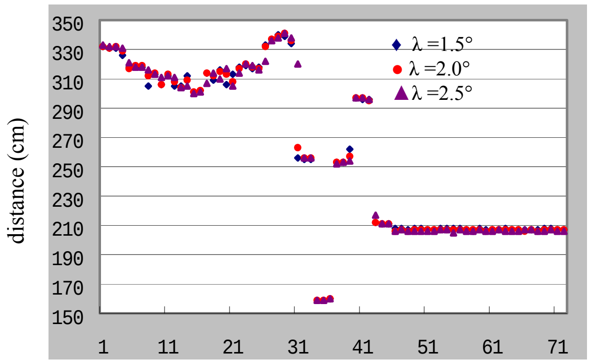
time (1:40ms)

(b) Data distribution after DAF

Fig. 7 DAF for stationary condition

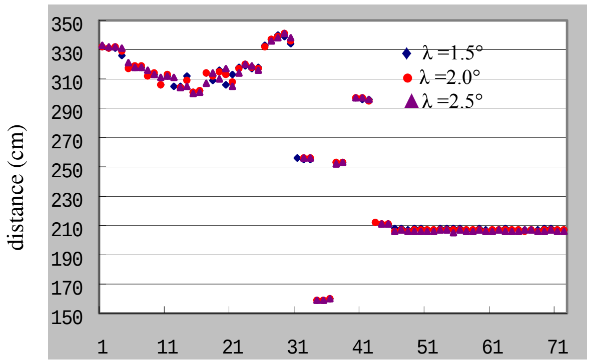
(2) Experiment when the rotating table rotates.

Then, we use DAF to filter ranging data when the rotating table rotates. Here $\delta(\rho, v) = 3$ cm. In figure 8, it can be seen that some discrete data are rejected.



time (1:40ms)

(a) Data distribution before DAF



time (1:40ms)

(b) Data distribution after DAF

Fig. 8 DAF for the rotation condition of rotating table

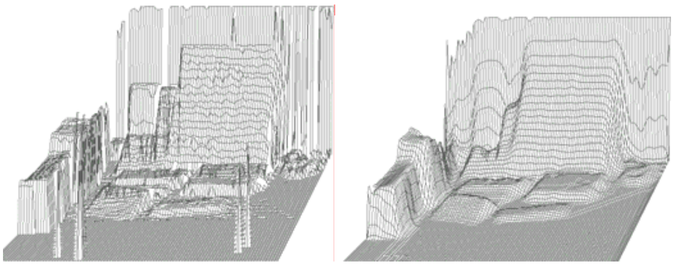
4.3 Design of Smoothing Filter

In addition, aimed at the object surface problem caused by scanning gap, the smoothing filer based on the Gaussian distribution is introduced to make a weighted smoothing filter to the adjacent grids and an interpolation to the default grids.

$$A'[m][n] = \frac{\sum_{i=-R}^{i=R} \sum_{j=-R}^{j=R} A[i+m][j+n] e^{-k(i^2+j^2)}}{\sum_{i=-R}^{i=R} \sum_{j=-R}^{j=R} e^{-k(i^2+j^2)}} \quad (12)$$

Where: k>0, R>0. R denotes the scale of neighboring areas that need to make a smoothing filter, k denotes the smoothing factor where the smaller k is, the better the smoothing effect is. The weighted smoothing filter can also farther weaken the disturbance from the mixed pixel. The rank number of smoothing filter should not be overhigh as the smoothing filter has a blurred and passivating effect on the edge of objects. We can see the filter effect on the elevation map after the median filter and then the 2-rank weighted smoothing filter from figure 9.

(a) Scan to the sundries of the wall corner in pitch direction



(b) 3D elevation map from LMS291 before and after filter

Fig. 9 Mapping of the wall corner

5. Terrain Analysis and Experiments for Obstacles Detection

5.1 Terrain Analysis

It need to analysis the terrain using the elevation map for mobile robot running in unstructured environment. In motion, mobile robot scans the front area at some pitch degree by laser scanner and the scanning information of the front area is converted into the elevation map. In order to classify the free area and obstacle area in navigation, terrain flatness analysis is implemented so as to guide mobile robot to avoid obstacles with formula (13) and (14).

$$g[m][n] \approx \max\{|A[m][n] - A[m+i][n+j]| i, j = -1,0,1\} \quad (13)$$

Where, $g[m][n]$ denotes the grads module of the changeable terrain elevation corresponding to the *m* and *n* coordinate in the plane. By the analysis of the 3×3 grid area, the maximum changeable value of neighboring terrain elevation is regarded as the approximate grads module.

Formula (14) is used to estimate the free or obstacle area in front of mobile robot. In our experiment, the threshold of the changeable height is 2 that correspond to the 4cm variation in actual environment. When the rotating table rotating in the pitch direction, mobile robot is only able to observe a piece of scanning thread. So, the action of mobile robot must rely on the accumulated environment map $map[m][n]$. The value of $map[m][n]$ denotes the unknown area if it is –1, the free area if it is 0 and the obstacles area if it is greater than or equals to 1.

$$map[m][n] = \begin{cases} map[m][n] + 2 & , \ if \quad g[m][n] > 2 \\ 0 & , \ if \quad g[m][n] \le 2 \end{cases} \quad (14)$$

If it is obstacle grid, the value of $map[m][n]$ pluses 1. the bigger the value is, the higher the likelihood that it is obstacle is and the longer the memory time is. The maximum value of $map[m][n]$ is limited to 9. In practice, the environment may be dynamic and the localization error for mobile robots navigation may exist. Therefore, it needs to update the obstacles information in the memory of mobile robot. The oblivious operation is adopted to update the memory information periodically that means the operation subtracting 1 is carried out for the 300×300 area centered by mobile robot in the map per 10 seconds.

In real-time running, the flatness of 100×10 grid area in front of mobile robot is estimated in every monitoring period. The data processing procedure based on the scanning information of laser scanner is shown in figure 10.

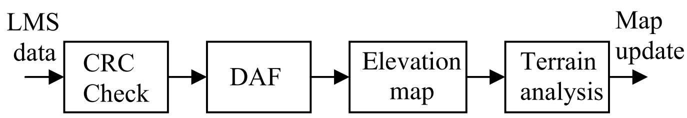
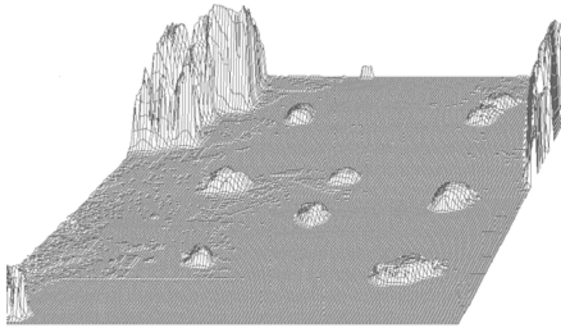


Fig. 10 Data processing procedure based on laser scanner

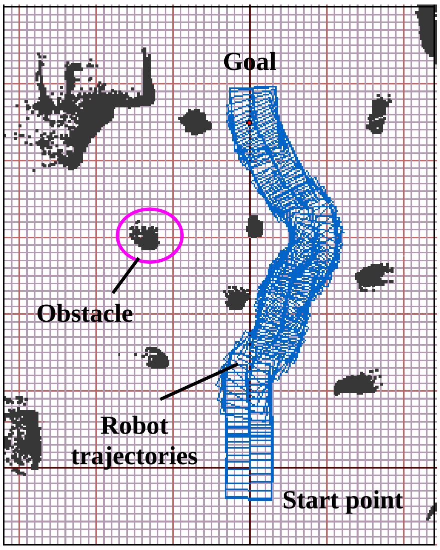
5.2 Experiments for Obstacles Detection

This 3D perceptive system can realize the overall observation to the ambient environment by the flexible rotation of its heading when robot is stationary. So, it is suitable for robot to map the local environment and to realize the self-localization. In advance, robot is also able to realize the terrain elevation mapping and terrain analysis by looking out upon the front of terrain to accumulate the measurement information.

(a) Obstacles detection in motion



(b) Elevation map with filter



(c) Obstacle avoidance based on terrain analysis

Fig. 11 Obstacle detection and terrain analysis

With experiments in figure 9, laser scanner make an observation to the terrain at some angle (-45º) by robot motion to scan the environment and accumulate the scanning information with the different height obstacles scattering in the operating environment. The programming software is Visual C++ and the program is able to display the local obstacles of 100×100 grids. The grid resolution is 3×3 (cm) in horizontal plane and 2×2 (cm) in height direction in figure 9 (b). Figure 9 (c) depicts the areas whether it is able to traverse or not segmented by the analysis of obstacles grids according to the elevation map of terrain, so robot is guided to avoid obstacles. In this experiment, the velocity of robot ranges from 20 to 35 cm/s.

6. Conclusions

It designs and realizes a perceptive system using laser scanner LMS291 to measure the elevation information of 3D environment in the paper.

With the statistic analysis of data alignment, ranging accuracy of laser scanner under the influence of various target surface property is studied. At the same time, the angular resolution is determinated by the measuring method of mixed pixel and the error model is built by the experiments on ranging performance of laser scanner.

Based on the description of system architecture, it fuses the information of robot's pose using dead-reckoning method and the range to obstacles by laser scanner. A terrain mapping method is proposed and an elevation map is built for the purpose of terrain analysis according to the corresponding coordinates transformation.

It also designs the dynamic adaptive filter to reduce the disturbance from the pulse noise and mixed pixel and use the smoothing filer based on the Gaussian distribution to compensate the drawbacks of scanning gap in object surface figure. The method for obstacle detection based on dynamic adaptive filter is flexible and can realize the reliable obstacle detection and terrain analysis under unstructured environment

The application of this perceptive system for mobile robot is in 2 facets. One is make an optimal decision to reduce the blind action with the environmental observation by this system when robot is stationary. The other is to analyze the front of area whether has obstacles or not with the terrain elevation information from the LMS291 scan at some angle when robot is moving.

This system has good flexibility for the perception in 3D environment and can realize the obstacle detecting and terrain analysis. So, it can provide a strong support for path planning and self-localization.

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Zi-Xing Cai received the B.S. in Electrical Engineering from Xi'an JiaoTong University in 1962. He is a Senior Research Scientist and Head of Intelligent System and Software Lab at Central South University. His research interests include intelligent control, robotics, and evolutionary computation.