# A Method for Mobile Robot Obstacle Avoidance Based on Stereo Vision

Meng Chen[1]
School of Automation Science and Electrical Engineering
Beihang University
Beijing, China
geminichenmeng@gmal.com

Zhihao Cai[2]
Institute of Unmanned Aerial Vehicles
Beihang University
Beijing, China
caizhihao@buaa.edu.cn

Yingxun Wang[3]
School of Automation Science and Electrical Engineering
Beihang University
Beijing, China
wangyx@buaa.edu.cn

***Abstract*—An obstacle avoidance method is researched based on stereo vision by using Pioneer3-AT wheeled mobile robots as research platform. Locating obstacles is realized quickly by means of image segmentation and stereo vision algorithm which can separate obstacles from the background and stereo match their contour features with the stereo vision calibration results to get the spatial point for 3D reconstruction. The obstacle avoidance method uses stereo vision and sonar sensors working cooperatively to get the information of the obstacles in the vicinity of the robot. Fuzzy logic control algorithm is adopted to avoid collision and bypass the enroute obstacles. In the development environment of Visual C++ and OpenCV, the validity and effectiveness of the method has been demonstrated in achieving the task of evading obstacles. The method is simple and quick which is significant for the further navigation.**

***Keywords*—Image Segmentation; Stereo Matching; 3D Reconstruction; Obstacle Avoidance**

## I. INTRODUCTION

The mobile robot is widely used in all kinds of fields, such as Cargo handling, planetary exploration, undersea operations, disaster relief and so on. And its environment information is almost unknown or uncertain [1]. As an important method, stereo vision is widely considered to perceive the surrounding environment because it has the significant advantage of providing a large amount of data information of environment, which makes the 3-D reconstruction work become more easy [2]. All those characteristics are vital for the high adaptability navigation of mobile robots, during which obstacles avoidance is a basic function. But the complex and time-consuming algorithm for stereo vision is not adapted to the real-time mobile robot vision system well enough and has many problems in practical applications. Therefore, how to quickly detect and avoid obstacles according to the surrounding environment is one of the key goals in this paper. For an autonomous local obstacle avoidance purposes, a simple and quick method is presented in this paper to recognize obstacles with obvious contour features from background. And sonar sensors are utilized to compensate blind detection of stereo vision in obstacle avoidance process.

## II. STEREO CALIBRATION AND 3D RECONSTRUCTION

### A. Camera model

The relation that maps the point $Q$ in the physical world with coordinates $(X,Y,Z)$ to the point $q$ on the projection screen with coordinates $(x,y)$ is decided by camera mathematical model. The pinhole camera model in Fig. 1 is used when it comes to describe a single camera.

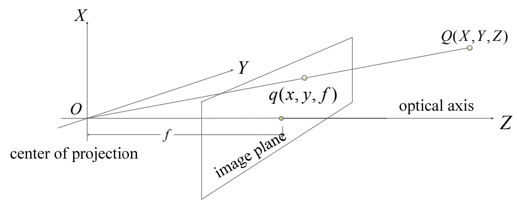


Figure 1. The Model of Pinhole Camera

A point $Q=(X,Y,Z)$ is projected onto the image plane by the ray passing through the center of projection, and the resulting point on the image plane is $q=(x,y,w)$.

$$q=MQ, q=\begin{bmatrix}x\\y\\w\end{bmatrix}, M=\begin{bmatrix}f_x & 0 & c_x\\0 & f_y & c_y\\0 & 0 & 1\end{bmatrix}, Q=\begin{bmatrix}X\\Y\\Z\end{bmatrix} \quad (1)$$

$c_x$ and $c_y$ are the offset of optical axis and the imager chip center. The focal length $f_x$ is the product of the physical focal length of the lens and the size $s_x$ of the individual imager elements. Similar statements hold for $f_y$ and $s_y$.

$M$ is called the camera intrinsic matrix and the point $q$ is in homogeneous coordinates[3].

## B. Stereo calibration and Stereo Rectification

Stereo calibration is the process of computing the camera parameter matrix. And it is often used to get rotation matrix and translation matrix which decides the geometric relationship between two cameras and the lens distortion vector to correct the lens distortions.

The stereo calibration is completed by using a method proposed by Zhang [4]. A single-channel chessboard of 9 lines and 6 columns in a pattern of alternating black and white squares is selected as the calibration object as shown in Fig. 2. The interior corners are located by translating and rotating the chessboard at different angles before the stereo camera. The coordinates is defined such that all of the points on the chessboard had a Z-value of 0.

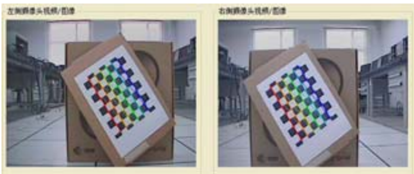

Figure 2. Stereo Calibration Pictures

A calibrated camera is already prepared for stereo rectification which is the process of correcting the individual images so that they appear as if they had been taken by two cameras with row-aligned image planes. With such a rectification, the optical axes of the two cameras are parallel. Bouguet algorithm[5] is put forward for stereo correction using the rotation and translation matrix. This method ensures the two image planes align exactly. And stereo correspondence will be easier because image rows between the two cameras will be row-aligned after rectification. Reliability and computational efficiency are both enhanced by having to search only one row for a match with a point in the other image.

## C. Three-dimensional reconstruction

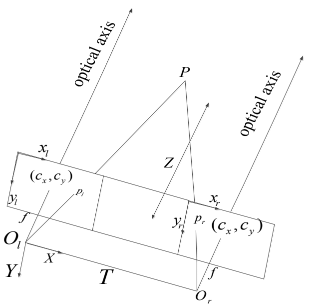


Figure 3. Ideal Stereo Vision System

In an ideally right-handed stereo coordinate system above, left camera's center of projection is supposed to be the origin of the camera coordinates and the z-axis is perpendicular to the image plane. The disparity of a real spatial point between relevant pixels in two different images can be computed by based on principle of triangulation [6]. Then the 3D depth can be derived given disparity d and 2D point $(x, y)$.

$$Q\begin{bmatrix} x \\ y \\ d \\ 1 \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \\ W \end{bmatrix} \quad Q = \begin{bmatrix} 1 & 0 & 0 & -c_x \\ 0 & 1 & 0 & -c_y \\ 0 & 0 & 0 & f \\ 0 & 0 & -1/T_x & (c_x - c_x^{'})T_x \end{bmatrix} \tag{2}$$

# III. STEREO MATCHING BASED ON OUTLINE FEATURES

Real-time requirements for visual navigation are very important. To reduce the computational burden of stereo matching process, feature-based match is proposed as it can obtain more reliable match results and fast speed. In this paper, the mobile robot wandered in the indoor environment and the matching method based on sparse feature is consistent with it. As the chosen feature information, contours which can be got to enhance the credibility of matching have a better continuity than corners. Then a window-based feature points matching algorithm is used to obtain disparity map.

## A. Contour feature extraction

The RBG format images are converted to gray images after stereo rectified in Fig. 4. Then the morphology algorithm is used not only to remove noise, isolate individual elements, and join disparate elements, but also to find obstacles which are intensity holes or bumps in an image as shown in Fig. 5. After opening operation, the repeatedly using of closing operation can clearly distinguish the obstacles region from the background. Finally the contour feature is obtained through Canny algorithm in Fig. 6. The most significant new character to the Canny algorithm is that it tries to assemble the individual edge candidate pixels into contours. This means that there are two thresholds, an upper and a lower [7]. And the two thresholds need to go through many experiments before determined.

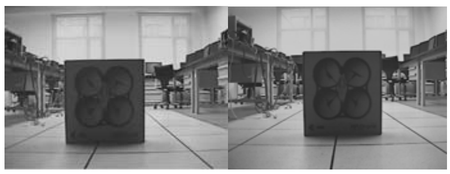

Figure 4. Gray Pictures

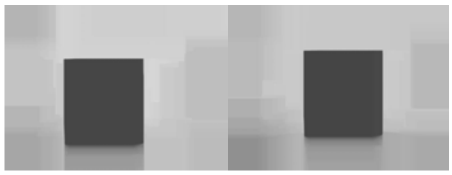

Figure 5. Morphological Pictures

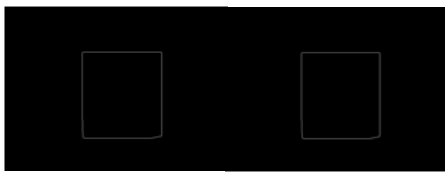

Figure 6. Contour Pictures

This simple method has a good usability. The experiments show that the contours of obstacles can be detected in 3-meter range which is suitable for the indoor or corridor environmental characteristics.

### B. *Window-based feature points matching*

This matching method [8] is to find matching points $p_1 = (x_1, y_1, 1)^T$ and $p_2 = (x_2, y_2, 1)^T$ between the left and right stereo rectified images and can effectively reduce the matching error. $p_1$ and $p_2$ are respectively centers of $N \times N$ size windows. All the points in the window whose center is $p_1$ constitute the vector $v_1$ shown in Fig. 7 and similar statements hold for $v_2$.

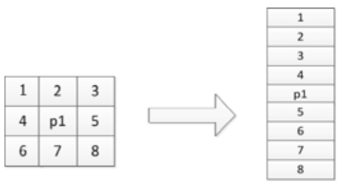


Figure 7. Vector of Gray Window

Smaller the angle $\theta$ between two vectors $v_1$ and $v_2$ is, higher the degree of matching points $p_1$ and $p_2$ is. The angle between two vectors is calculated as follows:

$$\cos\theta = \frac{v_1^T v_2}{\| v_1 \| \| v_2 \|} \quad (3)$$

When $\cos\theta = 1$, two vectors have the best match. Conversely, when $\cos\theta = 0$, two vectors have the worst match. Since no match points are considered to be removed out during the matching process, the minimum value of $\theta$ is 0.9 which means that when $\theta$ is less than 0.9, there are no match points.

For each feature in the left image, the corresponding row is searched in the right image for a best match with window-based matching algorithm. After rectification, each row is an epipolar line, so the matching point $p_1$ with the largest angle in the right image must be along the same $y$-coordinate of $p_2$ as in the left image. The larger the disparity is, the closer the distance is. Finally the largest disparity of the image is utilized as the output.

## IV. MOBILE ROBOT OBSTACLE AVOIDANCE CONTROL

Firstly the wireless transmission link between stereo camera and Host PC is vulnerable, so the captured image data from stereo camera could not arrive at the Host PC occasionally. Secondly the stereo camera without a rotating platform is fixed at the frond-middle of the robot, and the field of view is also limited especially when the mobile robot is so close to the obstacle where the collision may occur and avoidance measures needs to be taken. Considering the two factors above, this paper proposes a method using sonar sensors to get the environment information in left-front and right-front direction. The information from sonar sensors and stereo camera is used corporately to decide the direction and turning angle of the mobile robot during the obstacle avoidance process.

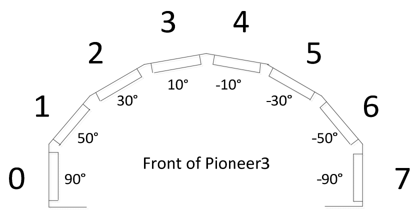


Figure 8. Sonar Ring of Pioneer 3

As shown in Fig. 8, the sonar positions in Pioneer 3 sonar arrays are fixed: one on each side and six facing outward at 20-degree intervals. An adaptive fuzzy control system of 3 inputs and 2 outputs is implemented. The vision area of Pioneer 3 AT is divided into three parts: front, left-front and right-front. 0~1 and 6~7 are selected to get the distance of respective right-front and left-front. The minimum value of each group is chosen as input parameters and the front distance is given by the stereo vision.

The input variables of the fuzzy controller are $x_1, x_2, x_3$ representing the left-front, right-front and front distance of the near obstacle respectively. The output variables from the fuzzy controller are $y_1$ and $y_2$ representing the left and right wheel speeds which decide two kinds motion of Pioneer 3: linear and circular motion.

The fuzzification of the inputs and outputs are defined by using a triangular membership function [9] as shown in Fig. 9 and Fig. 10.

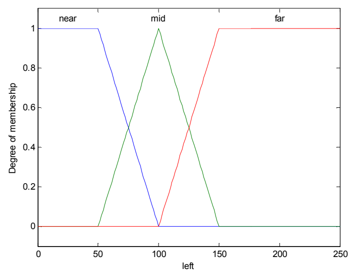


Figure 9. Input Membership Function

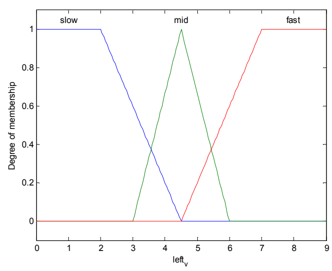


Figure 10. Output Membership Function

The essential rules are formulated for the proposed controller given in Fig. 11:

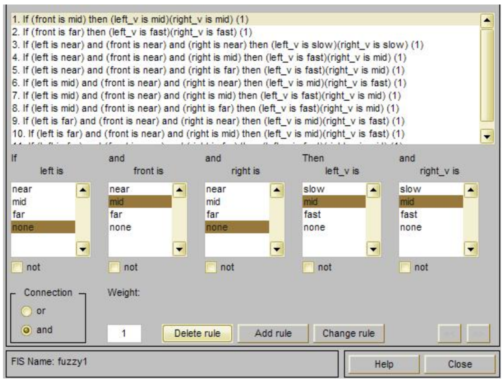


Figure 11. Fuzzy Control Rules

At the end, the outputs of the controller should be a crisp signal in order to be useful. And the center of gravity method is used in the proposed controller [10].

## V. THE STRUCTURE OF OBSTACLE AVOIDANCE TEST SYSTEM

This paper uses Pioneer3-AT wheeled mobile robots as research platform. Pioneer is a family of mobile robots which is one of the most high-performance mobile robot platforms firstly coming into China. The Pioneer3-AT mobile robot platform operates as the server in a client-server environment: Its microcontrollers handle the low-level details of mobile robotics. To complete the client-server structure, the platform requires an onboard computer connected with the robot's microcontroller via the HOST serial link to run client software for high-level, intelligent robotics command and control operations [11]. In this paper, the onboard PC computer is visited by the remote desktop and responsible for the evading obstacles task.

Double client-server structure is adopted: The microcontrollers and onboard computer of Pioneer3-AT constitute a client-server structure. The other client-server structure is composed of a Host PC operating as client and an onboard computer operating as server contacted each other by Wi-Fi. The Host PC takes the responsibility to calculate the environment information from stereo camera to get the depth information of obstacles and transmit the data to onboard computer via UDP network protocol. The data is used to plan and control mobile robot motion after further processing. The system designed for real-time obstacle avoidance is shown in Fig. 12.

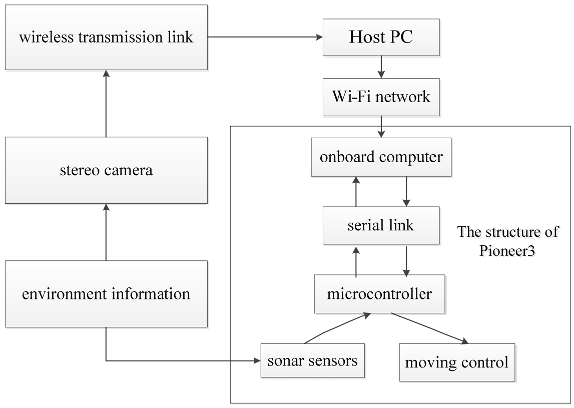


Figure 12. The Overall Structure of Obstacle Avoidance Test System

The operation of the system can be briefly explained as follows. A stereo camera mounted at the middle-front of Pionner3-AT in the indoor environment transfers the captured image data flow to Host PC by a wireless transmission link. A stereo image processing subsystem coded in VC++ is running in Host PC for extracting obstacles, stereo feature matching and 3D reconstruction. The current stereo images processing subsystem requires pre-knowledge of camera calibration. The onboard computer receives the indoor surrounding environment information from Host PC via Wi-Fi and sonar sensors via the standard SIP. The depth information calculated in Host PC and detected from sonar sensors is used together as inputs for fuzzy controller operating in onboard computer. According to the membership function and fuzzy control rules on the basis of practical experience, the decision signals of velocity parameter from fuzzy controller are sent to the microcontrollers to drive the mobile robot moving.

## VI. THE RESULTS

To test the method applied for obstacle avoidance in this paper, experiments were carried out. Beginning of the experiment, a remote desktop visited the onboard PC where the obstacle avoidance control program started firstly. Then an image processing subsystem in host PC began running to calculate the obstacle depth information and sent it to the onboard PC through WIFI. The mobile robot started moving at the speed of 350mm/s and began to avoid obstacles approximately 90mm away.

Fig. 13 illustrates that the fuzzy control algorithm is verified by simulation under MobileSim environments.

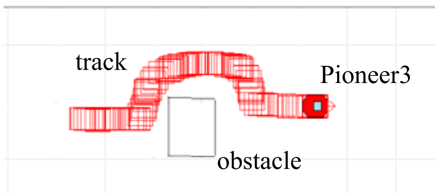


Figure 13. The Simulation of Obstacle Avoidance

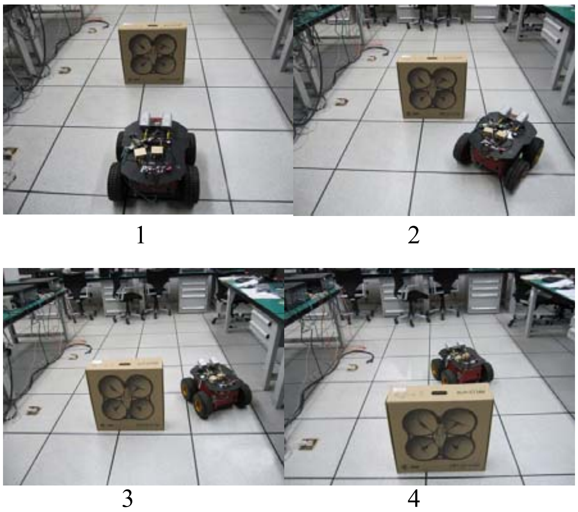


Figure 14. Obstacle Avoidance Processing

Firstly, the Pioneer 3 was going forward in picture 1. Once it detected obstacle, it began to bypass the enroute obstacle as show in picture 2 and picture 3. At last the obstacle is successfully avoided given in picture 4. Fig. 14 illustrates that the Pioneer 3 in indoor environment has been proved working well.

## *VII.* CONCLUSION

This paper proposes a simple and quick stereo vision image processing method which can separate the obstacles from background in situations where there is some degeneracy in the scene, such as the case that scene structure lies in a single plane. The stereo matching of contours can overcome the shortcomings of corners. Meanwhile the real-time requirements can also be met. The obstacle avoidance controller is designed based on fuzzy logic algorithm. Assisted by sonar sensors, the stereo vision provides a good guarantee for the avoidance.

The experiment result shows that the mobile robot can autonomously bypass the obstacles and the system is an effective application of obstacle avoidance methods by using stereo camera.

## ACKNOWLEDGMENT

The author is indebted to Mr. Wu who provided Pioneer 3-AT for the experiments and gave his constructive suggestions, and kindly eliminated many of the errors in it. The author is also own the sincere gratitude to friends and fellow classmates who offered their helps and times. And in the end, the author is appreciated these professors who watch this paper in busy time.

## REFERENCES

[1] Ying Xiong, Shide Xiao and Feng Zha, “An avoiding obstacle algorithm of mobile robot under complex unknown environments”, Mechanic Automation and Control Engineering (MACE), in Hohhot, Second International Conference , pp.1019 – 1022, July 2011.

[2] Li Linhui, Zhang Mingheng, Guo Lie and Zhao Yibing, “Stereo Vision Based Obstacle Avoidance Path-Planning for Cross-Country Intelligent Vehicle”, Fuzzy Systems and Knowledge Discovery, FSKD '09. Sixth International Conference, vol. 5, pp. 463 – 467, Aug. 2009.

[3] Gary Bradski and Adrian Kaehler , “Learing OpenCV”, in the United States of America, Published by O’Reilly Media, Inc., pp. 407-409.

[4] Z. Zhang, “A flexible new technique for camera calibration”, IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 22(11), pp. 1330-1334, 2000.

[5] Gary Bradski and Adrian Kaehler , “Learing OpenCV”, in the United States of America, Published by O’Reilly Media, Inc., pp. 433-436.

[6] Ling Zou, Yan Li, “A method of stereo vision matching based on OpenCV”, Audio Language and Image Processing (ICALIP), International Conference , in Shanghai, pp.185-190, Nov. 2010

[7] Gary Bradski and Adrian Kaehler , “Learing OpenCV”, in the United States of America, Published by O’Reilly Media, Inc., pp. 151-153.

[8] Chen chengyong, Liusheng, “Computer vision technology based on OpenCV”, Science press, pp. 342-347

[9] Mendez, M.A.O., Madrigal, J.A.F., “Fuzzy Logic User Adaptive Navigation Control System For Mobile Robots In Unknown Environments”, Intelligent Signal Processing, IEEE International Symposium on, pp. 1-6, Oct. 2007.

[10] Raguraman, S.M.,Tamilselvi, D. and Shivakumar, N., “Mobile robot navigation using Fuzzy logic controller”, Control, Automation, Communication and Energy Conservation, 2009 International Conference, pp. 1-5, Jun 2009.

[11] Pioneer 3 Operations Manual, MobileRobots Inc, Jan 2006, pp. 3-5