Fuzzy Target Tracking and Obstacle Avoidance of Mobile Robots with a Stereo Vision System

Chan-Hong Chao, Bo-Yan Hsueh, Ming-Ying Hsiao, Shun-Hung Tsai, and Tzuu-Hseng S. Li

Abstract

In this paper, a two-level hierarchical intelligent control system is developed on a mobile robot to deal with target tracking and obstacle avoidance tasks. A stereo vision subsystem is first introduced. It can perceive video information in the environment to locate objects, including locating targets and obstacles precisely. This subsystem possesses two CCD cameras mounted on the top of a robot to obtain images from the surroundings. And then, based on the sensed image data in the indoor environment, a robot behavior decision-making subsystem with a fuzzy control strategy is proposed for target tracking and obstacle avoidance. Under this decision-making strategy, the robot can respond correctly to complete the desired task. Finally, site experiments are performed to show that the proposed schemes are feasible and effective.

Keywords: Fuzzy control, Mobile robot, Obstacle avoidance, Stereo vision, Target tracking

1. Introduction

Mobile robots offer widespread applications, such as Mars exploration, material transportation, military missions, guidance tasks, and security systems. Visual feedback is an important function of mobile robots for path tracking, target tracking, and obstacle detection and avoidance.

When the mobile robot navigates in an indoor environment, it is important for it first to recognize objects. Methods are presented to find the target and obstacles, including ultrasonic sensors [1-2], laser range finder [3-4], radio detector [5], and infrared sensors [6,18]. However, these methods have some defects; for example, the searching angle and searching distance are limited. In order to solve these problems, some researchers have proposed using vision-based techniques including a single CCD camera [7-8], an omnidirectional vision system [9-10], stereo vision [11-12], and three cameras [13].

There have been many studies done on the target tracking problem [14-21]. A stable target tracking control that considers collision avoidance with obstacle has been proposed [14-15]. In [16], an approach to tracking a person by using stereo vision has been developed. Also, a color signal has been applied to the tracking and matching of objects [17]. The target tracking system is designed to use fuzzy control algorithms [18-24].

In recent years, stereo algorithms have been widely applied because distance information can be gathered. Therefore, we put the stereo vision system on the mobile robot to improve the target tracking and obstacle avoidance. More accurate position information is obtained from the real-time stereo system. In this paper, the two-level hierarchical system is developed to execute target tracking and obstacle avoidance. The first subsystem is the vision system, which perceives the environment information including target and obstacles. Based on the target position in the indoor environment, the target tracking strategy or obstacle avoidance strategy for a mobile robot will be selected. In this subsystem, the distance between the mobile robot and the target or obstacles is considered first. Then, the second subsystem is the intelligent control of a mobile robot.

This paper is organized as follows. In Section 2, the hardware architecture of the mobile robot is introduced. In Section 3, the image processing techniques are described. In Section 4, the fuzzy control strategy of the mobile robot for target tracking and obstacle avoidance is developed. In Section 5, some experiment results demonstrate the validity of the above methods. Finally, the conclusions are presented in Section 6.

2. Hardware Architecture of the Mobile Robot

The processing procedure of the mobile robot is briefly described as follows. The mobile robot is composed of three major modules as shown in Figure 1.

The first part is the vision system. The vision system consists of two CCD cameras, and an image processing program. CCD cameras are mounted on the top of the

---

Corresponding Author: Tzuu-Hseng S. Li is with the aiRobots Laboratory, Department of Electrical Engineering, National Cheng Kung University, 1 University Road, Tainan, Taiwan 701, R.O.C.
E-mail: thsli@mail.ncku.edu.tw
Manuscript received April 15, 2009; revised August 1, 2009; accepted September 1, 2009.

mobile robot continuously capture the image information of the environment. The mainly work of the image processing program is to analyze the information of the target and obstacles and to transmit the processed data to the strategy decision module.

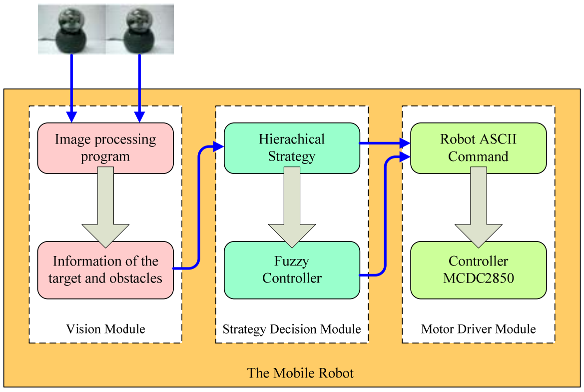


Figure 1. The mobile robot system.

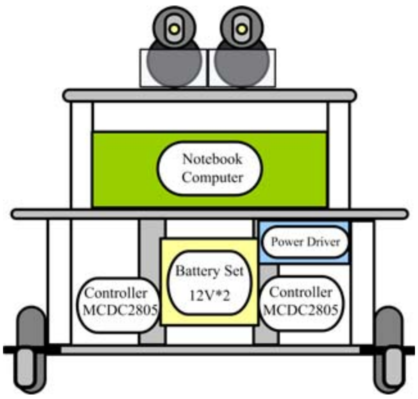


Figure 2. The configuration of the mobile robot.

Based on the information extracted from vision system, the strategy decision module makes a determination of an executing strategy. Simultaneously, commands are obtained through a fuzzy controller and then transmitted to the motor driver module. The motor driver module will decode and execute the commands. Hence, our mobile robot can choose the strategy of target tracking mode or obstacle avoidance mode during the navigation in the corridor.

The hardware architecture of the mobile robot is shown in Figure 2. The mobile robot consists of the stereo vision system, the notebook computer, the batteries, two motors, two differential wheels, four passive wheels, and so on.

3. Stereo Vision System

This section describes how to calculate the depth of objects, which is one of the most critical tasks for computer vision. Two CCD cameras take pictures of the same scene, but they are separated in the x-direction by some distance. In the stereo vision system [25], it is most important to find the corresponding points of the match parts. The match parts search the correspondence between the pair images. The best match part is used to calculate the distance, and it is used in our mobile robot to detect the distance of obstacles and target.

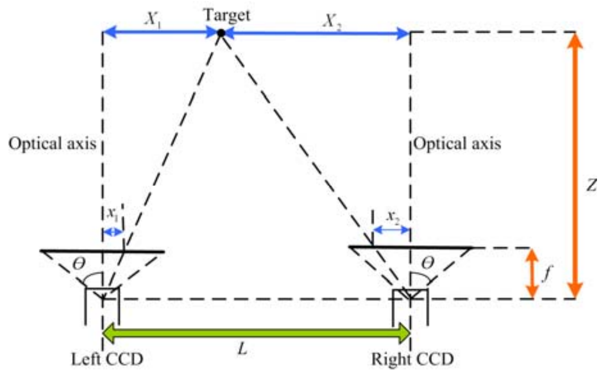


Figure 3. Triangulation of two parallel cameras.

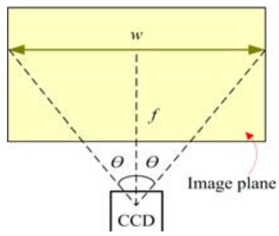


Figure 4. The maximum visual angle (2θ) of CCD.

Figure 3 assumes that the two CCD cameras are set on the same height of the surface and that the two optical axes are parallel. The real depth Z of the target in the world coordinate can be calculated by triangulation. L is the distance between two optical axes, and f is the focal length of a CCD camera. The maximum visual angle of CCD is 2θ. The distance from the target to the left camera optical axis is X_1, and x_1 is the projective length of X_1 on the left image plane. The distance from the target to the right camera optical axis is X_2, and x_2 is the projective length of X_2 on the right image plane.
From Figure 3, we can obtain

$$X_1 = \frac{x_1}{f} Z, \quad X_2 = \frac{x_2}{f} Z \tag{1}$$

$$L = X_1 + X_2 = \frac{Z}{f}(x_1 + x_2) \tag{2}$$

$$Z = \frac{fL}{(x_1 + x_2)} \tag{3}$$

Figure 4 shows the relative triangulation between the CCD cameras and image plane. The maximum visual angle of CCD is 2θ, w is the width that the CCD projects on the image plane, and the CCD focal length is f. Then, we can find the relationship:

$$w = 2f\tan\theta \quad (4)$$

Substitute Eq. (4) for Eq. (3), the depth Z can be rewritten as follows

$$Z = \frac{wL}{\left[2\left(x_1 + x_2\right)\tan\theta\right]} \quad (5)$$

Vision system is an important part for mobile robot. The robot can see and recognize various images by using two CCD cameras which are the eyes of the mobile robot. It detects the environment and searches the important features of obstacles and targets. The vision system is composed of two CCD cameras that are used to detect obstacles and target. According to the disparity between two CCD cameras, their distances from the robot to obstacles or to target will be known. The mobile robot will compare distances between target and obstacles, and then the control strategies which include target tracking mode and obstacle avoidance mode will be selected. So the mobile robot can find the safe region to avoid the collision with obstacles, and the mobile robot moves toward the target center.

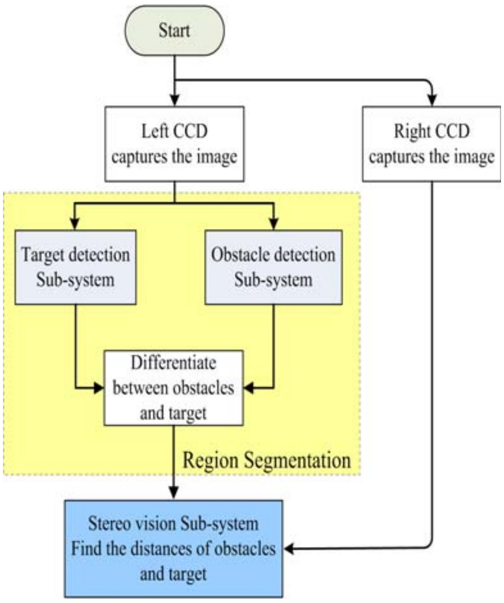


Figure 5. The procedure of vision system.

Figure 5 shows the procedures of vision system, the left CCD camera and right CCD camera capture the image individually. In order to reduce processing time, only left CCD camera deals with the image processing including target detection sub-system and obstacles detection sub-system. We can get the target candidate and obstacle candidates, and target candidate will be included in obstacle candidates. Therefore, target must be separated from obstacle candidates. We find the target and obstacles that mobile robot will track and avoid respectively. In other words, the purpose of region segmentation is to differentiate target with obstacles. As target and obstacles are detected in left image, they will also exist in right image. Therefore, stereo vision sub-system will search the right image to find corresponding region of target and obstacles that we had detected in left image. Finally, the depth of target and obstacles can be obtained by using Eq. (5).

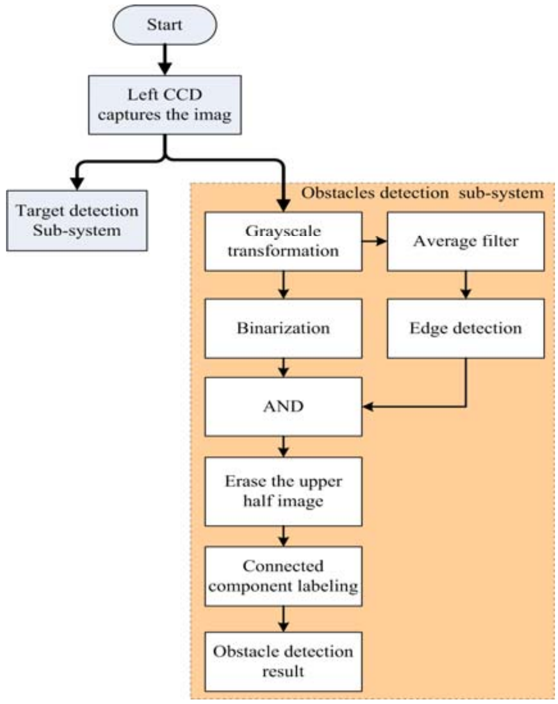


Figure 6. The procedure of obstacles detection.

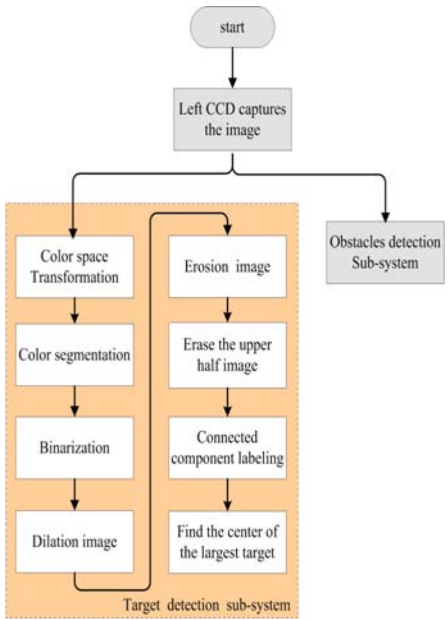


Figure 7. The procedures of target detection.

A. *Obstacles detection*

This section describes the segmenting or searching approach that is possible region of obstacles. Figure 6 shows the procedures of obstacles detection sub-system. As left CCD camera captures the image, and some image processing techniques are utilized to deal with the left image. In general, the contours are extracted from the original image first, and then these contours and edge points are possible candidates of obstacles. Finally, we use the connected component labeling method to find the obstacles in image plane.

B. *Target detection*

This section introduces the searching approach of possible region of target that mobile robot tracking. The mobile robot needs to find where the target is located. Our approach is to detect the color of target first, because it is the simplest approach to find the target with a specific color are filtered out from the original image. Therefore, we can find the color corresponding with the predetermined one. Figure 7 shows the procedures of the target detection sub-system, left CCD camera captures the image, and some image processing techniques are utilized to deal with the left image. In general, we detect the target using the color feature to find a designate color of target.

C. *Stereo Matching*

To get the depth of the obstacle, it is necessary to measure the similarity of the points. The adopted approach of feature matching is to compare the intensity of one point with that of another point. In this study, the sum of squared difference (SSD) method is applied in order to compare the small regions in stereo images. Then the corresponding block is determined by minimizing the sum of squared difference between two images.

$$SSD((i,j),(i',j')) = \sum_{n=0}^{w}\sum_{m=0}^{h}\left(R\left(i'+m, j'+n\right) - L\left(i+m, j+n\right)\right)^2 \quad (6)$$

where m and n denote correlation window size, i and j represent the position of pixel in image, h and w are height and width respectively, R and L represent left and right images respectively.

4. Fuzzy Control Strategy

A. *Obstacles detection*

When the target and obstacles are detected by the vision system, their distances are calculated by the stereo vision. We compare the distances between the target and the obstacles to find which is closer to the mobile robot. Figure 8 shows the distance relationship. If the distance of the target is closer to the mobile, then the control strategy for target tracking will be selected.

When the strategy for target tracking is selected, the pyramid is the target which is tracked to the middle of the image. The mobile robot starts to approach the pyramid according to the distance and the orientation. The current PWM values of right PWM_R and left PWM_L wheels can be obtained from the output of the FLC.

The mobile robot checks if the pyramid is near the mobile robot. When the distance between the pyramid and the mobile robot is short enough, the mobile robot will stop in front of the pyramid. The flowchart of the control strategy is shown in Figure 9.

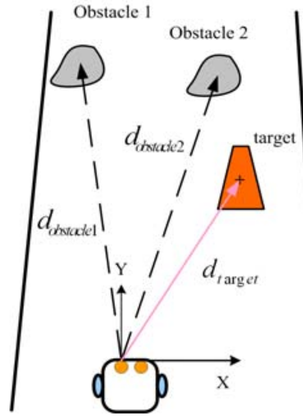


Figure. 8 The distance relationship.

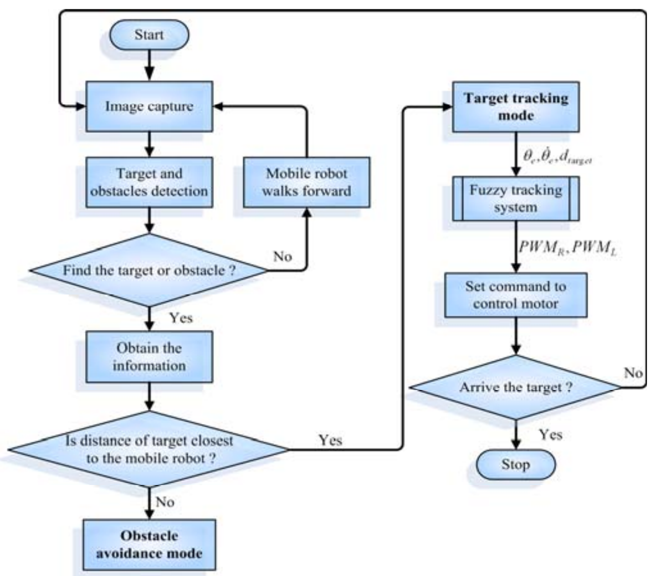


Figure 9. Flowchart of target tracking.

B. *Fuzzy Logic Control of the Mobile Robot for Target Tracking*

The main theme of the fuzzy target tracking control is to make the mobile robot chase the target. A two-input-single-output fuzzy system is presented based on the obtained information from the vision system. The parameters used to construct the fuzzy logic controller for target tracking problem are shown in Figure 10, θ_e is the current angle which is the angle between the robot and the target at the current time, while θ_{e-1} is the previous angle which is the angle between the robot and the target at the previous time. The current angle θ_e and its variation $\dot{\theta}_e = \theta_e - \theta_{e-1}$ are used as fuzzy inputs in our FLC. They are both decomposed into five fuzzy partitions, denoted by NB (Negative Big), NS (Negative Small), Z (Zero), PS (Positive Small), and PB (Positive Big). The control output CO is decomposed into seven fuzzy partitions. Figure 11 shows the membership function shapes of the fuzzy subsets adopted in this paper.

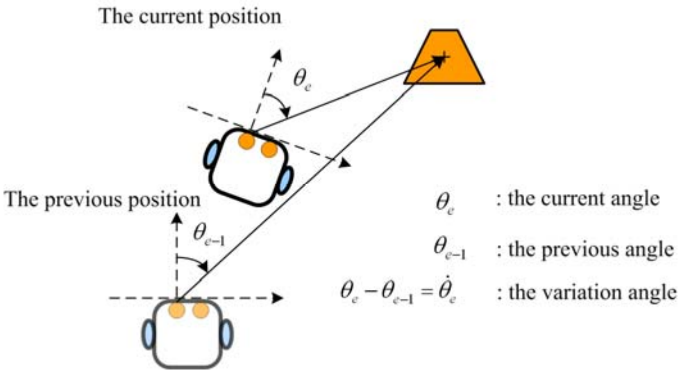
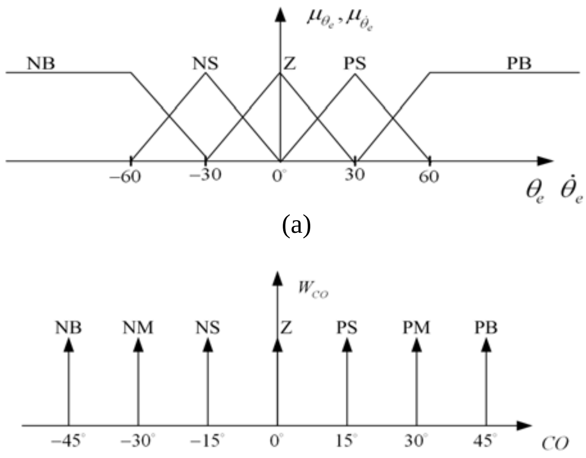


Figure 10. Definition of the fuzzy inputs.



(a)

(b)

Figure 11. The membership functions of the input and output: (a) The input θ_e , $\dot{\theta}_e$; (b) The output CO .

Since each discourse is divided into five subsets, denoted by NB, NM, NS, Z, PS, PM, and PB, two inputs will construct 25 fuzzy rules. For example, the situation of Figure10 shows that θ_e is PB and $\dot{\theta}_e$ is PS, we have to increase the velocity of left wheel and decrease the velocity of right wheel, i.e., the adjustment error of the PWM value must be NB. Therefore, the inference rules can be deduced and the corresponding rule table is shown in Table 1.

Table 1. The fuzzy rule table.

$\theta_e \backslash \dot{\theta}_e$	NB	NS	Z	PS	PB
NB	PB	PB	PM	PS	Z
NS	PB	PM	PS	Z	NS
Z	PM	PS	Z	NS	NM
PS	PS	Z	NS	NM	NB
PB	Z	NS	NM	NB	NB

The defuzzification interface is a mapping from a space of fuzzy control actions defined over an output universe of discourse into a space of crisp action. The defuzzification strategy used in our system is depicted as follows:

$$u = W_{crisp} = \frac{\sum_{i=1}^{n} w_{COi} \times \left(\mu_{\theta_i} \times \mu_{\dot{\theta}_i}\right)}{\sum_{i=1}^{n} \left(\mu_{\theta_i} \times \mu_{\dot{\theta}_i}\right)} \tag{7}$$

where n is the number of fuzzy sets of the inputs. W_{CO_i} is the weight of each fuzzy set i . μ_{θ_i} and $\mu_{\dot{\theta}_i}$ are the membership function values of the control input.

The DC servo motors are controlled by the PWM (pulse width modulation) value. We need to convert the crisp output of the fuzzy, which is the angular position, to the PWM value. The crisp output u is multiplied by weighting β, the adjustment error of the PWM value as

$$\Delta PWM = u \times \beta \tag{8}$$

where ΔPWM may be positive or negative, and it is used as the difference of velocity of two wheels.

The output from our FLC is the speed correction of the two wheels of the robot. A fundamental speed is also required to support the robot in maintaining a basic speed based on the distance between the mobile robot and the target. Eq. (9) is the definition of the basic speed used in our system.

$$PWM_{def} = PWM_{std} + W_{target} \times d_{target} \tag{9}$$

where PWM_{std} is the standard speed of the mobile robot, W_{target} is the weight of the distance to the target, and d_{target} is the distance that is calculated by the vision system between robot and target.

Therefore, the speed of each wheel can be obtained by the fundamental speed and the speed correction, as described in Eq. (10).

$$PWM_R = PWM_{def} + \Delta PWM / 2 \quad (10a)$$

$$PWM_L = PWM_{def} - \Delta PWM / 2 \quad (10b)$$

where PWM_R and PWM_L represent the current PWM values of right and left wheels, respectively.

C. *The Control Strategy for Obstacle Avoidance*

When the mobile robot chooses the obstacle avoidance mode to do collision avoidance, the mobile robot will only consider the two angles of every obstacle, which are the maximum angle and minimum angle. From Figure 12, the maximum angle θ_{robot_max} represents the angle obtained on the left side of the obstacle, and the minimum angle θ_{robot_min} represents the angle obtained on the right side of the obstacle. Because the mobile robot only chooses the path where the magnitude of the angle is smaller than the minimum angle or the magnitude of the angle is larger than the maximum angle, the mobile robot can pass safely.

If the number of obstacles is more than two, all of their maximum and minimum angles are determined individually. In order to reduce the procedure for processing, the obstacle does not consider if the distance is too far from the mobile robot. The mobile robot only considers these angles when their distances are in a specific range and sorted by their angle degree, and the serial number of obstacles will depend on the results of the sorting. Then the mobile robot finds out the angle range that the mobile robot can pass through safely between every two obstacles. In Figure 13, the safe range is between the left side of the right obstacle and the right side of the left obstacle. In the middle of this range is an output angle that is collision free for the mobile robot. Comparing with the head direction of the mobile robot, the minimum turning angle $\theta_{turning}$ can be obtained. Finally, we convert the angle $\theta_{turning}$ to the corresponding PWM value for the motor. The motors on the left and right are controlled to avoid a collision with the obstacles. When the mobile robot passes safely through the obstacles, the control strategy for target tracking will be selected to track the pyramid.

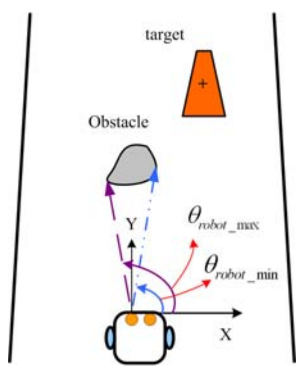


Figure 12. The angle of objects relative to the left camera.

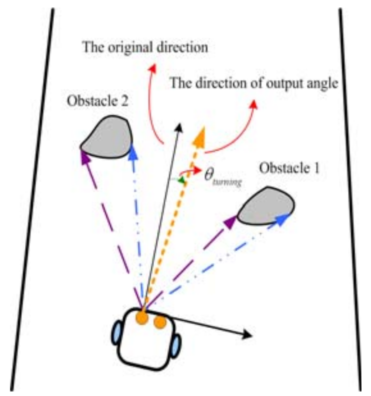


Figure 13. The safe region between two obstacles.

5. Experiment Results

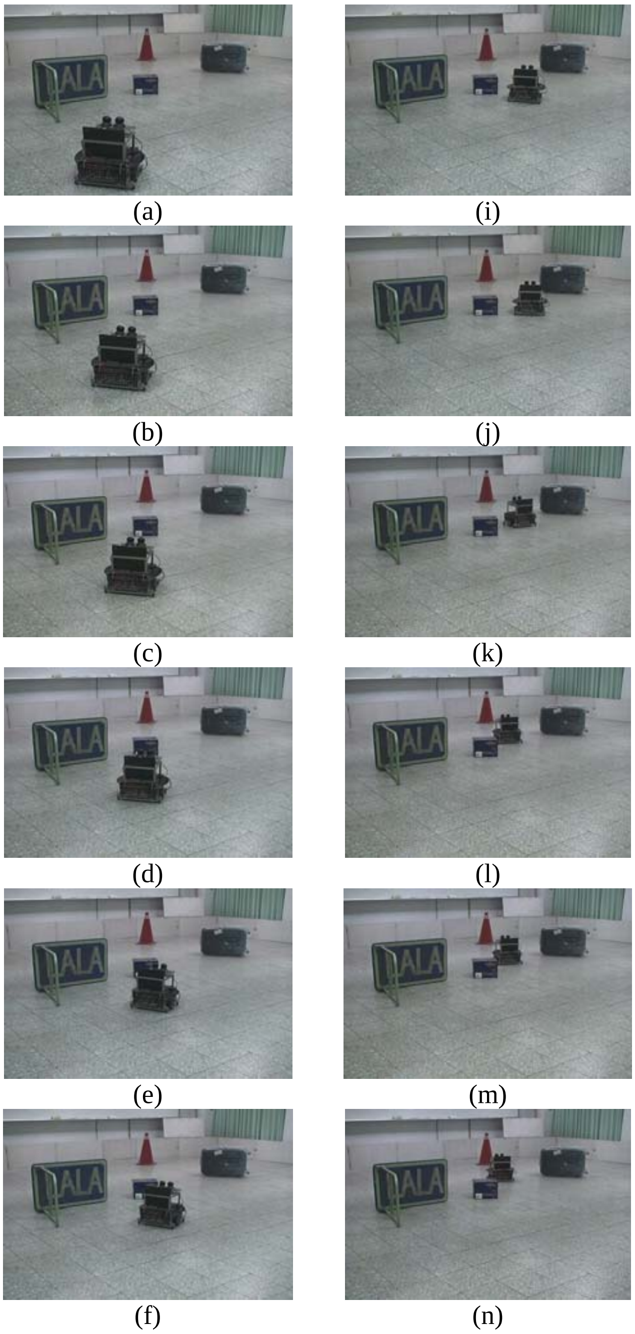
We placed a pyramid as our target and set three obstacles in front of the mobile robot as shown in Figure 14. The color of the pyramid is reddish-orange. The robot performs the detection of target and obstacles. When the robot finds the target, it will turn left or right and move toward the target center. The mobile robot would choose the safe region between these obstacles. Figures 14 (a)-(c) show that the mobile robot detected the obstacle in navigation, then it chose the collision avoidance mode to dodge the obstacle which was the closest distance to the mobile robot. The distance of the obstacle was too far, so our strategy would make the mobile robot keep approaching the target. When the distance of the obstacle was near the mobile robot, the mobile robot would turn right to do the avoidance collision in Figures 14(d)-(j). As the mobile robot was far away from the obstacle, it would detect the target as there were no obstacles in front of the mobile robot. The pyramid was detected, and then it chose the tracking mode and tracking the target as shown in Figures 14 (k)-(o). The mobile robot would stop moving in front of the pyramid when the distance was less than a specific distance, as shown in Figure 14 (p).

6. Conclusions

In this paper, the hardware architecture of the mobile robot has been established, and the obstacle avoidance and target tracking control for mobile robot combined with two cameras have been developed. Two image sensors are installed on the mobile robot to detect the distance between the objects and robot. The binocular image processing system is used to find out the same feature points of objects. For distance detection, the area-based matching is carried out using SSD method, and the depth of the object from the CCD is calculated by the triangular perspective theory. A target tracking control system is designed using fuzzy logic techniques, and the fuzzy controller generates the difference velocity command to the two wheels of the mobile robot. Collision avoidance is also considered for practical situations and the presented method can be easily realized to the mobile robot. The practically experimental results illustrate the feasibility and effectiveness of the proposed real-time target tracking methodology.

Acknowledgment

The support of this work is by the National Science Council of the Republic of China under NSC 98-2221-E-006-212-MY3 is gratefully acknowledged.



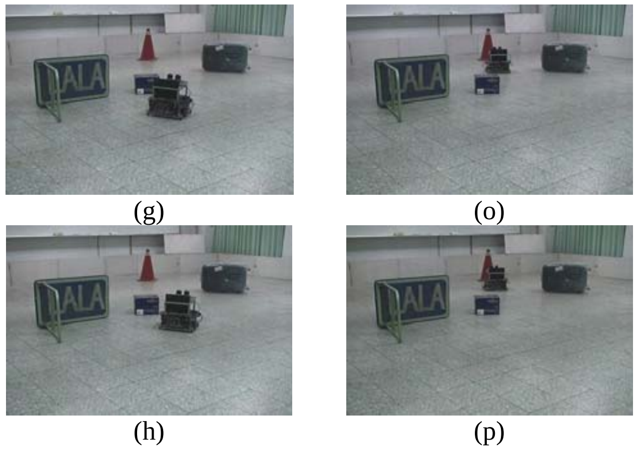


Figure 14. The obstacle avoidance mode with three obstacles.

References

[1] A. Elfes, “Using occupancy grid for mobile robot perception and navigation,” *IEEE Computer Magazine*, vol.22, no.6, pp. 46–57, Jun. 1989.

[2] H. Li, and S. X. Yang, “Ultrasonic Sensor based Fuzzy Obstacle Avoidance Behaviors,” *in Proc. IEEE Int. Conf. on System, Man and Cybernetics*, vol.2, pp. 644–649, 2002.

[3] J. Hancock, M. Hebert, and C. Thorpe, “Laser intensity-based obstacle detection Intelligent Robots and Systems,” *in Proc. IEEE/RSJ Int. Conf. on Intelligent Robotic Systems*, vol. 3, pp. 1541–1546, 1998.

[4] E. Menegatti, A. Pretto, A. Scarpa, and E. Pagello, “Omnidirectional Vision Scan Matching for Robot Localization in Dynamic Environments,” *IEEE Trans. on Robotics and Automation*, vol. 22, pp. 523–535, 2006.

[5] E. Elkonyaly, F. Areed, Y. Enab, and F. Zada, “Range sensory based robot navigation in unknown terrains,” *in Proc. SPIE on the International Society for Optical Engineering*, vol. 2591, pp. 76–85, 1995.

[6] C. Lin, and R. L. Tummala, “Adaptive Sensor Integration for Mobile Robot Navigation,” *in Proc. IEEE Int. Conf. on Multisensor Fusion and Integration for Intelligent System*, pp. 85–91, Oct. 1994.

[7] K. Sugihara, “Some location problems for robot navigation using a single,” *Computer Vision, Graphics and Image Processing*, vol. 42, No. 1, pp. 112–129, Apr. 1988.

[8] T. Tsubouchi, and S. Yuta, “Map assisted vision system of mobile robots for reckoning in a building environment,” *in Proc. IEEE Int. Conf. on Robotics Automat.*, pp. 1978–1984, Mar./Apr. 1987.

[9] Y. Yagi, S. Kawato, and S. Tsuji, “Collision avoidance using omnidirectional image sensor

(COPIS)," *in Proc. IEEE Int. Conf. on Robotics and Automation*, vol. 1, pp. 910–915, Apr. 1991.
[10] Y. Sun, Q. Cao and W. Chen, "An object tracking and global localization method using omnidirectional vision system," *in Proc. 5th World Congress on Intelligent Control and Automation*, vol.6, pp. 4730–4735, Jun. 2004.
[11] D. J. Kriegman, E. Triendl, and T. O. Binford, "Stereo vision and navigation in buildings for mobile robots," *IEEE Trans. on Robotics Automat.*, vol. 5, no. 6, pp. 792-803, Dec. 1989.
[12] C. Caraffi, S. Cattani, and P. Grisleri, "Off-Road Path and Obstacle Detection Using Decision Networks and Stereo Vision," *IEEE Trans. on Intelligent Transportation Systems*, vol. 8, pp. 607–618, Dec. 2007.
[13] N. Ayache and F. Lustman, "Trinocular Stereo Vision for Robotics," *IEEE Trans. on Pattern Analysis and Machine Intelligence*, vol. 13, no. 1, pp. 73–85, 1991.
[14] S. O. Lee, Y. J. Cho, M. H. Bo, B. J. You, and S. R. Oh, "A stable target tracking control for unicycle mobile robots," *in Proc. Int. Conf. on Intelligent Robots and Systems*, vol. 3, pp. 1822–1827, 2000.
[15] C. C. Wong, C. T. Cheng, K. H. Huang, and Y. T. Yang, "Fuzzy control of humanoid robot for obstacle avoidance," *International Journal of Fuzzy System*, vol.10, no.1, pp.261–270, 2008.
[16] T. Darrell, G. Gordon, M. Harville, and J. Woodfill, "Integrated person tracking using stereo, color and pattern detection," *in Proc. IEEE Computer Society Conf. on Computer Vision and Pattern Recognition*, pp. 601–608, Jun. 1998.
[17] J. Orwell, P. Remagnino, and G. A. Jones, "Multi-camera colour tracking," *in IEEE Workshop on Visual Surveillance*, pp. 14–21, Jul. 1999.
[18] T.-H. S. Li, S. J. Chang, and W. Tong, "Fuzzy target tracking control of autonomous mobile robots by using infrared sensors," *IEEE Trans. on Fuzzy Syst.* vol. 12, no. 4, pp. 491–501, 2004.
[19] C. C. Wong, H. Y. Wang and S. A. Li, "PSO-based Motion Fuzzy Controller Design for Mobile Robots," *International Journal of Fuzzy Systems*, vol. 10, no. 1, pp. 284-292, Mar. 2008.
[20] R. C. Luo, and T. M. Chean, "Autonomous mobile target tracking system based on gray-fuzzy control algorithm," *IEEE Trans. on Ind. Electron*. vol. 47, no. 4, pp. 920–931, 2000.
[21] S. F. Lin, S. S. Liao and J. Y. Chen, "Design of fuzzy predictor in the moving target system," *International Journal of Fuzzy Systems*, vol. 3, no. 1, pp. 323–330, 2001.
[22] N. S. Pai and T.-H. S. Li, "Tracking 3D moving targets with an integrated fuzzy Kalman filter," *International Journal of Fuzzy Systems*, vol. 5, no. 4, pp. 201–211, 2003.
[23] Y. Y. Chen and K.Y. Young, "An Intelligent Radar Predictor for High-Speed Moving-Target Tracking," *International Journal of Fuzzy Systems*, vol. 6, no.2, pp. 90–99, 2004.
[24] C. C. Wong, H. Y. Wang, S. A. Li, and C. T. Cheng, "Fuzzy controller designed by GA for two-wheeled mobile robots," *International Journal of Fuzzy Systems*, vol.9, no.1, pp.22–30, 2007.
[25] J. Lu, H. Cai, J. G. Lou, and Jiang Li, "An Epipolar Geometry-Based Fast Disparity Estimation Algorithm for Multiview Image and Video Coding," *IEEE Trans. on Circuits and Systems for Video Technology*, vol. 17, no. 6, pp. 737–750, 2007.

Chan-Hong Chao received the B.S. degree from Feng Chia University, Taichung, Taiwan, R.O.C., in 1999, and the M.S. degree from the National Cheng Kung University, Tainan, Taiwan, in 2001, where he is currently working toward the Ph.D. degree in the aiRobots Laboratory, Department of Electrical Engineering.

His main research interests include fuzzy control, autonomous mobile robot, machine vision, and sensor fusion.

Bo-Yan Hsueh received the B.S. degree from Yuan Ze University, Chung-Li, Taiwan, R.O.C., in 2006, and M.S. degree from National Cheng Kung University, Tainan, Taiwan, R.O.C., in 2008, all in electrical engineering.

In November 2008, he is an engineer for R&D alternative service in Holtek Semiconductor Inc., Hsinchu, Taiwan, R.O.C. His current research interest is IC design.

Ming-Ying Hsiao received the B.S. and the M.S. degrees in Power Mechanical Engineering from National Tsing Hua University, Hsinchu, Taiwan, R.O.C., in 1979 and 1981, respectively, and the Ph. D degree in Electrical Engineering, frm National Cheng Kung University, Tainan, Taiwan, R.O.C., in 2008.

He is currently an Associate Professor/Chairman with the Department of Multimedia Design, Fortune Institute of Technology, Kaohsiung, Taiwan. His current research interests include fuzzy control, type-2 fuzzy system, and adaptive sliding-mode control.

Shun-Hung Tsai received the B.S. degree from the Department of Industrial Education, National Taiwan Normal University, Taipei, Taiwan, R.O.C. in 1999, and the M.S. and Ph.D. degrees in 2001 and 2007, respectively, from National Cheng Kung University, Tainan, Taiwan, R.O.C., all in electrical engineering. He was an electriao6cal engineer in Philips Building Semiconductor from 2003 to 2005. From 2005 to 2006, he was a control engineer of China Steel Corporation. From 2006 to 2007, he served as a process integration engineer in United Microelectronics Corporation. In 2008, he was an associate researcher at the Energy and Agile System Development, Metal Industrial Research and Develop Centre (MIRDC), Kaohsiung, Taiwan. Besides, he was an Assistant Professor in the department of electrical engineering, Chang Gung University of Taiwan in 2008. He is currently an Assistant Professor in the Graduate Institute of Automation Technology, National Taipei University of Technology. His major research interests include nonlinear control, intelligent control, fuzzy modeling and control, optimal control, and robust control.

Tzuu-Hseng S. Li received the B.S. degree in 1981 from Ta-Tung Institute of Technology, Taipei, Taiwan, R.O.C., and the M.S. and Ph.D. degrees in 1985 and 1989, respectively, from National Cheng Kung University, Tainan, Taiwan, R.O.C., all in electrical engineering.

He has been a Professor in the Department of Electrical Engineering, National Cheng Kung University since 1994. He is now a Distinguished Professor. From 1999 to 2002, he served as a Director of Electrical Laboratories, National Cheng Kung University. In 2006, he received the Outstanding Automatic Control Award from the Chinese Automatic Control Society in Taiwan. He was elected as the President of the Chinese Automatic Control Society from 2008 to 2009. His current research interests include fuzzy control, singular perturbation, intelligent control chip design, mechatronics, mobile robots, humanoid robot, and automobile active suspension systems.

Dr. Li was a Technical Editor for the IEEE/ASME Transactions on Mechatronics and now is Associate Editors for the Asia Journal of Control, International Journal of Fuzzy Systems and International Journal of Nonlinear Science and Numerical Simulations.