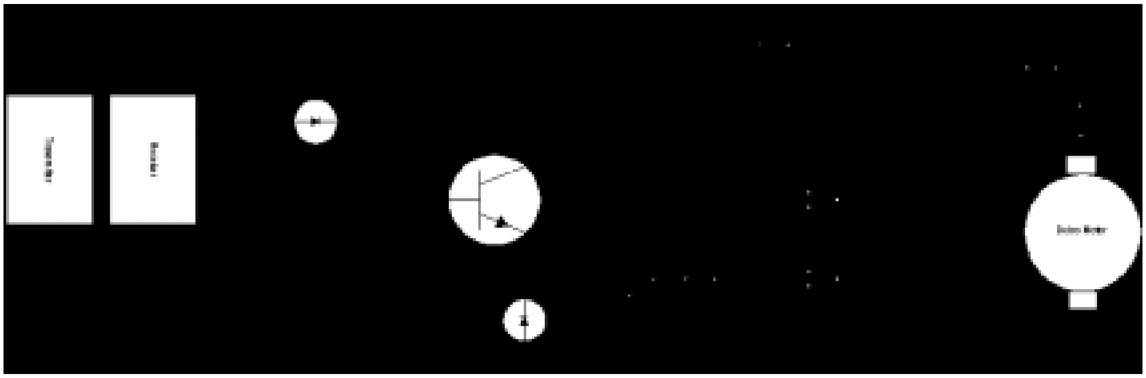
Remote Controlled, Vision Guided, Mobile Robot System

Raymond Ande, Tayib Samu and E.L. Hall

University of Cincinnati

Center for Robotics Research, ML # 72

Cincinnati, OH 45221



ABSTRACT

Automated Guided Vehicles (AGV's) have many potential applications in manufacturing, medicine, space and defense. The purpose of this paper is to describe exploratory research on the design of the remote controlled emergency stop and vision systems for an autonomous mobile robot. The remote control provides human supervision and emergency stop capabilities for the autonomous vehicle. The vision guidance provides automatic operation. A mobile robot test-bed has been constructed using a golf cart base. The mobile robot (*Bearcat*) was built for the Association for Unmanned Vehicle Systems (AUVS) 1997 competition. The mobile robot has full speed control with guidance provided by a vision system and an obstacle avoidance system using ultrasonic sensors systems. Vision guidance is accomplished using two CCD cameras with zoom lenses. The vision data is processed by a high speed tracking device, communicating with the computer the X, Y coordinates of blobs along the lane markers. The system also has three emergency stop switches and a remote controlled emergency stop switch that can disable the traction motor and set the brake. Testing of these systems has been done in the lab as well as on an outside test track with positive results that show that at five mph the vehicle can follow a line and at the same time avoid obstacles.

Index terms: vision guidance, remote control, mobile robot, tracking.

1. INTRODUCTION

The design of a mobile system is a challenging task. The specific challenge of designing an intelligent controller is in determining what information is needed, how to measure it and how to use this information in a manner that will satisfy the performance specifications of the machine. The design specifications were to build a robot that follows a line, avoids obstacles, and adapts to variations in terrain. This implied the design of separate subsystems with discrete design objectives integrated in an upper level control logic that enables the robot to function as an integral system meeting all the performance requirements.

At the subsystem level, the primary design considerations included the selection of equipment with the desired functional and operational features as well as reliability, commercial availability and affordability. Equally important was the compatibility of the software that controlled these units and their interfaces. All the subsystem components have been chosen to be modular in design and independent in terms of configuration so as to increase adaptability and flexibility. This is a unique feature of the design, since it enables replacement of existing components with more sophisticated or suitable ones, as they become available. To ensure desired performance of the individual sub-systems, several unique approaches were tried. These include, the implementation of a fuzzy logic controller for obstacle avoidance and a novel three-dimensional algorithm that for line following.

Hall[1] discussed the fundamental theorem of robot vision. The manipulation of a point in space x_1 by either a robot manipulator that moves it to another point x_2 or through a camera system that images the point onto a camera sensor at x_2, is described by the same matrix transformation, which is of the form

$$x_2 = Tx_1$$

The transformation matrix T can describe the first-order effects of translation, rotation, scaling, and projective and perspective projections. The robot vision theorem suggests that the sensing of a point or collection of points on an object have some relation. In an effort to exploit this relation, the calibration of the sensing becomes very essential.

Camera calibration is a complex problem since [2]: (1) all the intrinsic and extrinsic parameters should be computed from the two-dimensional projections of a limited number of feature points, (2) the parameters are inter-related, and (3) the formulation is non-linear due to the perspectivity of the pin-hole camera model.

Several studies have been done on calibration of cameras for various applications. Lovenitti, et al[3] presented a 3-D coordinate measurement technique that uses a single 2-D image of four coplanar points, which are arranged in a square of known size, to measure geometric features on an object, some of which may be hidden from the view of the camera. In this approach, a hand-held probe is positioned on the object and in the view of a camera. The perspective projection of the probe is used to determine the 3-D coordinates of the point of contact. The image of the square’s four vertices is used to calculate the probe position and point of contact on the object. The method for determining the probe position is dependent on knowledge of the probe side length; the image coordinates for each of the four vertices and camera parameters. The image distance (distance between the sensor or the image and the optical center of the lens-the effective focal length), the lens distortion, the horizontal pixel width and vertical pixel height of the CCD sensor, and the location of the optical center of the lens on the image frame buffer must be known. These camera parameters are determined by calibration. Some of the factors that can affect accuracy when determining position using image analysis techniques are lens distortion and horizontal pixel width.

Caution is required during calibration. Hong, et al[4] list two points that should be considered in camera calibration: (1) reducing the location error of image features as far as possible, by exploiting image processing technique, (2) compensating system error by the optimal pattern of approximating residual error of image points, namely the posterior compensation of the system error. Based on these two points, the calibration process discussed in [4] are of three parts: (1) The direct transformation error approximation camera calibration algorithm; (2) the subpixel image feature location algorithm combined with the 3D control point field delicate design and fabrication; (3) the precisely movable stage, which provides the reliable means of accuracy checking.

A method based on locating a few 3D coordinates and their corresponding image coordinates on the image plane may be used to obtain the perspective projection matrix elements. Parke.[5] describes the use of the corner points of a cube known dimensions as the reference points to measure object surface. Renner[6] described a method for calibration that uses 23 miniature light bulbs on a pyramid base to serve as the reference points. Measurements of these reference points require the use of accurate and reliable measuring devices. In a study done by Tio[7], an object was partitioned into grids and the selection of points was based on a widely dispersed set of points that provide information on each major grid line. These reference points were used with the image points on sets of matrix equations to obtain the parameters for the calibration of the camera.

Tsai[8] presented an algorithm that decomposes a solution for 12 transformational parameters (nine for rotation and three for translation) into multiple stages by introducing a radial alignment constraint. The radial alignment constraint assumes that the lens distortion occurs only in the radial direction from the optical axis Z of the camera. Using this constraint, six parameters are computed first, and the constraint of the rigid body transformation is used to compute five other parame ters. The remaining parameters are computed by radial lens distortion parameter and estimating it by a nonlinear optimization procedure. Liu, et al. [9] first suggested the use of straight lines and points as features for estimating extrinsic camera parameters. Line features are usually abundant in indoors and some outdoor environments are less sensitive to noise than point features. The constraint used for the algorithms is that a three-dimensional line in the camera coordinate system (X, Y , Z) should lie in the plane formed by the projected two-dimensional line in the image plane and the optical center. This constraint is used for computing nine rotation parameters separately from three translation parameters. They present linear and non linear algorithms for solutions. According to Liu et al's analysis, eight-line or six-point correspondences are required for the linear method, and three-line or three-point correspondences are required for the nonlinear method. A separate linear method for translation parameters requires three-line or two point correspondences. Haralick, et al.[10] reported their comprehensive investigation for position estimation from two-dimensional and three-dimensional sensed features. Other approaches b ased on different formulations and solutions include Kumar[11], Yuan[12], and Chen[13].

Point or line tracking is achieved through the medium of a digital CCD camera. An Iscan[14]-tracking device does image processing for the tracking. This device finds the centroid of the brightest or darkest region in a computer-controlled window, and returns its X, Y image coordinates as well as size information. This information is updated every 16 ms, however the program must wait 10 ms after moving the window to get new data. This results in a 52 ms update time for tracking two point s in sequence.[15] Recently artificial intelligence methods have been employed to develop control systems. Tanaka presented a fuzzy logic controller that guarantees stability of a control system for a computer-simulated model car in[16]. Altrock[17], et al discussed advanced fuzzy logic application for automobile application. Samu, Kelkar, and Hall presented a fuzzy logic approach to modeling a control system for a mobile robot using MATLAB simulation software[18].< /P>

2. SYSTEM DESIGN

An autonomous mobile robot is a sophisticated, computer controlled, intelligent system. The adaptive capabilities of a mobile robot depend on the fundamental analytical and architectural designs of the sensor systems u sed. The mobile robot provides an excellent test bed for investigations into generic vision guided robot control since it is similar to an automobile and is a multi-input, multi-output system. The major components of the robot are a vision guidance system , a steering control system, an obstacle avoidance system, a speed control, a safety and braking system, a power unit and the supervisor control PC. Following is a brief description on the design and development of the vision and remote control subsyste ms of the mobile robot.

2.1 Vision guidance system

The purpose of the vision guidance system is to obtain information from the changing environment such as an obstacle course that is usually bounded by solid as well as dashed lines. The robot then adapts this information through its controller, whi ch guides the robot along the obstacle course. For line tracking, two JVC CCD cameras are used for following the left and right lines. Only one line is followed at a time; however, when one camera loses the line, a video switch changes to the other camera. The Iscan image-tracking device accomplishes image processing. This device finds the centroid of the brightest or darkest region in a computer controlled window, and returns the X, Y coordinates of its centroid as well as size information of the blob. If no object is found, a loss of track signal is generated. The camera is angled down at 32 degrees and panned to the right at 30 degrees. This setup gives a 4 ft wide view of the ground. Once the data points are collected they are entered into the algorithm. From these calculations the angle and distance are then sent to the motion control sub-system.

Image coordinates are two-dimensional while physical coordinates are three-dimensional. The robot automatically accesses image coordinates of the points on the line. In an autonomous situation, the problem is to determine the 3D coordinates o f a point on the line given its image coordinates. As a solution to this problem an innovative algorithm is developed to establish a mathematical and geometrical relationship between the physical 3-D ground coordinates of the line to follow and its corresponding 2-D digitized image coordinates. The algorithm utilizes a calibration device to determine the focal length of the cameras and the orientation of the projection system with respect to the global coordinates system. The calibration device is constructed to obtain physical co-ordinates of a point on the line with respect to the centroid of the robot within an accuracy of ±0.0001". From the physical and image coordinates, the camera parameters (co efficients) are computed through a C program subroutine. Figure 1 compares the X and Y coordinates for the measured and computed vision calibration sample points. The deviation of the model points from the calibration points shown is found to be minimal. As a result of this reliable performance, the direct coefficient computation model is implemented to solve the vision problem.

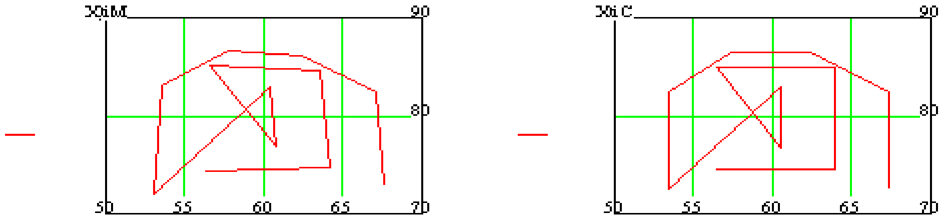


Figure 1. X and Y coordinates for the measured and computed vision calibration points

After the camera parameters are computed the next stage is computing the physical coordinates given any image coordinate. To show how the physical coordinates are computed given any image coordinate, another calibration is performed. Here, the z-co ordinate for each of the points is treated as constant because in the real time implementation of this method, the z-coordinate is constrained by the ground. Table 1 shows the results of the physical coordinate computations. Correlation plots for the original and the computed x and y coordinates are computed. The linearity of the plots means that the difference between the original coordinates and the computed ones is very small. Also computed to ascertain or test the discrepancies between the two sets of coordinates is the mean square error. For each of the correlation plots, the mean square error is 0.242 for the x-axis and 0.295 for the y-axis. With a mean square error of within one tenth of an inch, the calibration process is considered to be accurate and reliable enough to compute the physical coordinates of a real life point on a ground. Thus the vision algorithm computes the x and y coordinates of a physical point with respect to the centroid of the robot and establishes a geometrical relationship between the points relative to the centroid of the robot.

Points	Original Physical Coordinates			Image Coordinates		Computed Physical Coordinates	
	x	y	z	x	y	x	y
1	48.856	71.047	-22.533	341	220	48.464	70.745
2	56.346	71.054	-22.524	454	187	56.667	71.404
3	56.346	81.548	-22.564	329	135	55.949	81.358
4	48.831	81.583	-22.552	219	158	48.803	81.789
5	52.919	73.109	-19.057	377	153	53.33	73.475
6	52.87	79.537	-19.034	301	124	52.605	79.154

7	44.55	72	-24	265	245	43.97	71.762
8	47.75	72	-24	330	229	48.414	71.789
9	46.75	74.5	-24	265	221	46.229	74.649
10	46	79	-24	215	195	46.417	79.236
11	49.75	82	-24	236	168	49.908	81.871
12	40.15	83	-24	81	195	40.362	83.149

Table 1. Set of original and computed calibration data points.

A block diagram of the system is shown in Figure 2.

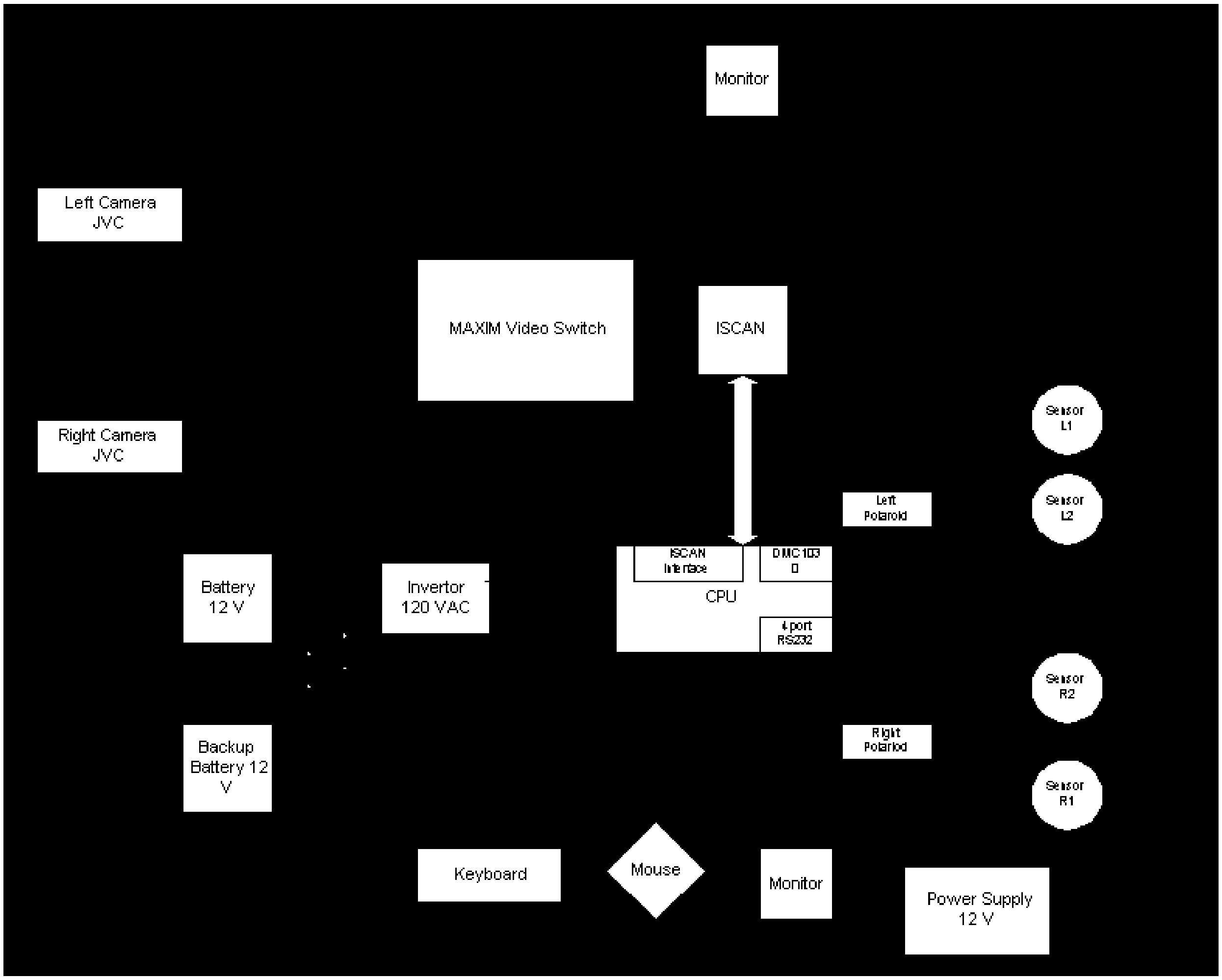


Figure 2. System block diagram.

2.2 Safety and Emergency Stop System

The safety and emergency stop system serves primarily to prevent accidents during operation of the vehicle. It consists of a remote controlled emergency stops, manually operated emergency stops, and the braking system.

The design requirements were to activate the remote unit from a distance of no more than 50 feet. The remote controlled emergency stop consists of a transmitter, a receiver, an amplifier and an electromagnetic relay. The JR Max6 transmitter uses 9V DC and transmits FM signals at 72.470 MHz over a range of 50 feet. These signals are received by the receiver and converted into a current that is amplified with a gain factor of 120. This amplified current activates the contacts of the relay that activates the brake and cuts power to the traction motor.

The manual emergency stop unit consists of three manual push buttons situated on easily accessible side surfaces of the robot. When pushed, the brakes are activated and the main power is shut down through two solenoids. A solenoid acts like a relay but it is capable of handling more current. Basically when current flows through its gates, it closes an internal switch shutting down the main power. This serves as a safety measure against possible "*runaway*" situations for the robot.

The braking system is accomplished by a high torque electric motor. It is capable of both clockwise and anti-clockwise directional motion. Upon activation, the motor turns in the counter-clockwise direction pulling the cable attached to the existing brake pedal of the cart. This brings the vehicle to a halt. To prevent the continuous rotation of the brake motor, a double pole contact switch was placed at the bottom of the motor. When the brakes are activated, the cable attached to the brake pedal gets pulled and the robot stops. However, this also actuates the contact switch that stops the rotation of the brake motor. To resume normal operation the tension in the cable needs to be relieved. This meant that the motor had to turn in the opposite direction. This is achieved through reversing the polarities of the motor through the relay board. Figure 3 below shows the schematic for the amplifier, relay, and the braking system.

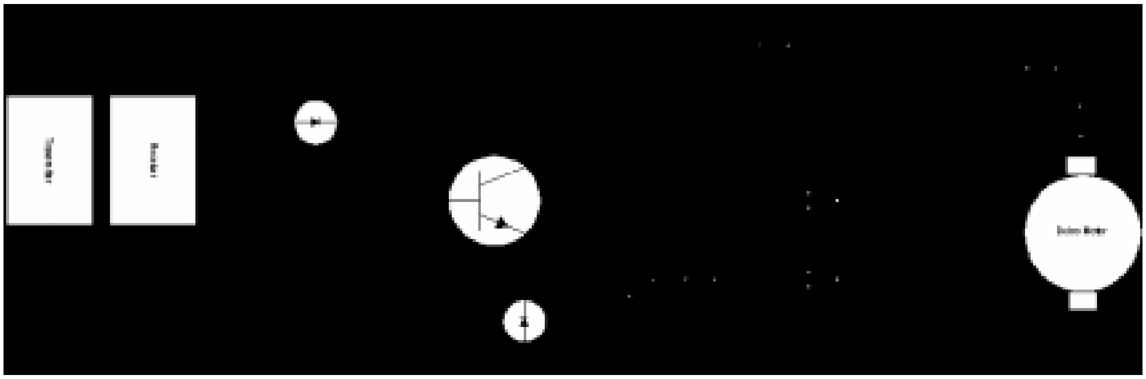


Figure 3. Brake control system

3. RESULTS of TESTING

After extensive laboratory testing of individual subsystems an oval outdoor test track was constructed to simulate the contest track with double lines, 4 inches wide spaced 10 feet apart with dashed segments and obstacles. Several outside tests were conducted.

Vision guidance system: The vision system was able to successfully track straight lines, curves negotiate sharp turns as well as switch control between cameras when the line on either side disappeared. However, the external conditions did present some problems. If the weather turned sunny to cloudy or vice versa during the actual run the Iscan threshold had to be manually readjusted. Also, in certain cases the reflection of the wet grass on the track appeared brighter than the white line itself and the vision system picked those points and went off-track.

Safety and Emergency Stop Braking System: This system was found to be extremely reliable and effective. The relay base was found to be drawing excess current in the initial test on the system. To protect it against the power spikes in the system , a 3-amp fuse was connected in the circuit. Also, it was found that the transmitter of the remote control unit drained its battery within 45 minutes. A provision was made to recharge the battery without physically removing it from the unit so as to ensure peak performance of the unit.

4. CONCLUSIONS

Two major components of a modular intelligent robotic system, vision guidance and remote control have been described in this paper. The three dimensional vision tracking system has now been tested extensively both indoors and outside in various weather conditions. The method measures the coordinates of ground points that are used to determine the direction of the line to be tracked. Two cameras are used so that when a line disappears from one side, the robot can look for the line on the other side.

The remote control system permits human supervision that is needed when algorithm failures cause the robot to behave erratically. The control has been tested and works to the design specifications. With a large mobile vehicle, human supervision is prudent. Situations such as runaway or collisions can occur in a great variety of ways.

ACKNOWLEDGEMENTS

This work has been a continual learning experience and could not have been completed without the devoted work and contributions of the previous team members especially: Bradley Matthews, David Perdue, Mike Ruthemeyer, Alan Lewis, Malik Spencer, Sanjeev Gupta, Fred Reckelhoff, Todd Brehm, Randy Smith and Rob Hicks. The authors would like to thank the following staff personnel for their technical assistance; Bo Westheider (electronics), Dave Breheim (machinist), Perry Morgan (computer) and Larry Schartman (computer). The vehicle has been sponsored in part by several generous contributions and we thank our current and past sponsors: 1997, Dr. Ray Asfahl, SME, ICRC, UC; 1996, SME, UC, ICRC; 1995, Michel Tire Company; 1994, GE, Ohio Board of Regents; 1993, Textron, IBM, GM, NSF.

REFERENCES

[1] Hall, E. L., "Fundamental Principles of Robot Vision", **Handbook of Pattern Recognition and Image Processing: Computer Vision,** Academic Press, pp. 543-575. 1994.

[2] Borenstein, J., et al ""Where am I?" Sensors and Methods for Mobile Robot Positioning," University of Michigan, Chapter 9, pp. 211.

[3] Lovenitti, P., Thompson, W. and Singh, M., "Three-dimensional Measurement using a Single Image," SPIE, **Optical Engineering** 35(5) 1496-1502. May 1996.

[4] Hong, F. and Baozong, Y., "An Accurate and Practical Camera Calibration System

[5] F. I. Parke, "Measuring three-dimensional Surfaces with two-dimensional Data Tablet," **Computer and Graphics**, Vol. 1, 1975, pp. 5-7

[6] W. D. Renner, et al., "The Use of Photogrammetry in Tissue Compensation Design**," Radiology**, Vol. 125, November 1977, pp. 505-510.

[7] Tio, J. B., "Single Image Surface Measurement for Robotics Application" Masters thesis, University of Tennessee, Knoxville, August 1982, pp. 20.

[8] Tsai, R. Y., "A Versatile Camera Calibration Technique for High-Accuracy 3D Machine Vision Metrology Using Off-The-Shelf Cameras and Lenses." **IEEE Transaction on Robotics and Automation**, vol. 8, no. 2, pp. 129-139.

[9] Liu, Y., Huang, T. S., and Faugeras, O. D., "Determination of Camera Location from 2-D to 3-D Line and

Point Correspondence." **IEEE transaction on Pattern Analysis and Machine Intelligence**, Vol. 12, no. 1, pp. 28-37, 1990.

[10] Haralick R. M. et al., "Pose Estimation from Corresponding Point Data." **IEEE Transactions on Systems, Man, and Cybernetics**, vol. 19, no. 6, pp. 1426-1445. 1989

[11] Kumar, "Determination of the Camera Location and Orientation." Proceedings of Image Understanding Workshop 88, pp. 870-881, 1988.

[12] Yuan, J. S. C., "A General Photogrammetric Method for Determining Object Position and Orientation." **IEEE Transaction on Robotics and Automation**, vol. 5, no. 2, pp. 129-142. 1989.

[13] Chen, H. H., "Pose Estimation from Line-to-Plane Correspondences." **IEEE Transaction on Pattern Analysis and Machine Intelligence**, vol. 13, no. 6, pp. 530-541.

[14] Iscan Inc., RK-446-R Video Tracking System Manual, Cambridge, Massachusetts, 1993.

[15] Ghayalod, M.P., E.L. Hall, F.W. Reckelhoff, B.O. Matthews and M.A. Ruthemeyer, "Line Following Using Omnidirectional Vision," **Proc. of SPIE Intelligent Robots and Computer Vision Conf.**, SPIE Vol. 2056, Boston, MA, 1993.

[16] Tanaka, K., "Design of Model-based Fuzzy Controller Using Lyapunov's Stabilty Approach and Its Application to Trajectory Stabilization of a Model Car," **Theoretical Aspects of Fuzzy Control**, John Wiley & sons, Inc, pp.31-50, 1 995. 2nd IEEE conference on fuzzy system, San Francisco, CA, 1993

[17] Altrock, C.V., et al. Advanced fuzzy logic control technologies in automotive applications. Proceedings of 1st IEEE International Conference on Fuzzy Systems, pp. 835-842, 1992.

[18] Samu, T. I. Kelkar, N., and Hall, E., "Fuzzy Logic System for Three Dimensional Line Following for a Mobile Robot," Proc. Adaptive Distributive Parallel Computing Symposium, Dayton, OH. pp. 137-148.