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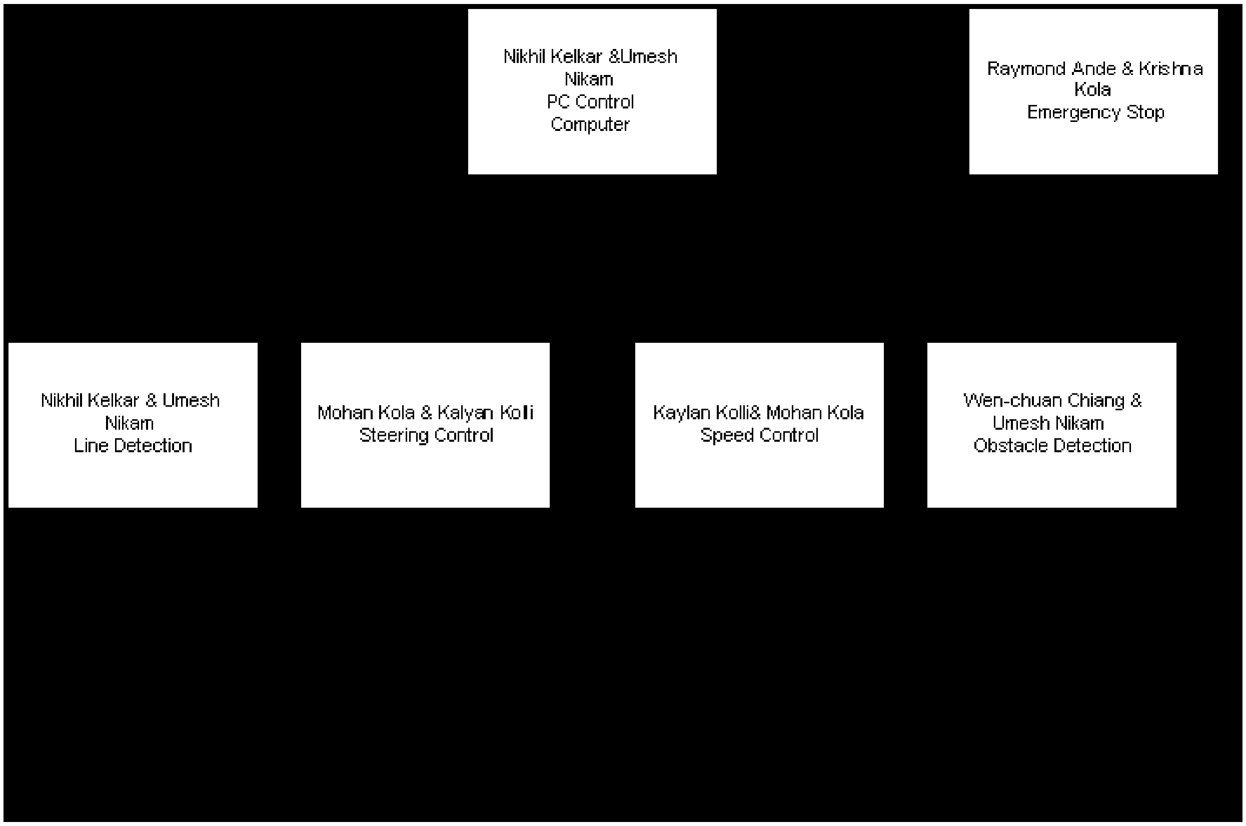

Design of a Mobile Robot for the 1997 AUVS Competition

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Abstract

Automated Guided Vehicles (AGV's) have many potential applications in manufacturing, medicine, space and defense. The purpose of this report is to describe the design, development and exploratory research with a modular autonomous mob ile robot built for the Association for Unmanned Vehicle Systems (AUVS) 1997 competition. The design has several key features and advantages related to its modularity. First, the system implements a fuzzy logic control. Next, the system has a three di mensional vision guidance algorithm. Also, components are portable and could be used on another vehicle. Finally, the system components are independently configured. The mobile robot test-bed has been constructed using a golf cart base. This cart has been modified to have full speed control with guidance provided by a vision system and obstacle avoidance using ultrasonic sensors systems. The speed and steering control are supervised by a personal computer through a multi-axis motion controller. The o bstacle avoidance system is based on a micro-controller interfaced with several ultrasonic transducers. This micro-controller independently handles all timing and distance calculations and sends a distance which can be used to modify the steering angle c orrection based on a fuzzy logic controller. 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 lan e markers. The system also has three emergency stop switches and a remote controlled emergency stop switch which can disable the traction motor and set the brake. Testing of these systems has yielded positive results by showing that at five mph the vehi cle can follow a line and at the same time avoid obstacles. This design, in its modularity, creates a portable autonomous controller applicable for any mobile vehicle with only minor adaptations.

1. Introduction

The design of a mobile system is a challenging task. The challenge of designing an intelligent controller is in determining what information to measure and how to use this information in a manner that will satisfy the performance s pecifications of the machine. The design specifications were to build a robot which could follow a line, avoid obstacles, and adapt to variations in terrain. An intelligent machine such as mobile robot that must adapt to the changes of its environment can also be equipped with vision system so that it can collect visual information and use this information to adapt to its environment by navigating around. The Center for Robotics Research at the University of Cincinnati has been involved in a nation wi de competition to build a small, unmanned, autonomous ground vehicle - a mobile robot - that can navigate around an outdoor obstacle course. The major components of the robot are: the supervisor control computer, speed control, steering control, obstacle avoidance, breaking system, emergency controls, and vision system. The purpose of the vision system is to obtain information from the changing environment - the obstacle course. The robot then adapts to this information through its controller, which gu ides the robot to follow the obstacle course.

Obstacle courses for navigational purposes are usually bounded by solid as well dashed painted lines. The obstacle courses can assume different shapes. Mobile vehicles navigate the course by keeping track of the changes in the orientation of one or b oth the lines with respect to the robot.

The adaptive capabilities of a mobile robot depend on the fundamental analytical and architectural designs of the sensor systems used. The mobile robot provides an excellent test bed for investigations into generic vision guided robot control since i t is similar to an automobile and is a multi-input, multi-output system. An algorithm was 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 digit ized image coordinates. This relationship is incorporated into the vision tracking system to determine the perpendicular distance and angle of the line with respect to the centroid of the robot. The information from the vision tracking system was used a s input to a closed loop fuzzy logic controller to control the steering and the speed of the robot.

2. Design Team

The design team consists of both undergraduate and graduate students was organized as shown in Figure 1.

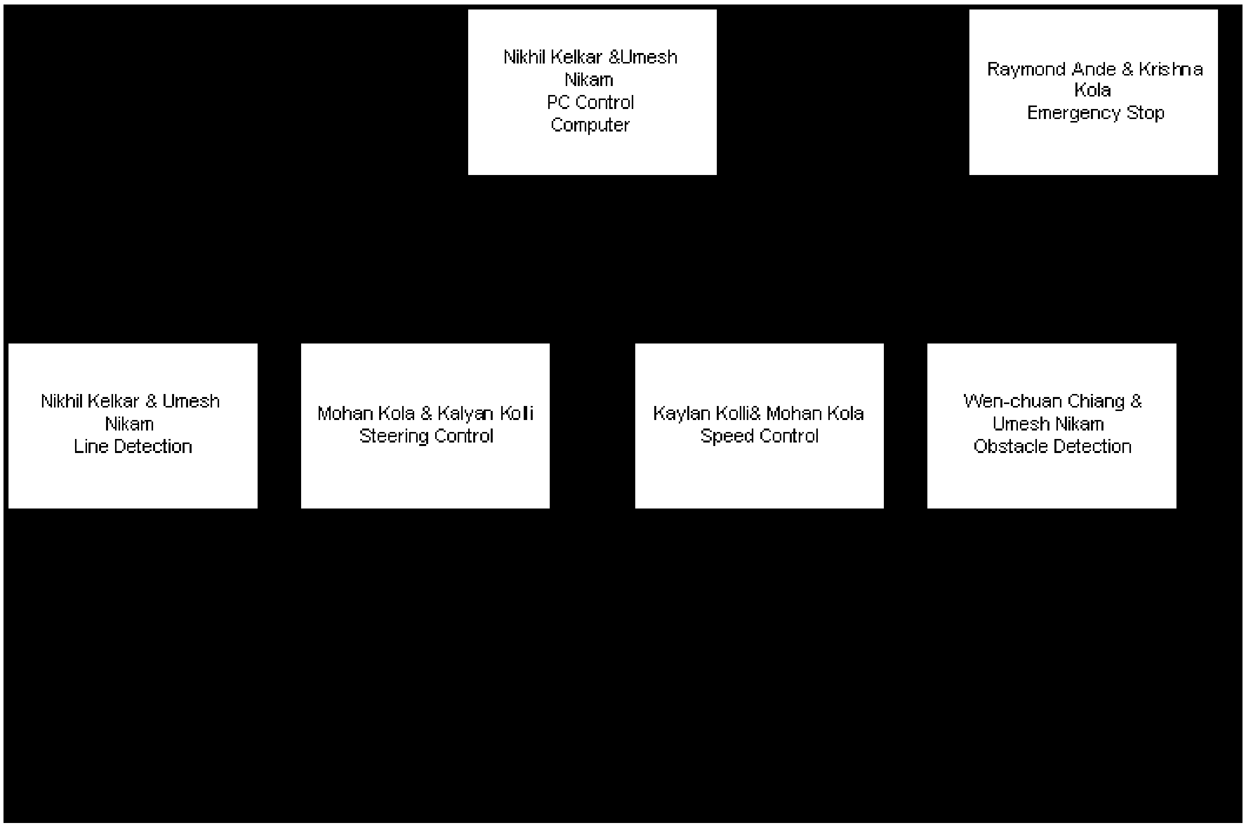

Figure 1 UC Bearcat Team Organization

The design was approached by several brain stroming sessions, then deciding on a plan, and finally deviding the work among the team. A strategy was adopted by the team that each person should not only know how to design their part, bu t should also understand and know how to operate each part of the system. Also, one person was selected to be quality control and troubleshooting diagnostic expert. The team leader, Nikhil Kelkar, was responsible for coordinating the overall team activ ities. He also designed the fuzzy logic controller and worked closely on the vision system with Tayib Samu. The sonar system was designed by Wen-chuan Chiang with assistance from Umesh Nikam and Raymond Ande. The steering control was designed by Kaylan Kolli, Krishnamohan Kola and Nikhil Kelkar. The speed control was designed by Krishnamohen Kola and others. The emergency stop was designed by Raymond Ande and Umesh Nikam. A major diagnostic program was designed by Umesh Nikam and the entire team. < /P>

3. Autonomous Vehicle Modifications

An autonomous mobile robot is a sophisticated, computer controlled, intelligent system. It consists of a supervisory control computer which implements a fuzzy logic control based upon inputs from the vision system, sonar range finder, speed encoder for steering, and emergency stop subsystems. The electrical layout of the UC mobile robot system is shown in Figure 2. The main elements are the control computer, speed control, obstacle avoidance, vision syste m, and emergency controls. Each of these major components will be described in the following sections.

Figure 2 Overall traction control system.

3.1 Speed control

The robot base is an E-Z-Go golf cart. This cart is driven by a 36-volt, 55 amp. traction motor. Several designs were considered for controlling the large amount of power required for the traction motor, including: re lays, power MOSFET's, and Insulated Gate Bi-polar Transistors (IGBTs). For the final design we choose the GE EV-1 speed controller. This is a commercial controller designed for fork-lift and other industrial electric vehicles. The EV-1 is a silicon con trolled rectifier (SCR), pulse width modulation (PWM) controller with a 0-10 volt control signal coming from the Galil DMC-1030 motor controller and sufficient output to drive the traction motor at full power. To complete the control loop, we have a BEI encoder mounted inside the front wheel. The encoder position signal is numerically differentiated to provide a velocity feedback signal.

Safety is of primary concern in the system design. For safety reasons, the EV-1 has a set of three sequential switches which must be activated in order for it to run. That is, the machine cannot be turned on by a single switch, a sequ ence of three switches must be activated in a prescribed order. Also in the main power loop is a solenoid connected through three E-stops, the remote stop, as well as through the computer. This design should prevent any possible runaway of the vehicle since it provides a disconnect of power to all systems and application of the brake, not just breaking the control circuits.

3.2 Steering Control

The steering system of the AGV helps maneuver it to negotiate curves and avoid obstacles on the course. The system uses a crank and connecting link mechanism which is actuated by the lead screw of a Parker linear actua tor. The lead screw is driven by an Electrocraft brushless DC motor, which in turn is controlled by an Electrocraft BDC - 12 brushless motor amplifier powered by a Galil power supply.

The design objective was to obtain an absolute control over the steering system with a good phase and gain margin and a good unit step response. For this purpose a Galil motion control board was used which has the proportional integral derivative controller (PID) digital control to provide the necessary compensation required in the control of the motor. The system was modeled in MATLAB using SIMULINK and an actual simulation was done with various values for the three parameters of th e PID controller. Some of the problems faced in the design process were in the estimation of the inertial load. An error in the calculation led to overloading the amplifier and burnt it out. The remedy was to specify a torque limit in the Galil motio n program which would limit the drive torque, current and voltage supplied by the amplifier. Other problems like setting the hardware control bias voltages on the amplifier were solved. Estimation of the torque was done analytically and then actually me asured using a torque wrench.

The objective of the design was to generate enough torque to move the front wheel even when the robot was stationary, to take input from the main control program to adjust to follow the line and avoid the obstacles, to steer in order to keep the robot on the track while trying to stay in the track.

The interface for the system was implemented using a Galil 1030 motion control computer interface board. A Galil breakout board permits the amplifier and encoded to be easily connected. The steering mechanism gets its input from the angle to be moved by two inputs : the angle from the obstacle avoidance and the angle from the vision algorithm. Feedback is provided at a low level by a position encoder and at a high level by the vision and sonar systems.

The original steering system of the 3 wheeled cart used a rack and pinion design. This was replaced by a computer controlled steering which is a lead screw design activated by a Parker linear actuator. This linear actuator produces 11 0 ft-lb. of torque creating a maximum turning speed of 20 degrees a second. This motor is controlled from the computer through the Galil DMC-1030. The DMC 1030 signal is amplified by an Electro-Craft amplifier which provides three phase voltages to the brushless DC motor amplifier. For position feedback, a BEI encoder is directly mounted on the steering wheel giving us a positive position feedback with 0.20 degree resolution.

Various tests were performed on the steering system. The frequency response was measured by supplying a sinusoidal input signal to the open loop system and recording the response through the encoder. A phase margin of 40 degrees and a gain margin of 10 decibels was achieved. Then the step response was checked to minimize the overshoot and select a critically damped response. The actual tests were made in three conditions: steering wheel off the ground, steering wheel on the ground w ith robot moving and steering wheel on the ground with robot stationary. The torques for these conditions were measured at: 15 foot pounds, 20 foot pounds and 30 foot pounds, respectively. Tuning of the amplifier parameters especially loop gain and sele ction of the PID parameters were very important and required iterative adjustments.

3.3 Emergency Stop and Braking system

The Emergency stop system must be activated by remote control from a distance of at least 50 feet. This is accomplished by a remote controlled circuit that activate the brake and cuts power to the traction motor. The brake motor is comprised of a Delco power window motor, attached through a cable, which pulls the existing brake pedal down. When the pedal is fully depressed a circuit holds the brake and upon release, reverses the direction to release the brake. The use of the existing brake mechanism has the advantage of being sized properly for the traction motor as well as keeping costs to a minimum. The brake is controlled through a separate power and control system, and is activate by remote control to accompli sh the emergency stop requirement. In addition, three emergency stop buttons are located on the rear and both sides of the vehicle. When activated, these cut the power to the traction motor. A schematic of the system is shown in Figure 3.

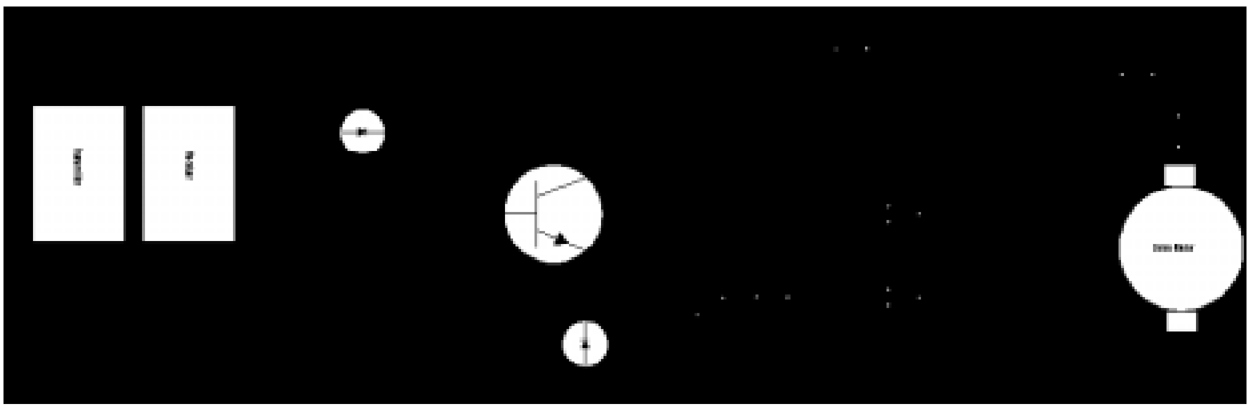

Figure 3 Emergency stop system

4. Obstacle avoidance

The obstacle avoidance system is based on Polaroid ultrasonic sensors. In testing the sensors, it was found that the sensors could accurately detect an obstacle from a distance of 32 ft; however, the most reliable distance measurements were from short distances. The design can accomodate up to six sonar transducers at 30 degree intervals, yielding a 180 degree coverage in the front of the vehicle. The six transducers are divided into two halves, left and right. This division was used for computing the steering angle correction. The system, like the human brain, is connected in a decussating pattern enabling individual left and right control. The disadvantage to this is that it leaves a 6.5 ft blind spot directly in front of the car; however, since the car is moving at 7.3 ft/sec, it would have had to detect any obstacle that close earlier to avoid it. Since the use of ultrasound involves an extensive amount of processor time, in waiting for the echo t o return, all obstacle avoidance control was handled by a Motorola micro-controller. This micro-controller does all timing and distance calculations. In using the sensors at different angles, we have associated with each one a maximum range and a maxim um steering angle as shown in Figure 4.

Communications is achieved using a four port RS-232 protocol over the control computer's serial port. The computer is continually scanning for steering corrections due to obstacles. Once an obstacle is detected at a minimum distance, the control program corrects the steering angle. While the vehicle is in obstacle avoidance mode it, completely ignores the lane markers; however, when the obstacle signal is gone the vision signal again takes over the control.

5. Line Tracking

5.1 Vision processing Equipment

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. Ima ge processing is accomplished by the Iscan image tracking device. 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. 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 the vision system.

5.2 Angle and minimum distance algorithms

To determine the angle and minimum distance to the lane markers, the following general algorithm is used:

1. Move window to first position

2. Capture first point

3. Move window to second position

4. Capture second point

5. Calculate angle and distance of the line, through the following method

5.3 Calibration algorithm

A calibration device was constructed to permit measurement of corresponding three dimensional object points and image points. The determination of the camera focal lengths and the orientation of the projection system (system identifi cation) with respect to the global coordinates system can be obtained by several methods as described in the introduction. In this study, a calibration device was constructed to accomplish system identification.

5.4 Calibration Device

Figure 5 shows the calibration device lying on a scaled graph sheet. The device comprises a wooden base, painted black for contrast, six white ping-pong balls shaped knobs, and two five inch long poles. The wooden base is 14.5" x 11.5" x 0.75". Four of the balls are placed on the same plane (the surface) of the wooden base while the other two balls are supported by the poles which are pinned to the wooden base. Six other darkened points are spotted on the graph sheet, bringing th e total points considered for the calibration to twelve. The points on the graph sheet are considered to be on the ground level. Starting from the surface of the wooden base, the balls are given alphabetic labels in a counter clockwise direction. Eac h of the corners of the wooden base is numerically labeled, also in a counter clockwise direction, with the corner #1 coinciding with ball A.

Accurate measurements of the exact coordinates of all the twelve points with respect to the reference point is an essential factor in the calibration process. To attain the needed high accuracy, a coordinate measuring machine, whose accuracy is about ± 0.0001", was utilized to measure the centroid of the six balls with respect to the tip of corner #1 of the wooden base. The darkened points on the graph sheet are also precisely located with respect to the tip of corner #1. To obtain the actual phy sical measurements of each of the twelve calibration points with respect to a reference point, in this case the centroid of the robot, the X and Y distances between the tip of corner #1 of the wooden base and the centroid of the robot is carefully and pai nstakingly measured.

Each point of the calibration system now has an accurate physical coordinate with reference to the centroid of the robot and their corresponding image coordinates are obtained via Iscan, the image processing tool. From the physical and image coordinat es, the camera parameters (coefficients) are computed.

5.5 Results of the Calibration Process Using the Direct coefficients computation approach

Unlike the stereo vision principles model where the scaling was expressed as a discrete equation, this model treated all the transformational operations, including scaling to be embedded into the coefficients. To solve for the coefficients, the follow ing set of calibration data points were utilized. Table 3 has the data points while the camera parameters is indicated in Table 4. Figure 6 shows the data point plots for the model and calibrations.

Table 3. Set of Calibration Data Points

Points	Physical Coordinates			Image Coordinates	
	x	y	z	x	y
1	56.481	74.547	-22.533	197	160
2	63.971	74.554	-22.524	316	187
3	63.971	85.048	-22.564	263	86
4	56.456	85.083	-22.552	152	54
5	60.544	76.609	-19.057	303	125
6	60.495	83.0375	-19.034	270	62
7	53.375	72.5	-24	134	182
8	53.375	82.5	-24	94	74
9	57.375	86.5	-24	143	55
10	62.375	86.5	-24	218	77
11	67.375	82.5	-24	305	131

	12	67.375	72.5	-24	356	230

Table 4. Camera Parameters

			Coefficients				
A11	A12	A13	A14	A21	A22	A23	A24
15.4	-4.353	14.213	-27.405	3.807	-9.919	-7.895	505.123

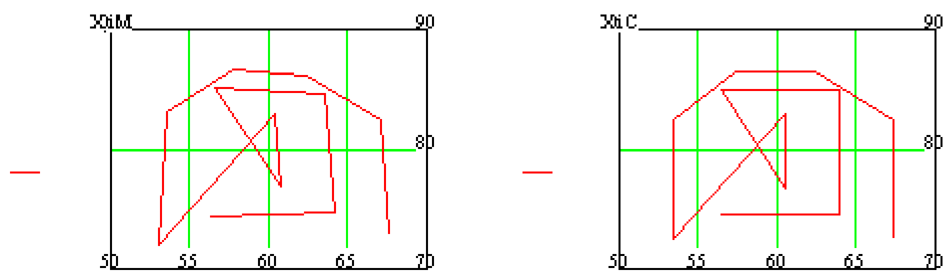

Figure 6. Data points for evaluating the direct coefficients computation model

The deviation of the model points from the calibration points shown in Figure 6 is minimal. With an accuracy of about tenth of an inch, this model has proven to be the best among the three models considered in this study. As a result of this reliable performance, the direct coefficients computation model was thus implemented to solve the vision problem.

5.6 Experimental Results for the Vision System

The computation of the camera parameters sets the stage for computing the physical coordinates given any image coordinate. To show how the physical coordinates are computed given any image coordinate, another calibration was performed to obtain camera parameters. As discussed in the previous chapter, the mathematical model implemented henceforth is the direct coefficients computation method. Equations (17-19) were used in the computation of the physical coordinates. Note that the z- coordinate for each of the points was treated as constant because in the real time implementation of this method, the z-coordinate is constrained by the ground. Table 5 shows the calibration parameters and the results of the physical coordinate computatio ns is shown in Table 6.

Table 5. Camera Parameters

			Coefficients				
A11	A12	A13	A14	A21	A22	A23	A24
14.7	-11.501	-1.189	415.456	-3.567	-5.521	-9.944	559.417

Table 6. Set of Original and Computed Calibration Data Points

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

Correlation plots for the original and the computed x and y coordinates were computed. The linearity of the plots means that the difference between the original coordinates and the computed ones is very small. Also computed to ascert ain 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 was 0.242 for the x-axis and 0.295 for the y-axis. With a mean square error of within tenth of an inch, t he calibration process is considered as accurate and reliable enough to compute the physical coordinate of a real life point on a ground. Having dealt with the computation of the x and y coordinate of a physical point with respect to the centroid of the robot, the next item considered in this study is how to spot more than one point, two points to be precise, on a line and establish some geometrical relationship between the points and relate it to the centroid of the robot.

5.7 Vision System

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 algorithms. From these calc ulations the angle and distance are then sent to the motion control sub-system.

6. Control System

The upper level control scheme is based on a fuzzy logic, hierarchical control system. The cart is, at its lowest level, told to go straight, at top speed. It is only when either of the sensors interrupts it, does it change. The visi on system, when it recognizes a discrepancy between the actual and desired position, will correct the steering. Whenever the ultrasound detects an obstacle, it will override the straight motion as well as the vision system. This order is designed for th e AUVS competition where the vehicles main objective is to go as far in as short of time, as possible, for other applications the order may be different, where the cart would only go if there were lines in sight.

7. Results Of Testing

7.1 Obstacle avoidance

In our obstacle avoidance testing, we first discovered that the sensors were too low, picking up the grass and forcing a constant side-to-side motion. This was corrected using blinders that direct the sonar signals awa y from the grass. While it worked, we found more blind spots in its forward looking view. Each sonar can see 30 degrees; however, the effective range at the outer limits decreases significantly. We will have to add more sensors at smaller angles. Also when the cart steers around obstacles, it has a tendency to resume line following too early and have the middle or rear collide with the obstacle. This can be corrected by again adding sensors, one in the middle of the length so that the car will only co rrect when it has passed the obstacle.

7.2 Vision

In the ongoing vision guidance testing, we have made several changes. The most notable was a test with the regular JVC camera. The system was capable of following shallow turns in either direction; however, as it appr oached a hard left turn, it crossed over. This was due to two major causes; first the speed of the cart was not proportional to the steering, leading to an insufficient amount of time to correct for the new angle. Even with this factor added in as it is now, it still crossed the line. This second failure was due to the fact that even while slowing down, the small viewing area of the camera lost sight of the line, and therefore still crossed over. This emphasizes the need for a non-lurching type mobile robot traveling at high speeds with sharp turns, to use the omni-directional system.

8. Conclusion and Recommendations

A stable test platform has been designed, constructed and tested. However, advanced control techniques need to be investigated. The system's modular design lends itself to a subsumption architecture, whereb y any number of sensor systems could be connected and with a minimal programming effort be efficiently utilized. Also the use of a more heuristic methodology in the obstacle avoidance should be investigated. For the system to be more efficient and able t o go at faster speeds, interrupt handling is a must. The program would then not have to constantly poll the obstacle avoidance or vision systems. Also, the motor control needs to have an interrupt to inform the control program when it has completed its move.

A modular system has been developed for the 1997 AUVS competition. The costs of this project have been kept at a minimum and to fully rebuild it would cost about $20,000. The system embodies speed control, vision line tracking and ult rasonic obstacle avoidance. The design utilizes independent sensor modules. These modules could be placed on any system and control it with minimal modifications.

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