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16. Abstract

The present system of urban transportation largely consists of a system of manually operated vehicles operating over a passive system of highways. The two have little interaction, and for the most part, were designed independently of each other. As traffic has increased so has congestion, but the traditional response of adding more lanes to streets and freeways has become undesirable or impractical. The unmistakable conclusion is that our system of passive highways and manual vehicles must be modified. An alternative approach is to apply automation techniques to vehicles and roadways to increase the capacity and efficiency of existing facilities while retaining the advantages of individualized mobility; this is the concept of an automated highway system. The objective of this research is to develop an autonomous vehicle which utilizes stereo camera sensors (using ambient light) to allow complex paths at speeds up to 35 mph and consideration of moving vehicles within the path. This task is intended to demonstrate the contribution to safety of a vehicle under automatic control. All of the long-term scenarios investigating future reductions in congestion involve an automatic system taking control, or partial control, of the vehicle. A vehicle which includes a collision avoidance system is a prerequisite to an automatic control system. This report outlines the results of a constrained test of a vision controlled vehicle. In order to demonstrate its ability to perform on the current street system the vehicle was constrained to recognize, approach, and stop at an ordinary roadside stop sign.

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AN AUTONOMOUS VEHICLE-CONSTRAINED TEST AND EVALUATION

by

Norman C. Griswold
Associate Research Engineer
Texas Transportation Institute

Research Report 1245-1

Research Study Number 2-1-90/1-1245
Texas Advanced Transportation Technology Project

Sponsored by

Texas Department of Transportation

Texas Transportation Institute
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College Station, Texas 77843

November 1991

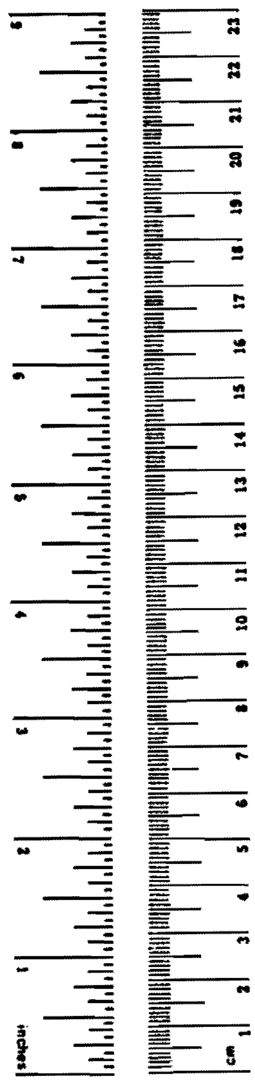
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

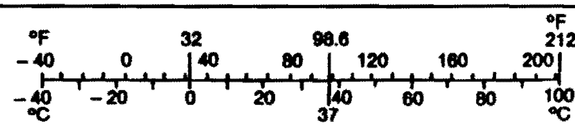
NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

IMPLEMENTATION STATEMENT

The Texas Department of Transportation is investigating methods of providing increased mobility for the major urban areas of Texas. California DOT through its Program for Advanced Technologies for the Highway (PATH) is looking to the future of using vehicle control systems as a method of making better utlization of the street and road system. This report investigates the posibilities of using an autonomous vehicle based on computer vision as a method of controlling vehicles. The safety of vehicles under control would have the potential of vastly reducing the number of accidents in areas where the vehicles were under control. While the findings of this report may not be installed as a part of the initial traffic management centers it should provide a context continueing to investigate the safety of the highway system.

DISCLAMER

ABSTRACT

The present system of urban transportation largely consists of a system of manually operated vehicles operating over a passive system of highways. The two have little interaction, and for the most part, were designed independently of each other. As traffic has increased so has congestion, but the traditional response of adding more lanes to streets and freeways has become undesirable or impractical. The unmistakable conclusion is that our system of passive highways and manual vehicles must be modified. An alternative approach is to apply automation techniques to vehicles and roadways to increase the capacity and efficiency of existing facilities while retaining the advantages of individualized mobility; this is the concept of an automated highway system. The objective of this research is to develop an autonomous vehicle which utilizes stereo camera sensors (using ambient light) to allow complex paths at speeds up to 35 mph and consideration of moving vehicles within the path. This task is intended to demonstrate the contribution to safety of a vehicle under automatic control. All of the long-term scenarios investigating future reductions in congestion involve an automatic system taking control, or partial control, of the vehicle. A vehicle which includes a collision avoidance system is a prerequisite to an automatic control system. This report outlines the results of a constrained test of a vision controlled vehicle. In order to demonstrate its ability to perform on the current street system the vehicle was constrained to recognize, approach, and stop at an ordinary roadside stop sign.

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1. DESCRIPTION OF THE RESEARCH

A. Introduction and Background

The past decade has witnessed an explosion in interest in the development of an autonomous land-vehicle (ALV). As the first word in the name indicates, an ALV is a mobile device which operates independently — that is, without human control. Such a vehicle requires some form of intelligence to make decisions based on it goals and what it learns from experience. No devices have been built which do these things, but rudimentary steps are being made toward this goal.

ALV's have been proposed for many applications. In the U.S., an unmanned land rover to be used in the exploration of Mars and an unmanned military vehicle have been the goals of work supported by the National Aeronautics and Space Administration's Jet Propulsion Laboratory (NASA JPL) and the Defense Advanced Research Projects Agency (DARPA) Strategic Computing Project. Other groups have worked on everything from a robotic lawn mower to a surveillance vehicle for use in a nuclear power plant.

The orientation of the majority of American research has been toward developing militarily useful ALV's, because DARPA has been heavily financing much of the work in the field. State-of-the-art processors, workstations, and range-finding equipment have been used in these systems. The commercial application of ALV's in the civilian world will demand that more inexpensive and practically adaptable systems be constructed.

Both Europe and Japan have major projects. In Europe, the projects are coordinated throughout the European Community (EC). DRIVE is largely sponsored by the governmental units with the primary objective of defining "road transport informatics" for the communities. A high priority of the European Community is to integrate DRIVE with the industry sponsored projects of EUREKA, of which PROMETHEUS is the best known in the United States. Japan has three major projects which combine vehicle navigation with real-time traffic information.

The Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration have had a continuing interest and involvement in advanced technologies which could improve traffic operation. This need has been emphasized by the support, cooperative meetings and workshops held such as *Mobility 2000*. The *Mobility 2000* program has evolved as a forum of exchange for projects funded in states such as Texas, Michigan, Massachusetts, and California. In major studies of highway operational needs for Project 2020 various State and Federal organizations have recognized the need for advanced technology in highway systems. Strategies are now being formulated to ensure national availability of useful technologies which address the problems of congestion relief, safety highway operations, high speed rural travel, automatic vehicle identification, use of robotics in maintenance and new methods of data gathering and analysis.

Mobility 2000 workshop reported the extent of congestion escalates from the smallest urbanized areas to the largest cities. Cost of delays in some 25 largest cities together with fuel costs and added insurance costs totaled $42 billion dollars. Data from current transportation management systems in California indicate 35 percent reduction in stops, 20 percent reduction in delays, 10 percent reduction in emissions and 13 percent less travel time. Vehicles equipped with driver information systems and communicating with a traffic management system can further reduce traffic incidents. Better control of any incident will assist in more rapid clean up of the incidents and minimize secondary accidents.

This technology helps make it possible to weigh vehicles in motion. Already, tolls can be charged to a vehicle in motion. Weighing-in-motion reduces delays at weigh stations and ports of entry. Checking and issuing permits can be made in motion. A regulator can check to determine if the vehicle has had a recent inspection under the Commercial Vehicle Safety Alliance. A vehicle carrying hazardous materials can be identified. The status of the driver can be checked, and the validity of his commercial driver's license. Compliance with hours-of-service can be checked. Vehicle speed can be monitored. Stolen vehicles can be identified. All of this can be done while the vehicle is in motion through the use of a programmable transponder in the vehicle and a compatible device in the highway. These will provide substantial benefits in productivity to carriers and cost reductions to regulators.

Substantial productivity improvements for commercial vehicle operators will occur when real-time routing can be achieved. It should be possible to provide real-time route information, projected arrival times, as well as local weather, and highway maintenance information as a part of an interactive program.

Systems that provide real-time routing will also meet the specific needs of emergency vehicles. There is a real need for improvement in the ability of public sector institutions to adopt efficient dispatch operations for police and fire vehicles.

It is possible to identify spin-offs in terms of safety, very high speed intercity travel, and high productivity use of the highway system.

While the European and Japanese programs address local problems, they also are intended to achieve a superiority in international competition for supplying the components required for an Intelligent Vehicle and Highway System. While the European and Japanese governments are funding such developments in the order of 20 M dollars in years '89 and '90 no *consensus* of what to do or how to approach Intelligent Highway Systems or Autonomous Vehicles (for highways) exists in the United States.

This is not an inditement of indecision but an awareness that research and technological problems exist which can only be resolved in an academic posture targeted to resolve these issues necessary for real implementation. The purpose of this task as part of this research is to attack some of these analytic problems.

B. Initial Objectives

The primary objectives of this task (Autonomous Land Vehicle) were to:

1. Complete installation of the system executive (a COMPAQ 386/20 computer) in conjunction with a computer vision sensing system.

2. Demonstrate constrained tests consisting of complex routing, obstacle avoidance and a full stop at intersections.

This task is part of an overall program to develop an autonomous vehicle which will provide a test bed for knowledge-based systems. Proof of concept will be provided by navigation, guidance, and planning tasks autonomously. Texas A&M's approach to an autonomous vehicle is by necessity a building block approach intended to establish a demonstration of the technology and attract major funding. It is our contention that this model will allow our Artificial Intelligence developments to far surpass what is presently being accomplished.

The major thrusts in this program are: (1) utilization of stereo camera sensors as opposed to radar; (2) architecture which allows complex paths and speeds up to 35 miles/hour; and (3) consideration of moving obstacles.

2. Status of Task

A. Autonomous Vehicle Structure and Environment

The program objectives fall into two major categories. The first consists of completing the installation of the system executive (a COMPAQ 386/20) in conjunction with the vision system for recognition and vehicle control. Secondly it is necessary to provide the supporting research and software programming to demonstrate vehicle performance under the constrained test environment. In this section we discuss the structure and installation changes associated with this task. In this regard the COMPAQ 386/20 system executive needed modification. The computer architecture for the Texas A&M Vehicle is shown in Figure 1. The system executive must have sufficient memory to perform the executable programs.

Typical programs are: 1.) pointing the camera system; 2.) frame grabbing the video data for processing; 3.) determining range to an object; 4.) general signal processing tasks; and 5.) output commands to the system controller.

Additional RAM memory was needed to allow an additional "D-disk" [executable programs in RAM memory] to be installed.

Approximately 10 M-bytes of RAM have been installed. It was then necessary to write a "DRIVER" to access this disk memory and actually allocate space and instructions to peripheral equipments.

A. 2. Micro-Soft "C"

The next installation type task was that of programming all software modules and installation of Micro-Soft "C" libraries to perform writing, editing, compiling and executable file generation (Linking). This task was completed and all system modules are now operating in the programming language "C."

A. 3. Frame-Grab

A video frame grab system was purchased from Imaging Technology Corporation. The purpose of such a peripheral is to connect the visual system to the computer by storing sequential frames of video as stereo pairs. This system, referred to as a FG-100 has been installed and tested.

It was necessary to modify the ITEX manufactured software to store up to sixteen images of size 256 x 256. This is equivalent to eight stereo pairs. Stereo imaging is necessary to provide control and range calculation. The modified program was generated and successfully compiled in an IBM-PC. Library malfunctions delayed installation of this software in the COMPAQ 386 within the vehicle. The problems were over come in January of '89 and a complete stereo ranging system was installed in the vehicle. After tests a practical processing time limits the system to 4 stereo pairs per second. However, depending on the necessary processing time for algorithms and real-time control, prediction between frame grab sequences proved to be necessary.

A. 4. Power Supply:

In most vehicles it would seem practical to operate with a d.c. (direct current) battery type system. However, the COMPAQ expects an A.C. (alternating current) input, namely; 120 Volts identical to laboratory capability. The choices seem to be apparent. We could

1. Modify the power supply on the COMPAQ

2. Operate with "Lap Top" type d.c. input computer

3. Generate the A.C.

The first two options were discarded because the COMPAQ 386/20 was needed in both Laboratory and Vehicle Tests. Secondly, "lap top" type computers, simply cannot contain sufficient memory and peripheral bounds to operate all the modules and systems aboard the vehicle.

The third option was chosen for its expeditious possibilities. A system off our Gell Cell batteries and an associated 1200 Watt invertor was installed. It was estimated that all functions and programs could be operated for about twenty minutes before recharging was necessary. Unfortunately this was not the case. After running for about five to ten minutes the waveform for the 120 Volts was sufficiently distorted that the COMPAQ 386 would shut down. Secondly, the d.c. current drawn from the batteries (about 10 Amps continuously) made the cables to the invertor sufficiently hot creating a possible fire hazard.

To preclude any possible accident this system was replaced with a portable A.C. generator mounted on the right rear bumper of the vehicle. This system a has provided several days of stable, high capacity, utilization without difficulty.

During August a "driver" board for the stepper motors which control, the steering failed. This board was returned to the manufacturer without success. In early September the board was repaired at Texas A&M. Subsequent tests indicate the system was then fully functional. However, this untimely failure did preclude obtaining a video of the vehicle during the days prior to the end of the project period.

B. Research Tasks

Since the vehicle is capable of complex paths when driven in the open loop model (Pre-programmed with no error correction) the more difficult task of stop-sign recognition was attempted first.

B. 1 Stop Sign Recognition Test

In order for the autonomous land vehicle (ALV) to stop at a stop sign, it must first detect the sign and then issue commands to slow down and stop. It detects the stop-sign by searching the video image for features which define the sign. Once it finds such a feature, it compares that feature with a reference feature or template and decides whether they matched or not. A standard technique for such comparison is correlation. In correlation, a numerical measure of the "sameness" of two features is calculated, where a value of 1.0 indicates a perfect match and a value of 0.0 indicates no match between object and template. The major difficulty with this technique is that practical implementations require tens to hundreds of seconds of processing time, but decision-making when simulating actual driving conditions must be accomplished within a few seconds. (In fact, as the desired speed of the ALV increases decision-making must occur more quickly.)

Image processing speed can be improved by using logical operations rather than numerical operations. Morphological operations use this strategy to extract features from an image. Feature extraction typically takes a few seconds using a morphological edge detector on a 256 by 256 image. Then matching becomes a process of making a yes or no decision without time consuming *numerical* calculations.

The goal of this project was to endow the ALV with the ability to stop itself in front of a stop-sign using only video input as the sensor. In order to do this, the ALV needs to detect the sign, calculate range to the sign, decelerate, and stop. The test for this goal may be performed under the following constraints:

1. The ALV will start with a stop-sign already in its field-of-view;

2. The ALV will make a straight-line approach to the sign;

3. Initial range calculations of the distance to the sign will be obtained from the stereo-camera pair; and

4. There will be no speed requirements for the ALV.

B. 1. 1 Stop-Sign Recognition and Analysis

In this report, a stop-sign recognition system is viewed from a morphological filtered response in the log-polar domain. This tessellation makes it feasible to predict and calculate closure rates for a visually controlled autonomous land vehicle. Development of the recognition system for octagonal shape and its subsequent mapping to the log domain were investigated. Simulation and prediction of a vehicle's closure rates as a function of angle of view and velocity are compared to actual video when a vehicle is approaching an intersection. The impact of this research on vehicle navigation and guidance is given. A polar exponential grid sensor mapped to the log domain possesses subtle and powerful properties which may be applied in mobile applications. It is concluded that mapping to the log conformal domain makes optical flow a manageable problem in dealing with vehicle motion.

Overview of the Vision Module

The vision module proposed for the ALV consists of two parts: (1) The stereo camera portion and (2) the monocular camera portion. In the stereo portion, two cameras, which are installed within the cab of the ALV, are used for stereo calculation of range (using a convergent camera model). In the monocular portion, another camera which is mounted parallel to the body of the ALV is used for stop-sign recognition. Because color analysis requires three times the memory required than that for black and white analysis which increases the amount of information which must be analyzed, and decreases overall processing speed, it has not been used in this paper. This precludes using the red color of a stop sign in the algorithm.

In this paper, the recognition algorithm assumes that the stereo cameras supply the range to their fixation point and that the fixation point and the stop-sign are the same plane (which is perpendicular to the direction of motion of the ALV). Also, it assumes that the field-of-view and the focal length of the camera are known quantities which do not change throughout the analysis. This simplifies the problems associated with projecting the position of the sign through time.

The goal of the system is to detect and track a stop-sign as the ALV approaches, and to issue an advisory to stop at the proper time. The recognition algorithm consists of three phases Figure 2: (1) initialization, (2) stop-sign extraction or recognition, and (3) projection or prediction. These three phases have been implemented as subroutines in a main vision program. The initialization phase is designed to obtain camera parameters and supply information to the rest of the system at the beginning of a run. The extraction phase uses a morphological edge detector to pick up edges in the image. The edge map produced is analyzed for the presence of circular features by a Hough transform algorithm. This method is used because an octagon of small radius in a digital image is quite similar in appearance to a circle of small radius due to the effects of quantization. Because the stop-sign needs to be detected at a great range with respect to the focal length of the camera, the stop-sign will appear to be of small radius at the initial range. The output of this algorithm is a feature vector (x_0, y_0, r), which consists of the x and y coordinates of the center of the circle and its radius (in pixels). The projection phase then uses this vector along with the estimated range of the vehicle to determine where the sign should be in the next image acquired.

<u>Initialization Phase — Camera Set-Up</u>

Initialization of the monocular vision portion of the vision module consists of running camera set-up and complex-logarithmic-grid set-up subroutines. The camera set-up subroutine is designed to be run interactively at the beginning of the test run. It asks the experimenter for the following information: focal length of the camera (f), field-of-view (FOV) of the camera, range to the fixation point of the stereo cameras, and the number of pixels per row of the image (assuming that the image is square). It calculates the width of a pixel at the initial range, the width of the range plane (W_{rp}), and the width of the image plane (W_{ip}) (Figure 3). These calculations are based upon simple trigonometry. Here,

$$\tan\left[\frac{FOV}{2}\right] = \frac{W_{ip}}{2f} = \frac{W_{rp}}{2(f+range)}$$

thus,

$$W_{ip} = (2f)\tan\left[\frac{FOV}{2}\right] ,$$

$$W_{rp} = (2f+range)\tan\left[\frac{FOV}{2}\right] .$$

and

$$pixelwidth = \frac{W_{ip}}{N},$$

where N is the number of pixels per row. Assuming that the image is square, these relationships are the same for the vertical dimension. This information is passed to the visual knowledge base. Next, the constant speed of the vehicle must be obtained from the controller, and the user must supply the frame rate of image acquisition and the prediction rate between frames.

Initialization — Complex-Logarithmic Grid Set-Up

The second step of the initialization procedure consists of constructing a simulated polar-exponential grid (PEG) sensor and mapping each PEG pixel to its complex-logarithmic grid equivalent. The complex-logarithmic grid is useful because rotation and magnification in the PEG correspond to simple translations in the complex-logarithmic domain. Thus, image processing required to track an object which is moving toward or away from the observer becomes a simplified procedure. Weiman provides an excellent tutorial on polar-exponential and complex-logarithmic grids.

If a circle with radius r is centered at the origin of a PEG, then its representation in the complex-logarithmic grid is that of a straight line in the row $ln(r)$. A larger circle with radius $r + r_0$ is represented by a line at row $ln\ (r + r_0)$. If the radius of a circle is scaled, the corresponding line in the complex-logarithmic grid undergoes a simple translation along the log-of-radius axis. This has practical ramifications for the recognition module. If a stop-sign is a close approximation to a circle in the image plane, then its outline or edge map is simply a line in the complex-logarithmic grid. Then, decreasing the range to the stop-sign increases the "radius" of the sign in the image plane, and the line in the logarithmic grid shifts away from the origin. Based on the set-up parameters of the camera, finding the size of the sign is a matter of trigonometry. When this size reaches a value which corresponds to the stopping distance required for the speed of the vehicle, then the stop advisory should be sent to the controller. The stopping distance can be found from elementary physics.

How does one go about setting up the spacing of a PEG? The inner and outer rings of the PEG are specified by the smallest sign that the system is designed to recognize at the initial range (approximately 300 ft.) and the largest sign that will fit in the search window, respectively. The resolution in (or the **grain** of) the PEG is controlled by the distance between frames, according to the following equation:

$$\frac{Z0}{Z1} = e^{\frac{2\pi}{grain}}$$

where Z_0 is the initial range, Z_1 is the initial range minus the distance between frames, and **grain** is the number of wedges in the PEG. Thus the ratio of change in depth per image pixel transit in the PEG is fixed for *any* 3-D point in the field of view.

Mathematical Basis for the PEG and Complex-Logarithmic Grid

Given a standard image plane, one can construct a polar-exponential grid (PEG) (or its cartesian equivalent — a complex-logarithmic grid) as follows. Let the x-y image plane be a complex plane W with x the real axis and y the imaginary axis (Figure 4). Then any ordered pair (x, y) is related to the ordered pair (u, v) in the PEG by the mapping

$$W = e^{Z} ,$$

or

$$x+y = e^{u+iv} ,$$

where Z is the complex plane $(u + iv)$. By substitution using Euler's formula it can be shown that:

$$u = \ln(r) .$$

Similarly, the angular displacement of a point from the x-axis in the x-y image plane is given by

$$\theta = \arctan\left[\frac{y}{x}\right] .$$

Substituting, as before, for x and y, the equation becomes

$$\theta = \arctan\left[\frac{e^{u}\sin(v)}{e^{u}\cos(v)}\right] ,$$

Now, the complex-logarithmic grid is set up in terms of u and v (not exp $(u + iv)$), so the inverse mapping $Z = ln\ (W)$ must be found. Here,

$$\ln(x + iy) = \ln\left[e^{u+iv}\right] = \ln(r) + i\theta .$$

Thus, the coordinate axes in the complex-logarithmic domain are in terms of the natural log of the radius and the angular displacement from the original x-axis.

If the number of pixels in the complex-logarithmic grid is set equal to the grain, then since Θ ranges from 0 to 2π, there will be $\frac{2\pi}{grain}$ radians per pixel. Thus, to find the row p in which Θ is located, one must solve the equation

$$p = \frac{\theta}{\frac{2\pi}{grain}},$$

where $0 \leq p \leq$ grain. Since it is desirable to have square pixels, this same $\frac{2\pi}{grain}$ factor must be included in the other dimension as well. So, the column q in which $ln(r)$ is located may be found by solving the equation

$$q = \frac{\ln(r)}{\left(\frac{2\pi}{grain}\right)}$$

where $ln\ (r_{min}) \leq q \leq ln\ (r_{max})$. This means that, given any radial displacement r (in radians) from the center of the PEG, we can find the ring number q, where q corresponds to a particular row in the complex-logarithmic grid. Given another radial value $r + r_0$, the corresponding q is simply some new row number $q + q_0$.

Stop-Sign-Extraction Phase-Edge Detection

The most crucial part of the whole analysis is obtaining an accurate edge map. There are many edge operators that could possibly be used. However, the edge operator that the ALV uses must be noise-tolerant and have a fast implementation. The Laplacian enhancement operator and the Laplacian-of-Gaussian edge operator were tested on frames from a "home-made" videotape of stop-signs taken from a moving automobile. (The images were quite noisy and uncalibrated because the videotape was taken for feasibility studies, not for actual experimental use.) Neither of these operators did not produce useable edge maps. The same frames were tested with a morphological edge filter. These edge maps were of good quality, so the morphological edge filter was selected for use in this research.

Morphological filters are derived from the branch of image analysis called mathematical morphology [12], [27]. This set-theoretic field of study is based upon two simple yet powerful binary operations, called **dilation** and **erosion**. The kernel in both operations is called a structuring element. Given in set notation, the dilation operation performed on the image A by the structuring element B is

$$A \oplus B = \bigcup_{b \in B} (A + B) ,$$

where b is a non-zero element of B. In essence, each non-zero pixel in image A is translated by a non-zero element of B to produce a new image A'. The erosion operation is

$$A \ominus b = \bigcap_{b \in B} (A + b)$$

b is a non-zero element of B. Now, if the "eroded" image is subtracted from the "dilated" image, an edge feature is obtained. The edge filter is given by

$$E = (A \oplus B) - (A \ominus B)$$

where A is the image array and B is the structuring element.

The algorithm assumes that the image obtained by the "frame-grabber" is a 512-by-512 pixel image. This size (about 260 K pixels) significantly increases the time required to analyze the image for features. In order to circumvent this problem, the program removes for analysis a smaller window of size 64-by-64 pixels (or 4 K pixels). The program assumes that this window can be taken from any position within the 512-by-512 image.

Stop-Sign Extraction Hough Transformation

If an edge map is produced, the circular Hough transform is used to approximate the extraction of an octagon. The Hough transform is an image processing technique which has been widely used in a variety of applications. The circular form used here finds circular features by locating their center coordinates and radius values. In essence, the method maps a circle in the image into a point or cell in the parameter space. Sign extraction consists of sorting the contents of the parameter space to find the desired feature.

The general equation which describes the locus of a circle is $(x - x_0)^2 + (y - y_0)^2 = r^2$, where (x_0, y_0) are the center coordinates and r is the radius. x_0, y_0, and r can be treated as a vector in the three-dimensional parameter space (x_0, y_0, r). For a given pixel (x, y) in the image, there is a cone-shaped locus of points in the parameter space which satisfies the general equation. By specifying the values of x_0 and y_0, one can solve for r.

In this paper, some constraints and enhancements have been added to the Hough analysis. The program keeps track of the three largest values as it searches the "parameter space." If the largest feature corresponds to a sign which would not fit within the 64-by-64-pixel window, then it is eliminated as a candidate, and the next largest is checked. This helps the program eliminate background features of large radius. If none of the three is selected, then the program returns to the image acquisition procedure to begin again.

Projection Phase

The projection portion of the algorithm applies the most constraints to the video data. It also provides the advisory to stop the ALV.

It is assumed that the vehicle moves in a straight line which is perpendicular to the plane of the stop-sign. Furthermore, it is assumed that the distortion of the sign that occurs when an object reaches the edge of the field-of-view is small enough not to change a circle to an ellipse. The sign must be small enough to fit in the 64-by-64-pixel window until the ALV reaches the distance at which stopping must begin. If the sign exceeds the boundaries of the window before then, the program will cause the vehicle to prematurely stop.

The projection algorithm allows the ALV to make predictions about where the stop-sign will appear in the sequential views. The last known center coordinates and radius of the sign are used to extrapolate the position of the center coordinates and radius in the next instant. Typically four frames are predicted for every one actually stored in the frame grab memory. The range of the prediction plane is a function of initial range, frame rate, frame number, and camera parameters. Since we assume that the sign never changes its horizontal distance from the path of the vehicle,then the sign will appear to move away from the center of the image with time as the vehicle approaches the sign.

The first time that the sign is located in the image plane, the distance of the center of the sign from the path of the camera is estimated. Then, as the width of a pixel changes, the location of the center of the sign shifts in the image. For example, suppose that the width of a pixel in the frame corresponds to a distance of 0.5 meters in the range plane, and the center of the sign is displaced by 5 pixels from the center of the image. Then, the sign should be 2.5 meters away from the path of the camera in the range plane. Suppose that when the ALV advances, the width of a pixel is calculated to be 0.4 meters. Thus, the center should be displaced by $2.5/0.4 = 6.25$ pixels. Since the pixels are referred to in terms of whole numbers, the displacement would be truncated to the nearest whole number, and the projection would show a one pixel shift from 5 to 6. This calculation is done for each projection made between frames. The last projection in the sequence is compared with the next frame acquired to obtain a difference vector, which may be used for error correction in future projections.

3. RESULTS

In order to demonstrate the capabilities of the algorithm, a sample frame from a videotape is analyzed below. (In the following images, the origin is located in the upper left corner, the x-axis points toward the right, and the y-axis points down.) The 512-by-512 pixel frame contains a gray-scale image of a typical intersection with a stop-sign (Figure 5). Figure 6 highlights the 64-by-64-pixel search window in reverse video. This window is centered at $(x, y) = (370, 270)$ in the 512-by-512 image. Figure 7 contains the edge map produced by morphological edge detection. The best-fitting circle based on the Hough transformation is shown in Figure 8. For this case, the parameter space vector is $(x_0, y_0, r) = (42, 36, 10)$; that is, the best-fitting circle is centered at $(x, y) = (42, 36)$ in the search window and has a radius of 10 pixels. For purposes of illustration, the algorithm has been supplied with the following set-up parameters: range = 91 meters, FOV = 5 degrees, f = 11 mm, frame rate = 1 frame/sec, speed = 20 miles/hr, prediction rate = 4 estimates/sec. The four projection vectors produced are P1 = (45, 36, 10),P2 = (48, 36, 10), P3 = (51, 36, 10), and P4 = (55, 36, 10). Figures 9-12 show the estimated position of the sign which corresponds to these four projection vectors. The fourth vector tells the ALV where to look for the sign in the next frame. Thus, the search window will be placed at $(x, y) = (393, 274)$ in the next frame. The mapping of the "radius" of the sign to the complex-logarithmic grid is shown in Figure 13. The dashed line is the stopping threshold and the dotted line shows the current "radius." Obviously, the current "radius" is larger than the threshold, so the ALV would have received the stop command before this time if this frame has been part of an actual test sequence.

4. DISCUSSION

In this section, the weakness and capabilities of this system are discussed. The weaknesses are treated first. The stop-sign recognition system is predicated on being able to accurately calibrate the camera. This means that pixel (256, 256) corresponds to the focus-of-expansion of every frame analyzed, that the lens is virtually distortion-free, and that the focal length and field-of-view are accurate. Second, it is assumed that the cameras are analyzing a scene in which the contrast between the stop-sign and background is sufficient for detection of edges. Scenes in which contrast is small may produce indistinguishable features which reduces the quality of the edge map. Based on trial-and-error threshold-setting, the gray-scales value 165 was found to produce a good edge map in several scenes from the videotape mentioned earlier. This threshold may not be the most effective for other scenes with different environmental conditions. Third, the Hough transform algorithm depends upon receiving an edge map which contains a reasonable outline of the stop-sign. Misidentification is possible if other features are similar in the background and have a high accumulator value.

The strength of the system is found in its ability to reduce the stop-sign to a three-dimensional vector. This vector can be sent without modification to the rest of the system for processing. Projection of the vector through time between frames is considerably simplified. By storing information in the visual knowledge base at initialization, the data bus can be kept clear for the transfer of vital information. The complex-logarithmic grid provides a simple display form to allow the user to keep track of the status of the vehicle.

The PEG (Polar Exponential Grid) has proven useful in two ways. We have already seen that it makes tracking the apparent growth in size of the stop-sign a much simpler image processing problem. However, it also allows the ALV to "know" that the ratio of maximum range error and range is a constant (Figure 14). By contrast, in a simple cartesian representation, the ratio increases with the range. (Figure 15). The utility of this knowledge is best illustrated with a simple example. Suppose that a stop-sign is located 300 feet away from the observer. Then the ALV moves 30 feet closer, which causes the sign to be displaced by one ring in the PEG. If the sign were located 3000 feet away, then moving 300 feet closer would cause an apparent shift in the sign by the same amount, namely, one ring.

C. Other Tasks:

Two other tasks were given attention during this effort.

1. Development of a strategic plan for development of a Intelligent Highway Center

2. Collision avoidance with moving obstacles

5. CONCLUSIONS

This research has provided a framework for the development of an video-based stop-sign recognition system which can be incorporated into an autonomous land vehicle. By using a morphological edge filter to detect edges in a gray-scale image, stop-signs can be extracted from a scene. Because the edge map of an octagon is similar to that of a circle, a circular Hough transformation algorithm can be used as an approximation to finding an octagon. Once the stop-sign is identified, a complex-logarithmic grid can be used to track the approach of the ALV to the sign. The growth in the apparent size of a stop-sign in the image plane is converted to a shift in row position in the complex-logarithmic grid. By estimating the position and size of the sign between frames, vehicle control can be maintained between frames. Finally, when the stop-sign grows to size which corresponds to the required stopped distance for the ALV, the procedure sends a stop advisory to the command executive.

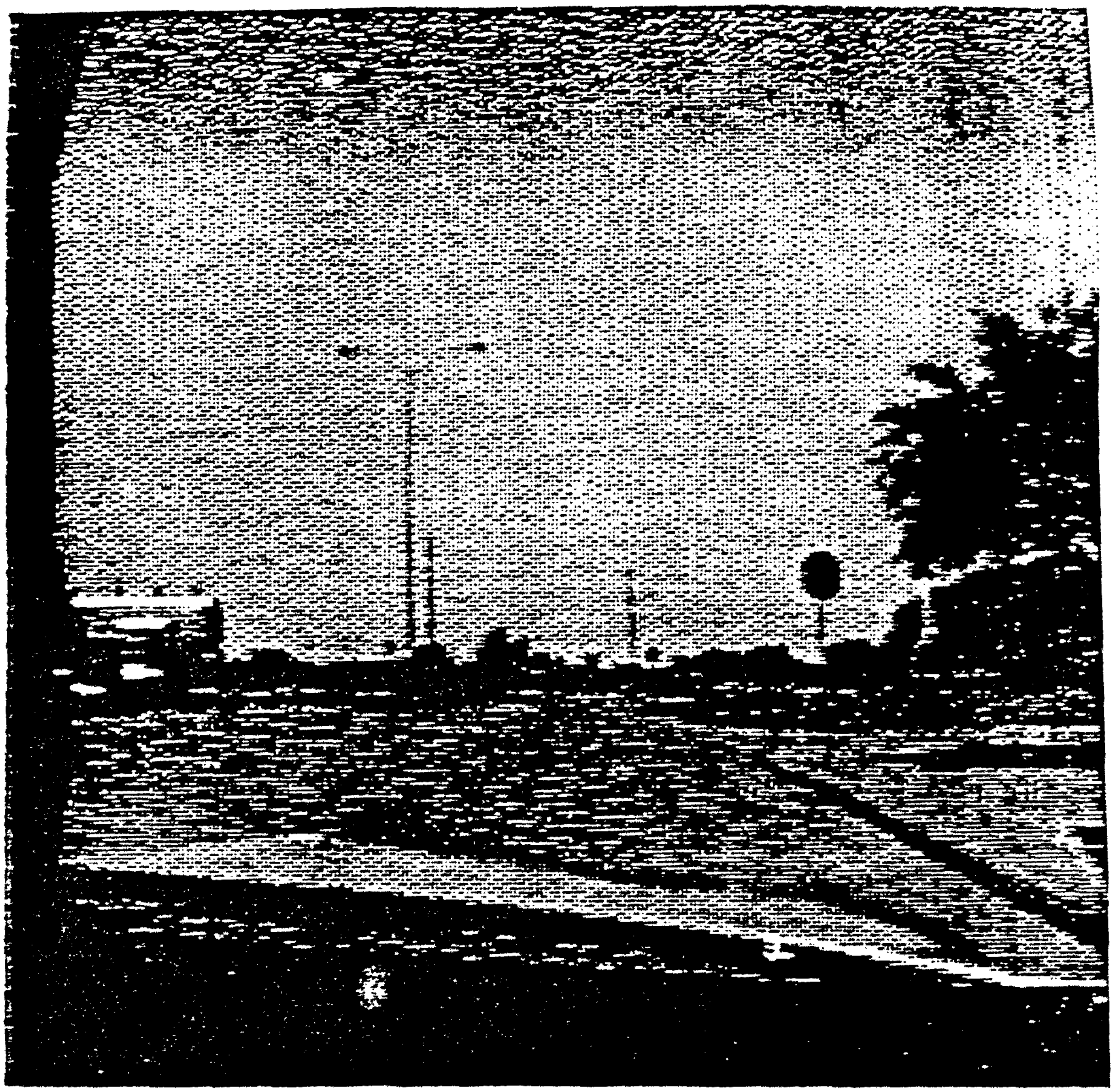

Figure 5 Sample frame of a stop-sign at an intersection.

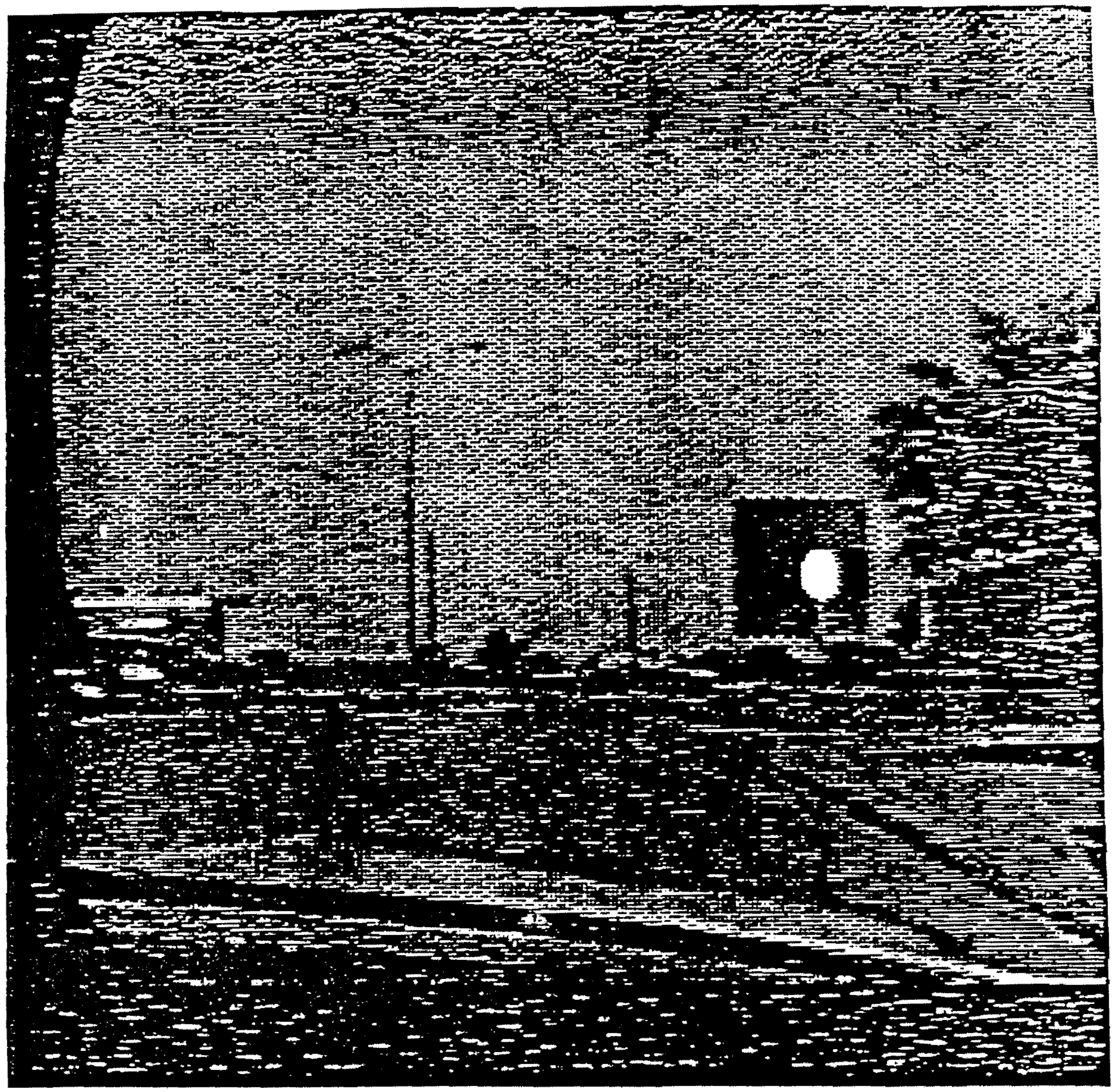

Figure 6 Sample frame with the search window displayed in reverse video.

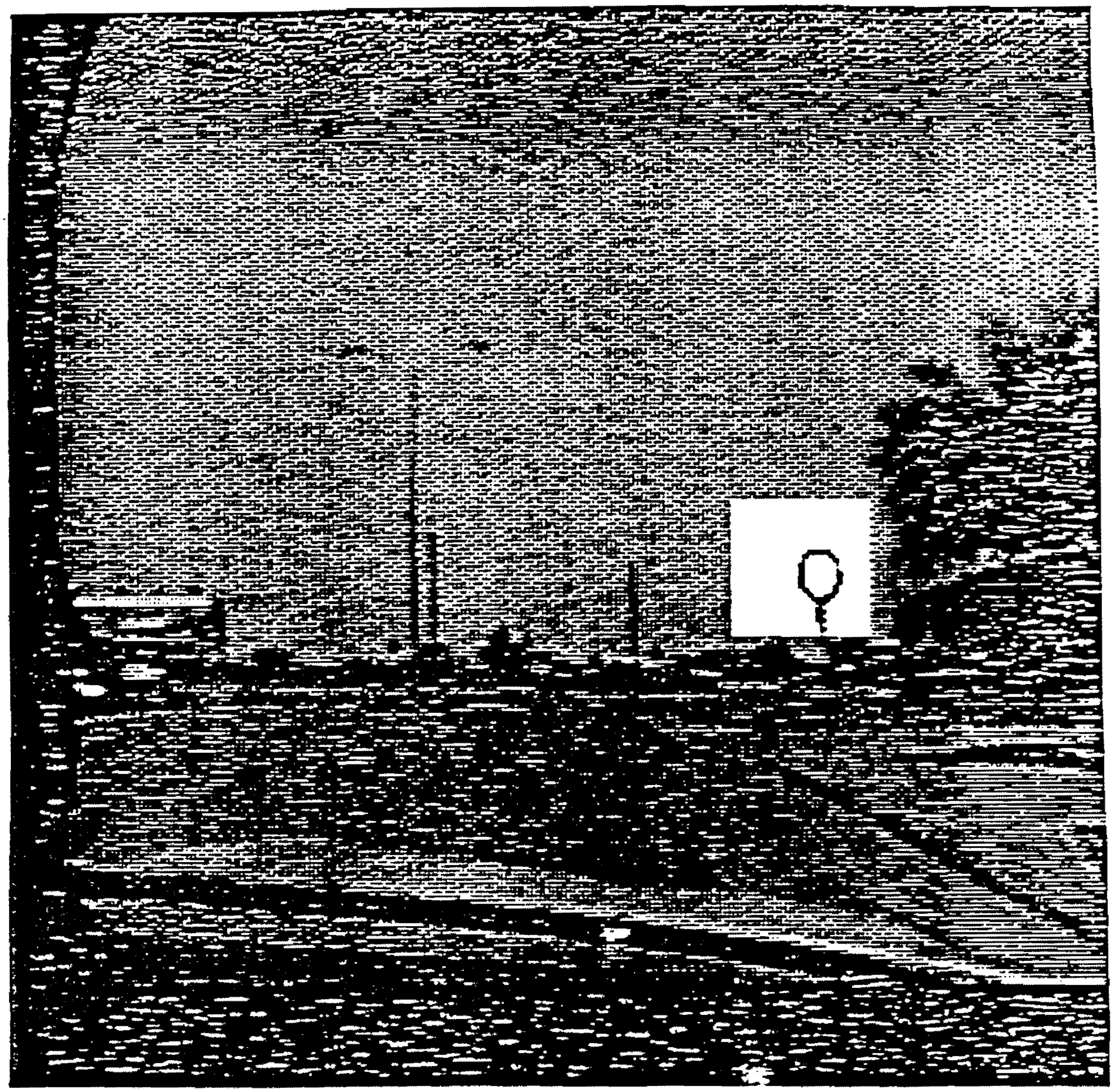

Figure 7 Edge map of the stop-sign (threshold = 165).

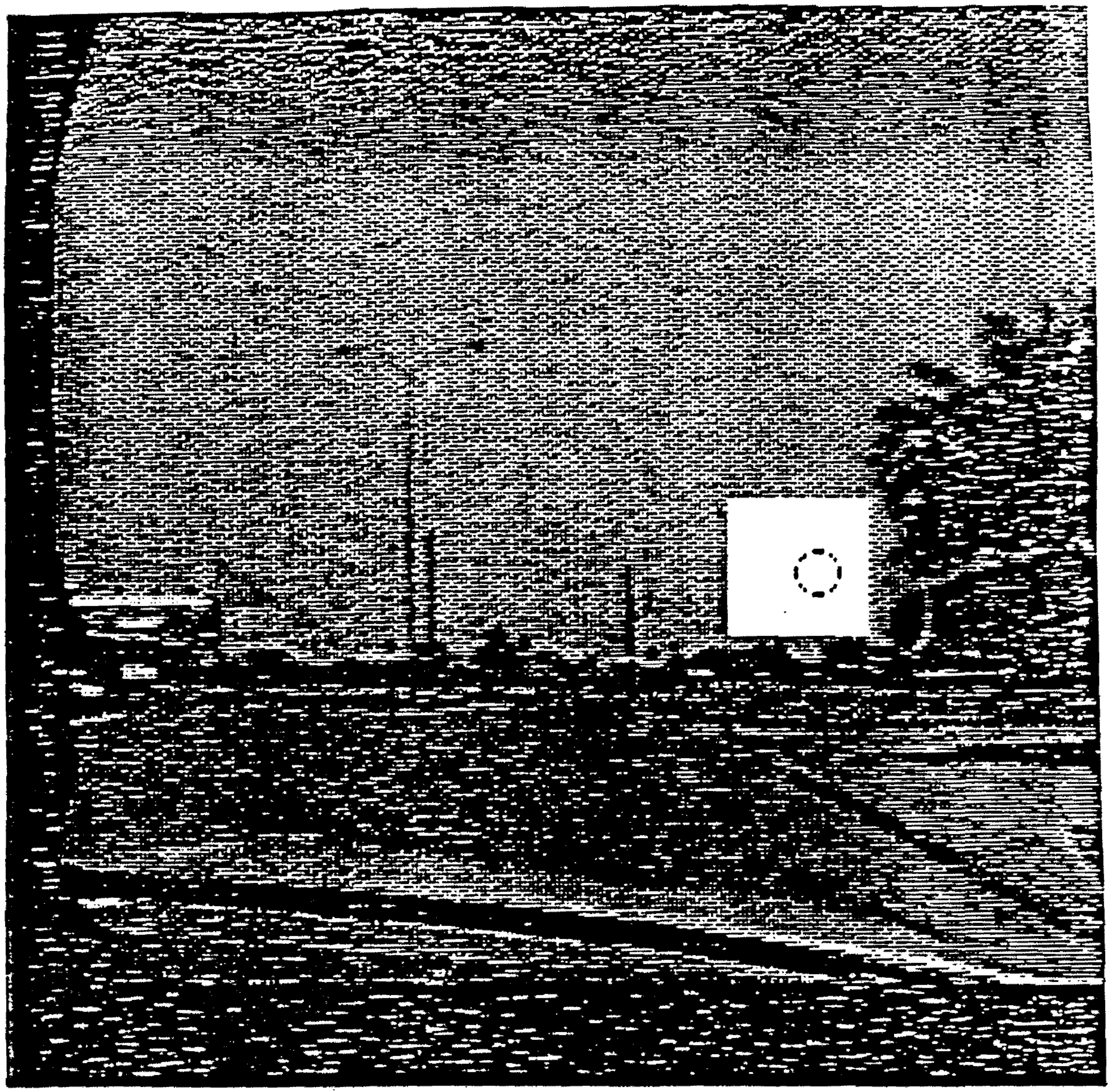

Figure 8 Best-fitting circle which approximates the stop-sign.

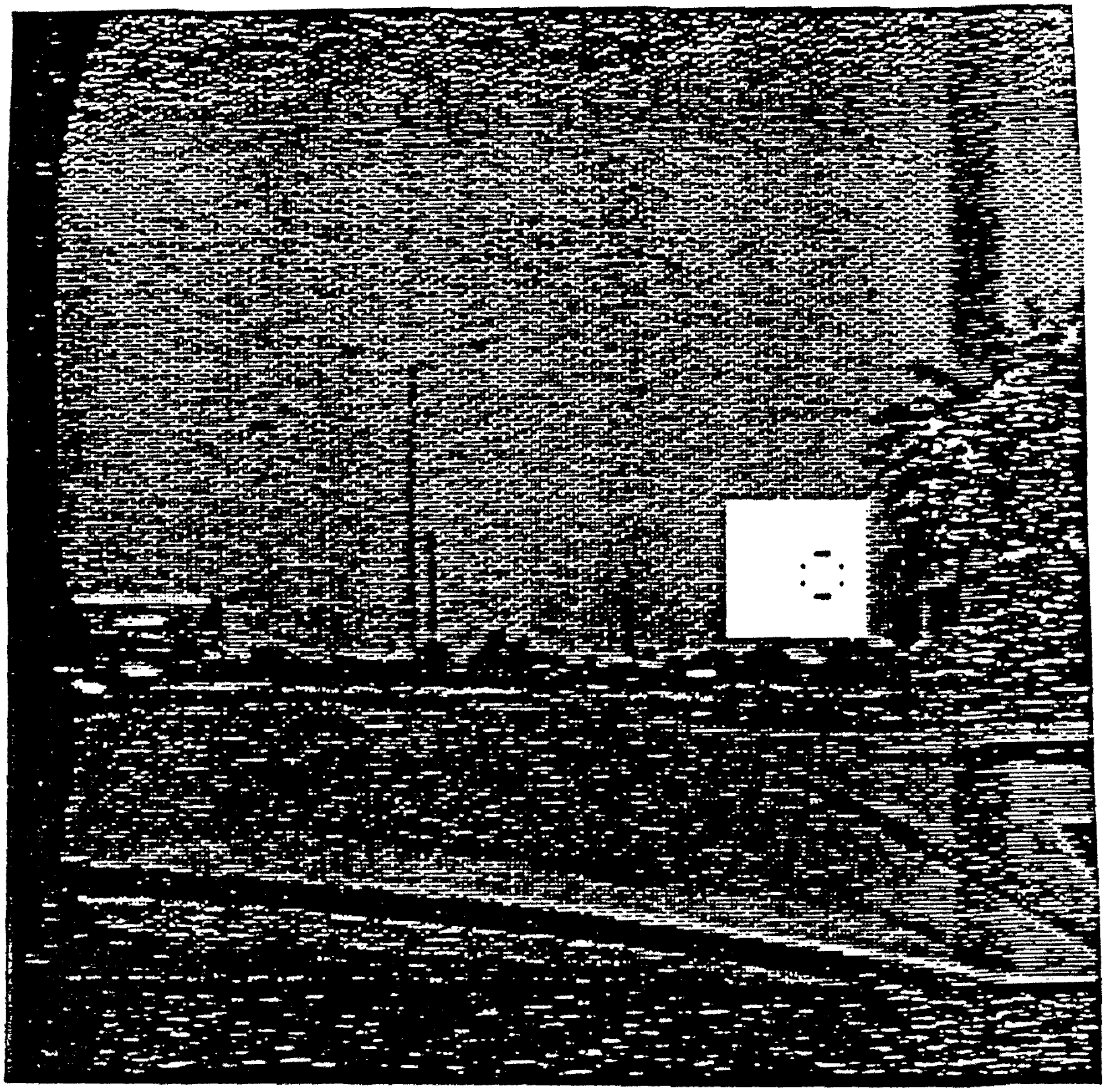

Figure 9 The first projection.

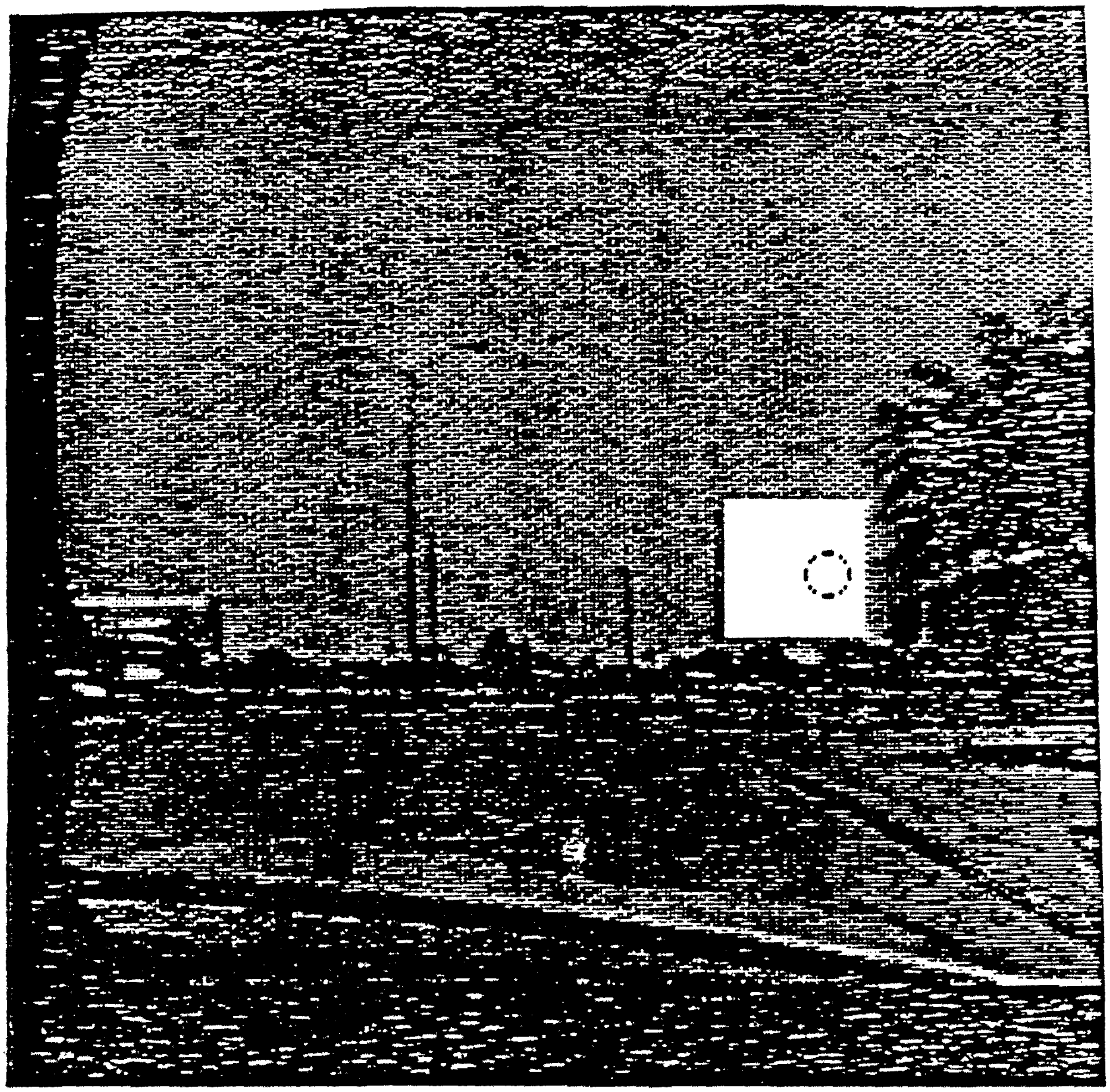

Figure 10 The second projection.

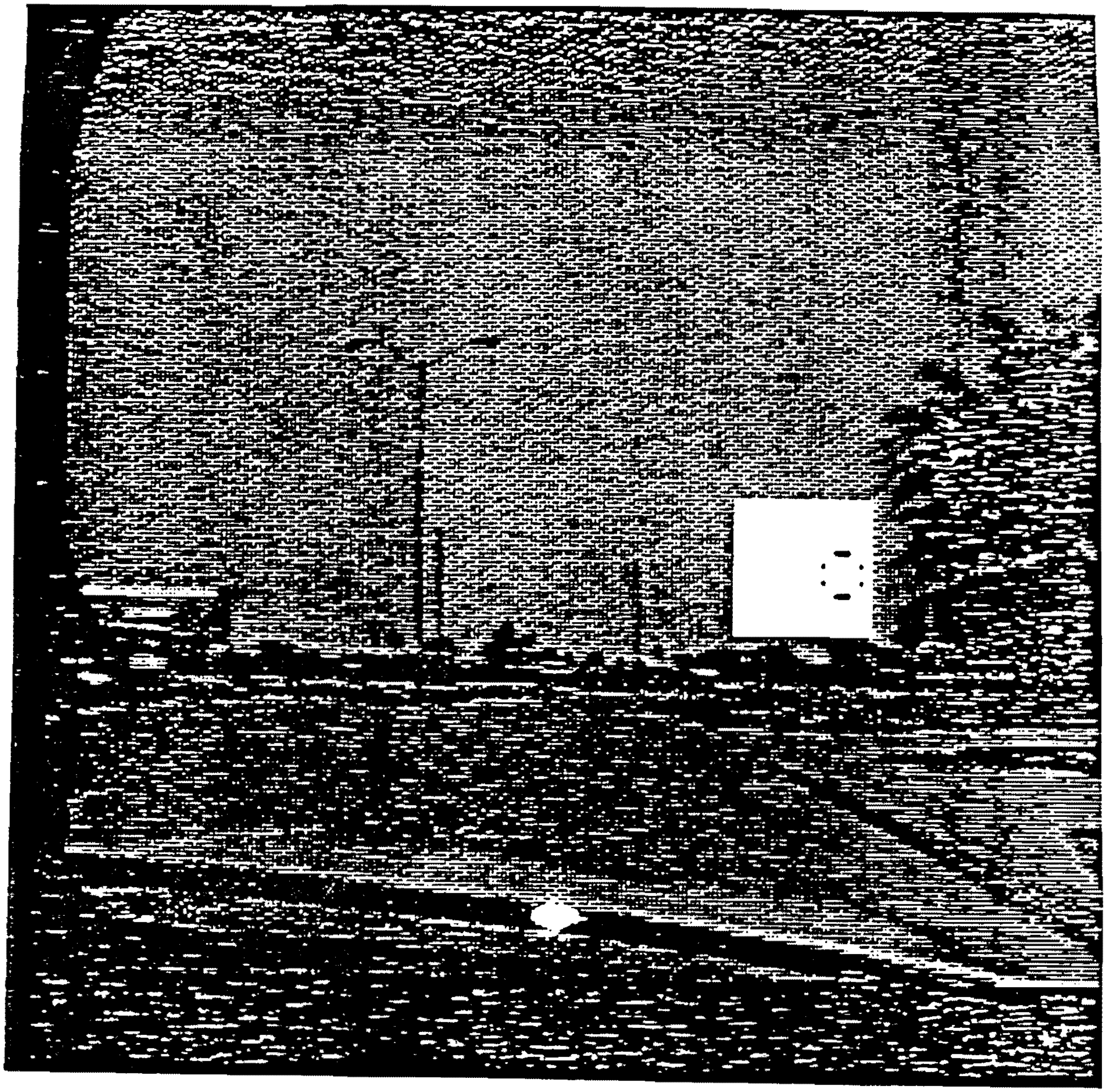

Figure 11 The third projection.

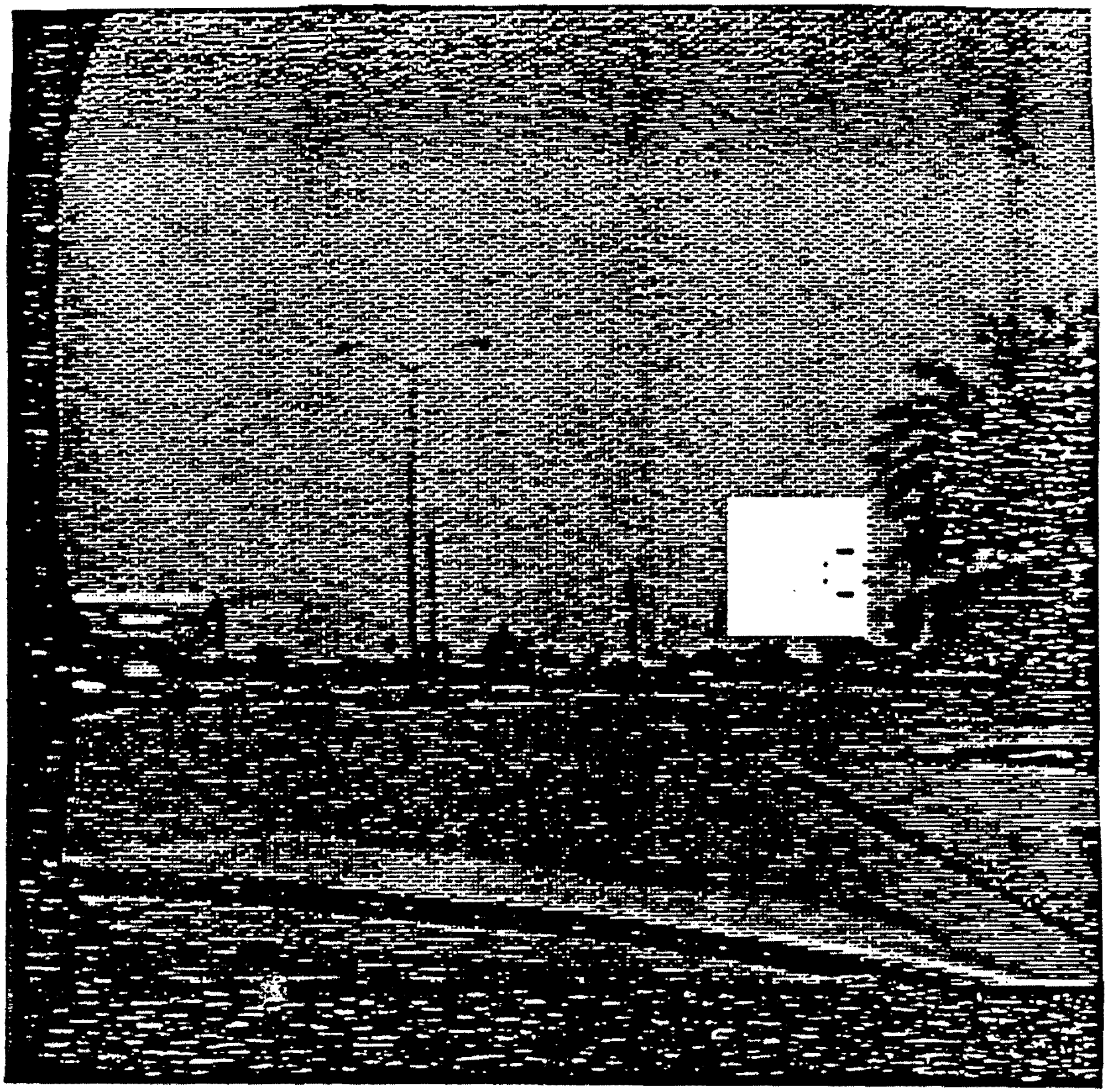

Figure 12 The fourth projection.

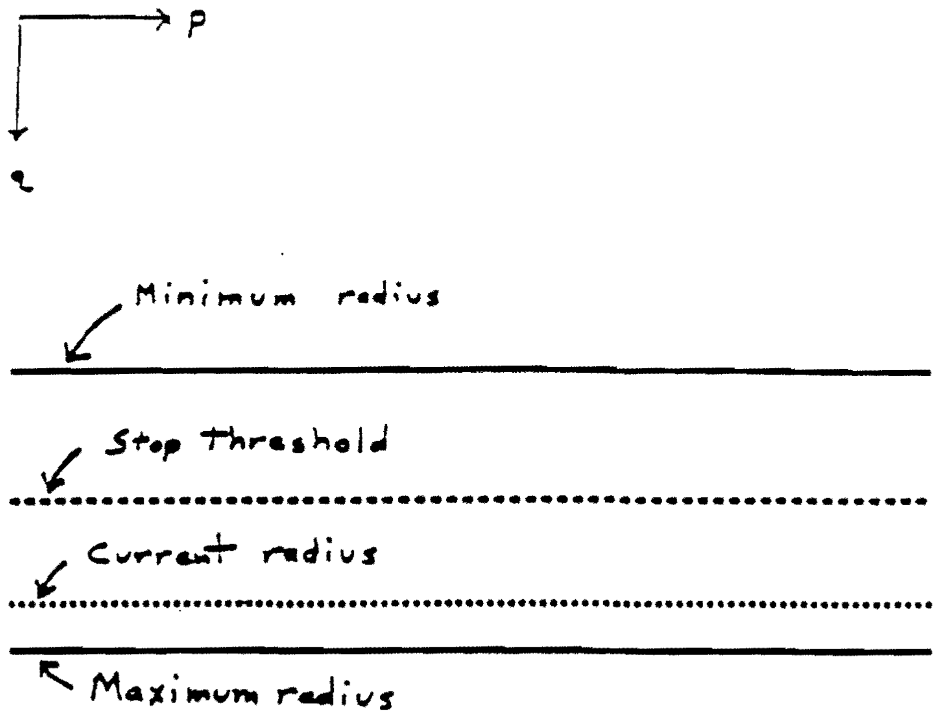

Figure 13 The complex-logarithmic image which results from the best-fitting circle.

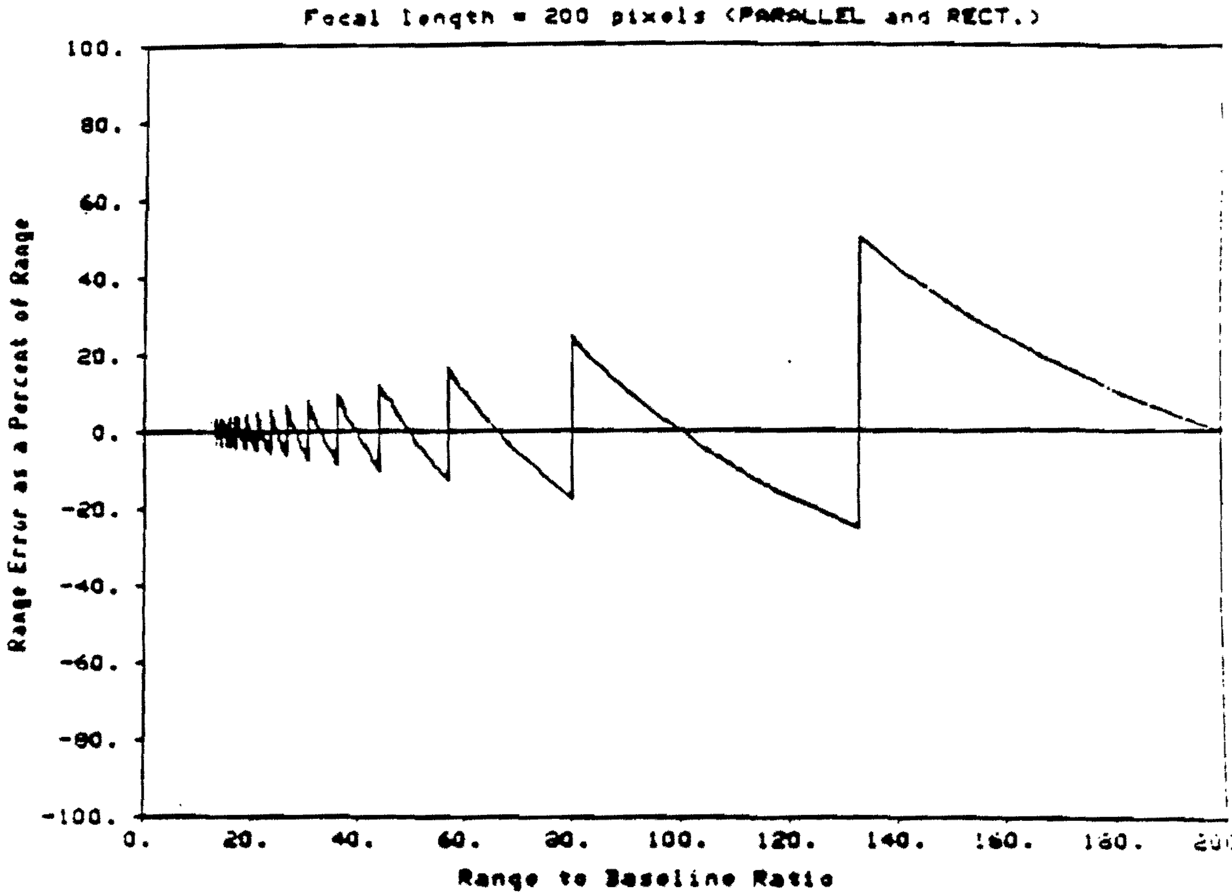

Figure 14 Range error as a function of range for a parallel stereo camera system using two raster sensors (courtesy of Dr. N. Griswold).

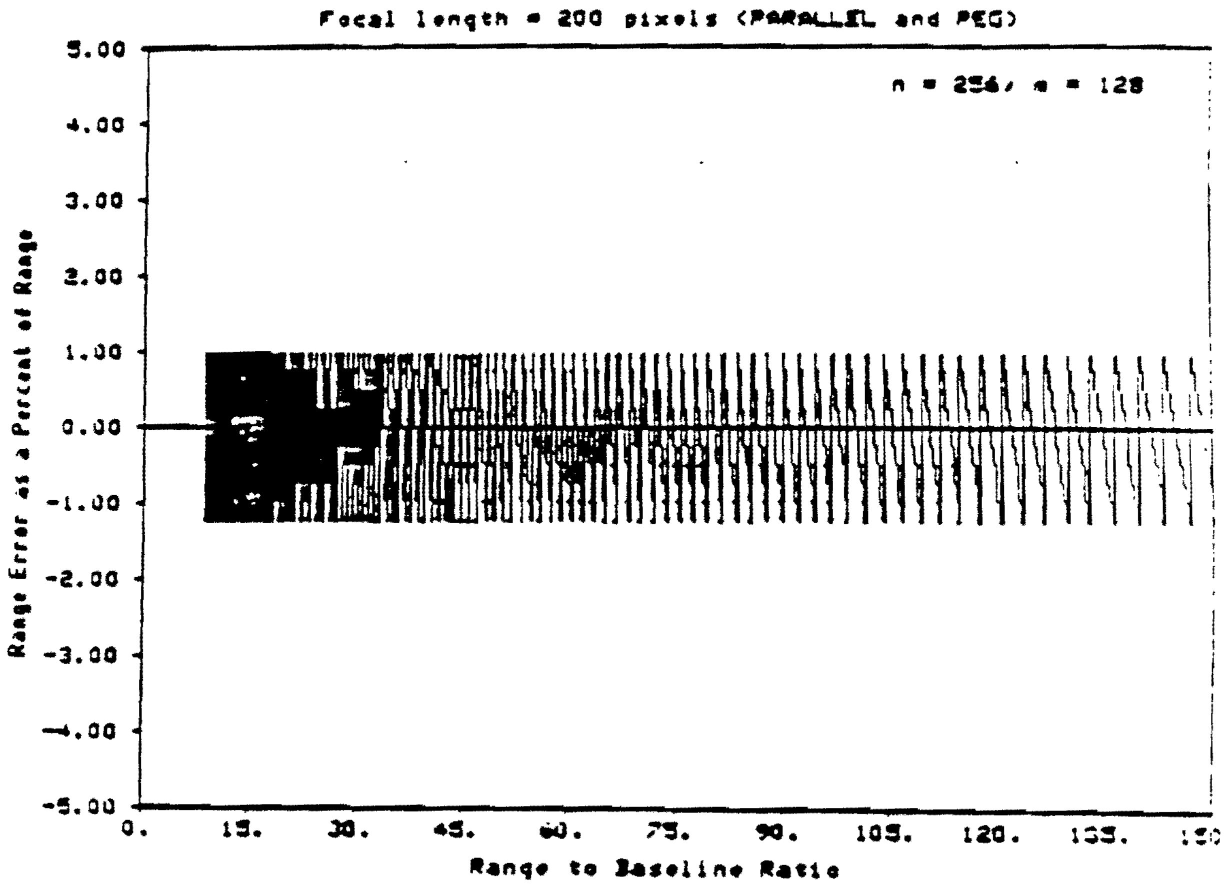

Figure 15 Range error as a function of range for a parallel stereo camera system using two PEG sensors

BIBLIOGRAPHY

(1) J. Beyer, C. Jacobus, F. Pont, "Autonomous vehicle guidance using laser range imagery," in *Mobile Robots II*, SPIE, Vol. 852, Cambridge, MA, 1987, pp. 34-43.

(2) W. Chun, "Ground vehicle options," in *Mobile Robots II*, SPIE, Vol. 852, Cambridge, MA, 1987, pp. 188-194.

(3) B. K. Cooper, J. M. Cameron, R. A. Solo and B. H. Wilcox, "Planetary rover mobility control," in *Mobile Robots*, SPIE, Vol. 727, Cambridge, MA, 1986, pp. 330-335.

(4) L. S. Davis and T. R. Kushner, "Road boundary detection for autonomous vehicle navigation," in *Intelligent Robotics and Computer Vision*, SPIE, Vol. 579, Cambridge, MA, 1985, pp. 362-366.

(5) L. S. Davis, T. Kushner, J. LeMoigne, A. M. Waxman, "Road Boundary detection for autonomous vehicle navigation," *Optical Engineering*, Vol. 25, 1986, pp. 409-414.

(6) A. R. de Saint Vincent, "A 3D perception system for the mobile robot Hilare," in 1987 *IEEE International Conference on Robotics and Automation*, Raleigh, NC, 1987, pp. 1444-1449.

(7) E. D. Dickmanns and A. Zapp "A Curvature-based scheme for improving road vehicle guidance by computer vision," in *Mobile Robots*, SPIE, Vol. 727, Cambridge, MA, 1986, pp.161-168.

(8) E. D. Dickmanns and A. Zapp, "Guiding land vehicles along roadways by computer vision," In *AFCET, Congres Automatique 1985, The Tools For Tomorrow*, Toulhouse, France, October, 1985, pp. 233-244.

(9) R. T. Dunlay, "Obstacle avoidance on the autonomous land vehicle using the Warp systolic array machine," in *Mobile Robots II*, SPIE, Vol.852, Cambridge, MA, 1987, pp. 44-53.

(10) R. T. Dunlay and D. G. Morgenthaler, "Obstacle avoidance on roadways using range data," in *Mobile Robots*, SPIE, Vol. 727, Cambridge, MA, 1986, pp. 110-116.

(11) D. W. Gage and J. B. Pletta, "Ground vehicle convoying," in *Mobile Robots II*, SPIE, Vol. 852, Cambridge, MA, 1987, pp. 319-328.

(12) C. R. Giardina and E. R. Dougherty, *Morphological Methods in Image and Signal Processing*. Prentice-Hall: Englewood Cliffs, NJ, 1988.

(13) P. E. Green and K. S. Hall, "The WPI autonomous mobile robot project: a progress report," in *Mobile Robots II*, SPIE, Vol. 852 Cambridge, MA, 1987, pp. 11-18

(14) N. C. Griswold and C. P. Yeh, "A new stereo vision model based upon the binocular fusion concept," *Computer Vision, Graphics, and Image Processing*. Vol.41, 1988, pp. 153-171.

(15) K. Hanahara, T. Maruyama, and T. Uchiyama, "High speed Hough transform processor and it's applications to automatic inspection and Measurement," in *1986 IEEE International Conference on Robotics and Automation*, San Francisco, CA, 1986, pp. 1954-1959.

(16) S. Y. Harmon, "USMC ground surveillance robot (GSR) : lessons learned," in *Mobile Robots*, SPIE, Vol. 727, Cambridge, MA, 1986, pp. 336-343.

(17) Y. Y. Huang, Z. L. Cao, S. J. Oh, E. U. Katton and E. L. Hall, "Automatic operation for a robot lawn mower," in *Mobile Robots*, SPIE, Vol. 727, Cambridge, MA, 1986, pp. 344-354.

(18) S. Ishikawa, H. Kuwamoto, S. Ozawa, "Visual navigation of an autonomous vehicle using white line recognition," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 10, No. 5, 1988, pp. 743-748.

(19) D. Kuan, G. Phipps, and A. Hsueh, "A real-time road following vision system for autonomous vehicles," in *Mobile Robots*, SPIE, Vol. 727, Cambridge, MA, 1986, pp. 152-160.

(20) D, Kuan, G. Phipps, and A. Hsueh, "Autonomous robotic vehicle road following," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 10, No. 5, 1988, pp. 648-658.

(21) K. Kuhnert, "A vision system for real time road and object recognition for vehicle guidance," in *Mobile Robots*, SPIE, Vol. 727, Cambridge, MA, 1986, pp. 267-272.

(22) T. R. Kushner and S. Puri, " Progress in road intersection detection for autonomous vehicle navigation," in *Mobile Robots II*, SPIE, Vol. 852, Cambridge, MA, 1987, pp. 19-24.

(23) D. T. Lawton,"Motion analysis via local translation processing," in *Workshop on Computer Vision Representation and Control*, Rindge, NH, 1982, pp. 59-72.

(24) J. W. Lowrie, M. Thomas, K. Gremban, and M. Turk, "The autonomous land vehicle (ALV) preliminary road-following demonstration," in *Computer Vision and Intelligent Robots*, SPIE, Vol. 579, Cambridge, MA, 1985, pp. 336-350.

(25) J. E. McKisson, "Guidance and navigation of intelligent mobile autonomous systems", *M. S. Thesis*, University of Florida, Gainesville, 1983.

(26) B. D. Mysliwetz and E. D. Dickmanns,"Distributed scene analysis for autonomous road vehicle guidance," in *Mobile Robots II*, SPIE, Vol. 852, Cambridge, MA, 1987, pp. 72-76.

(27) J. Serra, *Image Analysis and Mathematical Morphology*. Academic Press: New York, 1982.

(28) U. K. Sharma, "Road following by an autonomous vehicle using range data," in *Mobile Robots*, SPIE, Vol. 727, Cambridge, Ma, 1986, pp. 169-179.

(29) U. K. Sharma and L. S. McTamaney, "Real time system architecture for a mobile robot," in *Mobile Robots II*, SPIE, Vol. 852, Cambridge, Ma, 1987, pp. 25-31.

(30) E. B. Silverman, F. E. Gelhaus, R. K. Simmons, J. Lewis, "Surveyor a remotely operated mobile surveillance system," in *1986 IEEE International Conference in Robotics and Automation*, Vol. 3, San Francisco, CA, 1986, pp. 1936-1940.

(31) C. Thorpe, M. H. Hebert, T. Kanade, and S. A. Shafer, "Vision and navigation for the Carnegie-Mellon Navlab," *IEEE Transactions and Patterns Analysis and Machine Intelligence*, Vol. 10, No. 3, 1988, pp. 362-373.

(32) C. Thorpe and T. Kanade, "Vision and navigation for the CMU Navlab," in *Mobile Robots*, SPIE, Vol. 727, Cambridge, Ma, 1986, pp. 261-266.

(33) T. Tsukiyama and T. Huang, "Motion stereo for navigation of autonomous vehicles in a passageway," in *3rd Workshop on Computer Vision: Representation and Control*, Michigan, 1985, pp. 148-155.

(34) S. Tsugawa, T. Yatabe, T. Hirose, and S. Matsumoto, "An automobile with artificial intelligence," in *Sixth International Joint Conference on Artificial Intelligence*, Tokyo, 1979, pp. 893-895.

(35) M. A. Turk and M. Marra, "Color road segmentation and video obstacle avoidance." in *Mobile Robots*, SPIE, Vol. 727, Cambridge, MA, 1986, pp. 136-142.

(36) M. A. Turk, D. G. Morgenthaler, K. D. Gremban, and Martin Marra, "VITS - a vision system for autonomous land vehicle navigation," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 10, No. 3, 1988, pp. 342-361.

(37) A. M. Waxman, J. J. LeMoigne, L. S. Davis. B. Srinivasan, T. R. Kushner, E. Liang and T. Siddalingaiah, "A visual navigation system for autonomous land vehicles," *IEEE Journal of Robotics and Automation*, Vol. RA-3, No. 2, 1987, pp. 124-141.

(38) C. F. R. Weiman, "3-d sensing with polar exponential sensor arrays," in *Digital and Optical Shape Representation and Pattern Recognition*, SPIE, Vol. 938, Orlando, FL, 1988, pp. 78-87.

(39) C. F. R. Weiman, "Exponential sensor array geometry and simulation," in *Digital and Optical Shape Representation and Pattern Recognition*, SPIE, Vol. 938, Orlando, FL, 1988, pp. 129-137.

(40) J. R. White, H. W. Harvey and K. A. Farnstorm, "Testing of mobile surveillance and robot at a nuclear power plant," in *1987 IEEE International Conference on Robotics and Automation*, Vol 2, Raleigh, 1987, pp. 714-719.

(41) B. H. Wilcox, D. B. Gennery, A. H. Mishkin, B. K. Cooper, T. B. Lawton. N. K. Lay and S. P. Katzmann, "A vision system for a Mars rover," in *Mobile Robots II*, SPIE, Vol. 852, Cambridge, MA, 1987, pp. 172-187.