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INTELLIGENT INTERMITTENT SPRAY SYSTEM FOR REDUCED HERBICIDE CONTROL OF VEGETATION

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ABSTRACT

A feasibility study was conducted to determine if a computer vision system could be used to control the intermittent application of herbicides to roadside vegetation. Results show that currently available off-the-shelf computer vision technology can be used to accurately target herbicide application at vehicle speeds ranging from 3 km/hr to 13 km/hr.

EXECUTIVE SUMMARY

The concept of intelligent application of herbicides for roadside vegetation control was evaluated in a feasibility study. The study demonstrated the feasibility of using a computer based visual control system to apply herbicides only to targeted vegetation and not to areas of the roadside which contained no vegetation. This finding indicates that a substantial reduction (up to 90%) in the amount of herbicide required to control the vegetation on California's roadsides may be feasible.

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AHMCT GOAL STATEMENT

(i) "The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology Program (AHMCT), within the Department of Mechanical Engineering, Aeronautical and Materials at the University of California, Davis and the Division of New Technology and Materials Research at the California Department of Transportation. Is evolutionary and voluntary. It is a cooperative venture of local, state, and federal governments and universities."

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INTRODUCTION

The California Department of Transportation expends a considerable amount of human and financial resources in its highway maintenance program for the control of vegetation along the shoulders of roadways. Effective weed control has multiple benefits including increased visibility and safety for drivers, reduced loss of natural resources (e.g. water) to unwanted vegetation and a reduction in alternative hosts for insect pests and diseases. Application of herbicides is one of the most effective methods for weed control.

A major issue in California is the current reliance on chemical methods of pest control. Helsel[1] estimated that in 1984 16 billion dollars were spent worldwide on pesticides. Further, Helsel reported the United States as the largest pesticide user in the world applying more than three times the quantity of pesticides as the number two country (Japan). Unfortunately, the continued reliance on chemically based pest control practices has potentially detrimental effects upon the environment and human health in the form of contamination of water supplies and soils. In addition, the effect of chemical residues is often cumulative and their continued use can be increasingly detrimental to the environment.

There is a need to develop improved means of weed control in a reduced herbicide environment. One possible solution is to develop new chemical spray technology that could be intelligently controlled. If a system could be developed to apply herbicides only to the targeted plant material the energy and material costs involved in weed control could be reduced and the amount of herbicides that are released into the environment could also be greatly reduced.

The concept of intermittent spray control for plant sprayers has been previously investigated. Reichard and Ladd[2] discussed work in which plant conductivity and a charged probe were used to detect the presence of target plants. They also developed intermittent spray control systems which detected vegetable plants through spring steel wires and systems based on photodetectors. Season-long field tests of the control systems (Ladd et al.[3] and Ladd and Reichard[4]) found reduction of applied spray material to range from 24 to 51% with little or no reduction in pest control efficacy. The systems were physically limited to target plants which could fit between the sensor system since the basis of operation was the interruption of a light beam or the tripping of a wire switch.

Several researchers (e.g. Hollaender[5]) have documented the distinct absorption characteristics of chlorophyll which peak in the 675 nm region of the visible spectrum. Others have attempted to use this information to develop a non-contact sensor for detecting chlorophyll containing materials (e.g. plants) vs. non-chlorophyll containing materials (e.g. soils). For example, Hooper et al.[6] developed a photoelectric sensor that used a ratio of infrared to visible radiation under tungsten-halogen illumination to detect sugar beet, lettuce and cabbage seedlings in an automated thinning operation. This sensor, although fairly effective has the disadvantage of requiring tungsten-halogen illumination and is not well suited to the rugged environment of outdoor operations such as highway maintenance. Haggar et al.[7] developed a hand-held weed sprayer that also used a ratio of infrared to visible radiation as a means of detecting vegetation. Even though the sensor developed by Haggar et al. was evaluated in a hand held operation where the operator carried the device while walking down the field, results indicated that the concept of using ratios of reflected light to detect vegetation was worth pursuing and could be developed into a practical implementation. Recently, two private companies have developed commercial prototypes of intelligent boom spraying systems that are based upon concept originally proposed by Hooper et al.

OBJECTIVE

The goal of this study is to demonstrate that a real-time computer vision system can be developed to detect live (green) plant material growing along the roadside and that this vision system can be coupled to a set of rapid-response spray control valves and nozzles to permit selective application of herbicides to the detected plant material. The implementation of this technology could allow the California Department of Transportation to reduce the amount of resources required to maintain an effective weed control program using herbicides while at the same time reduce the amount of chemicals unnecessarily released into the environment.

The technical objective of this research is to determine the feasibility of an intelligent "offset" spray system where the spray vehicle is driven along the edge of the roadway and a computer vision system determines the presence of plant material in real-time. Spray material is delivered, upon command from the computer control system, horizontally to the region adjacent to the vehicle in which the plant lies and not to the surrounding soil which is void of plants.

METHODS AND MATERIALS

A prototype intelligent intermittent spray system (IISS) was developed from two fundamental elements: 1) a computer vision system, and 2) a rapid-response intermittent spray system. Shown in figure 1 is a photograph of the experimental prototype developed for this study. The components and configuration of these two systems is described below.

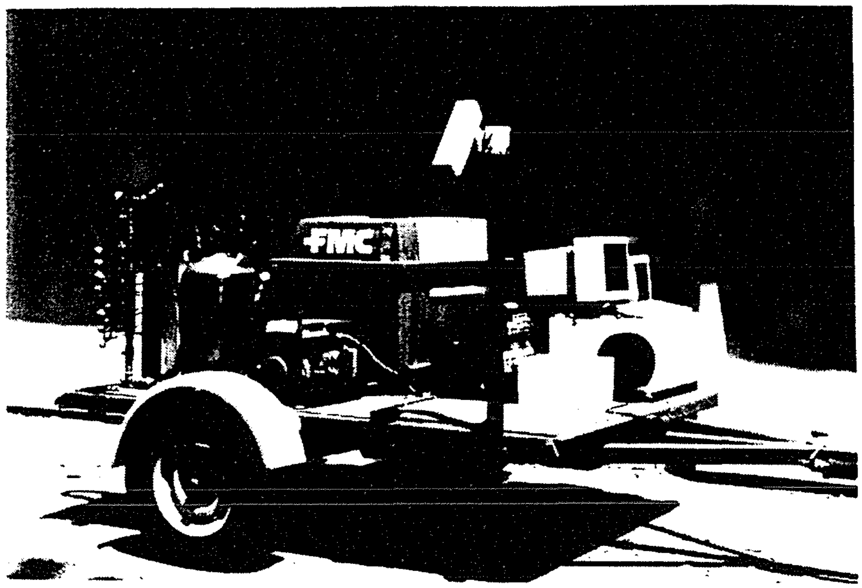

Figure 1. Photograph of the intelligent intermittent spray system.

Computer Vision System

A color computer vision system was developed to demonstrate the feasibility of detecting green plant material growing adjacent to the roadway. This system consisted of a solid-state color video camera (Sony, model XC-711), a computer video interface circuit board (RasterOps framegrabber, model 24 XLTV), and a computer (Apple, model Macintosh IIfx). The framegrabber was capable of digitizing true-color video images at a rate of fifteen frames per second. The resolution of the digitized color images was 640 columns by 480 rows. Once a video image was digitized it was stored in the memory of the framegrabber and could be accessed directly by the computer.

A color reference table was developed which could be used by the computer in real-time to determine if the color of a picture element (pixel) corresponded to one of several shades of green commonly observed in live plant material. The color reference table was stored in computer memory as a color look-up-table (CLUT) and was used by the computer to determine if any plant material was present in the field of view.

Each image was subdivided into eight regions of interest (ROI) where each ROI corresponded to a region of soil perpendicular to the right edge of the vehicle carrying the intelligent intermittent spray system (IISS), see figure 2. The IISS was equipped with eight spray nozzles and each of the eight image ROIs corresponded to one and only one of the eight spray nozzles. Each image ROI was defined as that portion of the computer image which contained the view of the soil which could be sprayed by its corresponding nozzle. For example, the left most ROI viewed the area of soil closest to the vehicle and this area of soil could be sprayed by the bottom spray nozzle. The resolution of the digitized image allowed the computer to identify plants as small as 80 square millimeters under ideal conditions.

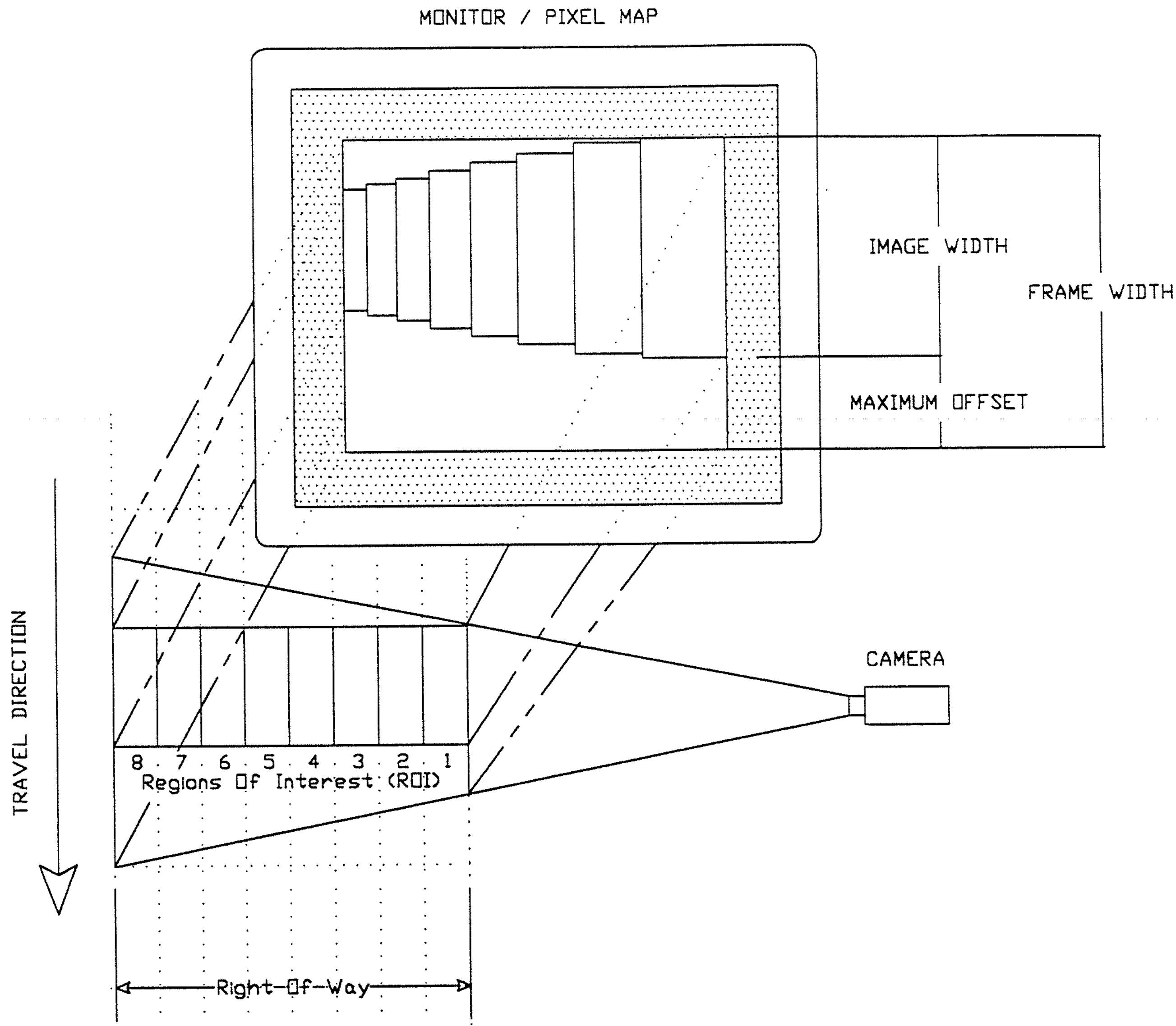

Figure 2. Schematic diagram showing the camera field of view and individual regions of interest.

The computer would examine each of the eight ROIs and determine which regions contained green plant material. If a region contained green plant material, a computer memory flag was turned on to indicate that the appropriate valve should be turned on in time to spray the plant detected in that region. The computer maintained a series of memory flags for each spray valve in a circular memory buffer and turned each spray valve on and off independently as needed to spray plant material in each region.

Rapid-Response Intermittent Spray System

A schematic diagram of the rapid-response intermittent spray system is shown in figure 3. The system consisted of a pump, filter, pressure regulator, pressure relief valve, manifold, eight solenoid valves, and eight spray nozzles. A manifold pressure of 517.1 kPa was required to provide a 63.1 ml/s flowrate through the spray nozzles. To maximize system response the valves were modified to allow the nozzle to be mounted very close to the exit port of the valve. Each valve was controlled by the computer through a series of electronic relays which allowed the computer to open or close each of the eight valves independently.

Intelligent Intermittent Spray System Operation

A schematic diagram of the overall layout of the intelligent intermittent spray system (IISS) is shown in figure 4 and a flowchart showing the general sequence of events for operating the IISS is shown in figure 5. The sequence begins with a test to determine if the width of a spray region has been traveled by the system. The IISS used a radar displacement sensor (Raven Industries) to determine the distance traveled. The sensor emitted 130 electronic pulses per meter traveled and was capable of operating at travel speeds from 1.5 km/hr to 110 km/hr. Once the vehicle arrived at the new region to be analyzed the computer would begin the process of acquiring a new computer image of the new region. The acquisition of an image was conducted by the framegrabber as an independent task allowing the computer to monitor the travel of the vehicle and to control any of the eight valves as needed. Once the image was digitized and stored in the computer's memory analysis of the eight individual ROIs in the image was conducted. If any of the eight ROIs contained a weed a flag was set in computer memory marking that ROI to be sprayed when the spray nozzle was positioned above the region of soil containing the weed. The computer used displacement information from the radar sensor to determine when the correct time to open each valve had occurred.

Testing Procedure For The Intelligent Intermittent Spray System

Image resolution tests were conducted to determine the minimum target size which could be detected by the IISS while traveling at various speeds (3.2 km/hr, 8.0 km/hr, and 12.9 km/hr). A grid of forty-eight green sponges was arranged so that the area of the sponges decreased in the direction of travel. Two sponges of equal size were placed 2.5 spray regions apart in the direction of travel for each of the eight ROIs associated with the eight spray nozzles. This pattern was repeated for a total of four sponge sizes. The three sponge sizes used in this test were 5 cm x 5 cm, 2.5 cm x 2.5 cm, and 1.25 cm x 1.25 cm. The IISS vehicle was then driven past the grid of sponges at a constant velocity and the accuracy of sponge detection was recorded by the computer vision system.

System tuning tests were conducted to determine the speed compensation coefficients for each of the eight spray ROIs. These coefficients were used to adjust the amount of lead time required after a valve was turned on to insure accurate spray targeting as a function of travel speed. These coefficients compensated for valve signal delays and the different time-of-flight of the spray stream for each of the eight valves. The IISS vehicle was driven by a set of eight green sponges (one sponge was located in each of the eight ROIs) at 8.0 km/hr with all of the coefficients initially set to 0. The distance (in the direction of travel) between the target location and the actual location of spray deposition was then measured for each sponge. The coefficients were then determined by dividing theses distances (m) by the travel speed (m/s).

A series of tests were conducted to determine the performance of the target image mapping and the valve control operations and to determine the amount of spray material deposited on the target by the IISS versus that applied by a conventional non-intelligent spray system at various travel speeds. A total of 30 tests were conducted. Half of the tests were conducted with the IISS set to operate as a conventional spray system with full spray coverage applied independent of plant density. The other half of the tests were conducted with IISS operating in the intelligent intermittent spray mode where only plant material was sprayed. Five target patterns were used with three travel speeds (3.2 km/hr, 8.0 km/hr, and 12.9 km/hr) for each pattern. Plant location and the travel speed sequence were randomly selected for each test. The location at which the framegrabber detected each plant and the valve control information was recorded by the computer system for each target plant. Green sponges (7.6 cm by 11.4 cm) were used as targets for this test. A Zn tracer in water (5 ppm, mass) was used as a spray material to allow determination of the spray deposition applied to each target. After each test the green sponges were collected and stored in sealed containers for laboratory analysis. The laboratory analysis consisted of a multi-step process to determine the amount of spray materiel deposited on each sponge. The analysis steps are listed in Table 1.

Table 1. Laboratory Analysis Steps For Spray Deposition Measurement

1	Rinse the Zn from each sponge using a known volume of 0.26 N HCl to obtain a Zn / HCl solution for each sponge.
2	Measure the Zn concentration in the HCl / Zn solution using a spectrophotometer (model #3030) to obtain the amount of Zn in the solution (ppm, mass).
3	Calculate the amount of Zn in the HCl / Zn solution using the measured concentration to obtain the mass of Zn applied to the sponge in the spray material application.
4	Calculate the amount of spray material applied to the sponge using the original Zn concentration (5 ppm) in the spray material and the mass of Zn deposited on the sponge measured in step 3.

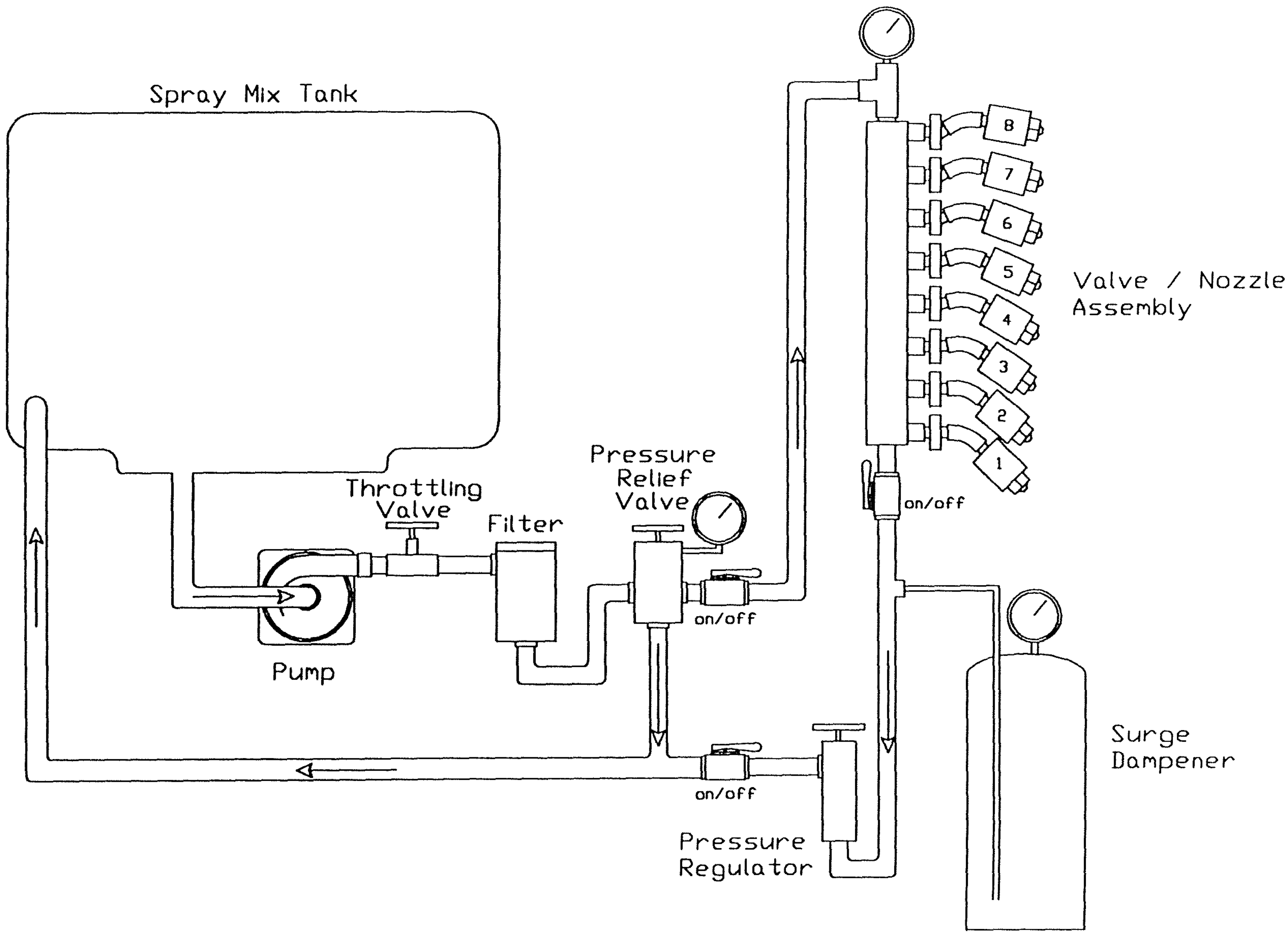

Figure 3. Schematic diagram of the rapid-response intermittent spray system.

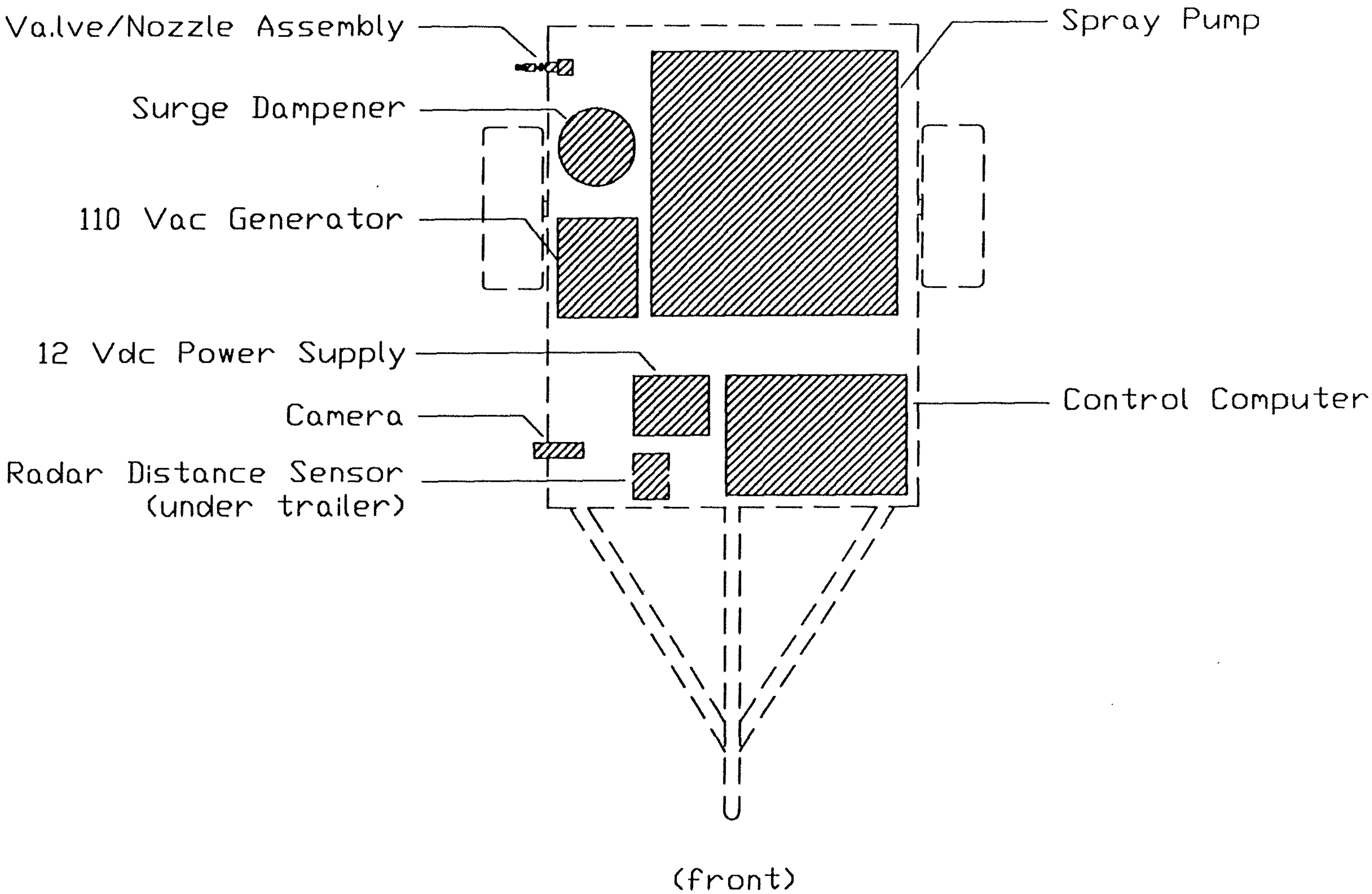

Figure 4. Schematic diagram (top view) of the prototype Intelligent Intermittent Spray System.

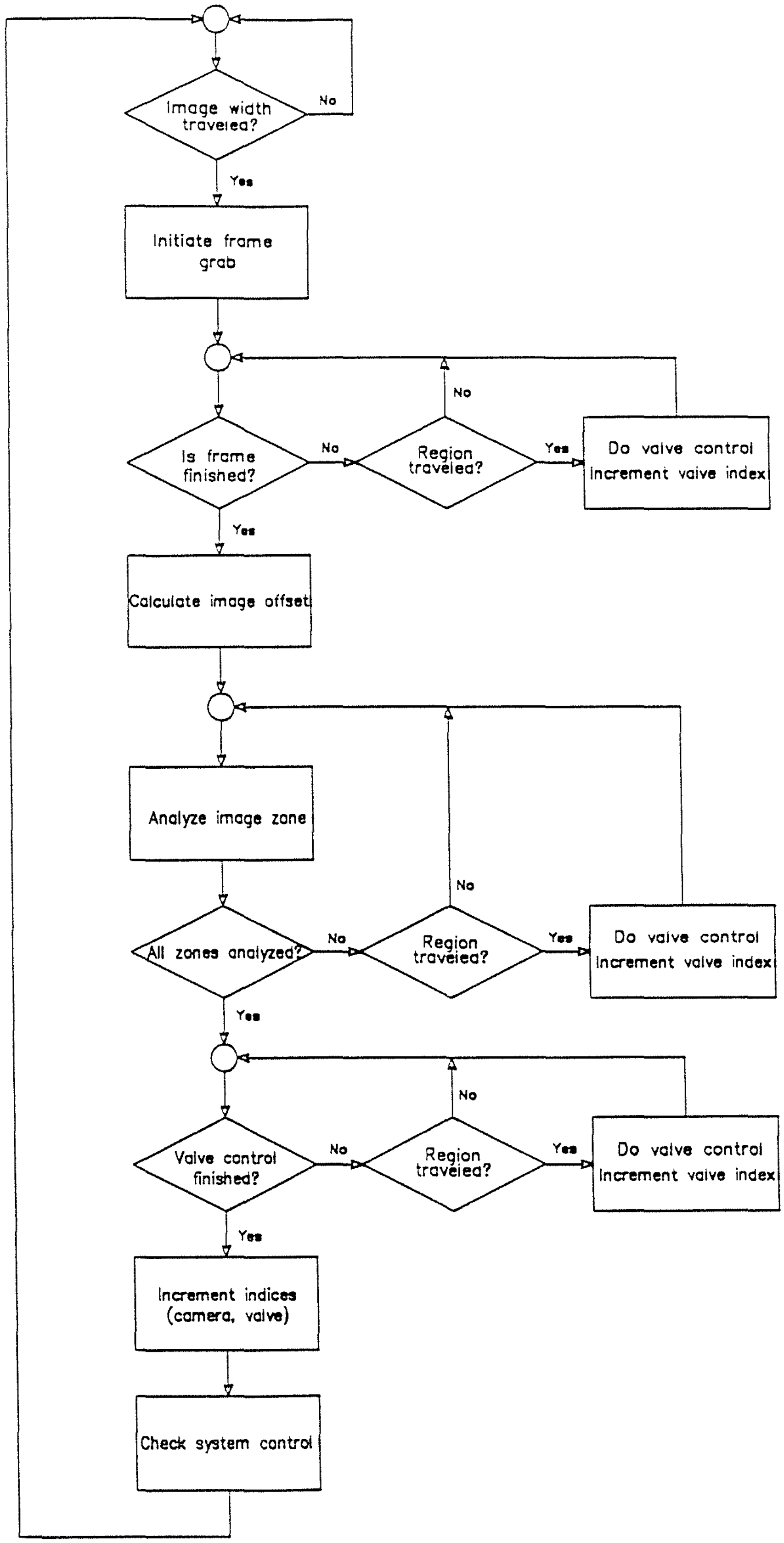

Figure 5. Flowchart showing the sequence of events for operating the IISS.

RESULTS AND DISCUSSION

Computer vision resolution tests were conducted from a moving vehicle at three travel speeds (3.2 km/hr, 8.0 km/hr, and 12.9 km/hr). The theoretical minimum resolution under ideal conditions with a stationary camera would be 80 mm^2. At all three travel speeds the system was able to detect a 2500 mm^2 (5.0 cm x 5.0 cm) target 100% of the time. The system was able to detect a 625 mm^2 (2.5 cm x 2.5 cm) target at 3.2 km/hr and 8.0 km/hr 81% of the time on the average, and 67% of the time at 12.9 km/hr. The system was able to detect the 156 mm^2 (1.25 cm x 1.25 cm) sample between 17% and 33% of the time depending upon speed. This indicates that, with the equipment used in this test, the minimum resolution from a moving vehicle under natural outdoor illumination was approximately five times greater than the theoretical minimum. The minimum resolution might be improved by using a camera with higher resolution, more light sensitivity with less noise and by optimizing the shutter speed for different vehicle speeds.

The speed compensation coefficients determined in the system tuning tests are shown in Table 2. These results were used to determine how far in advance the spray valve should be opened to allow sufficient travel time for the spray to hit the target from the moving vehicle.

Table 2. Speed Compensation Coefficients For Each Of The Target Regions

SPRAY ROI	DISTANCE TO TARGET (m)	SPEED COEFFICIENT (s)
1	0.3	0.090
2	0.6	0.105
3	0.9	0.120
4	1.2	0.135
5	1.5	0.145
6	1.8	0.155
7	2.1	0.165
8	2.4	0.170

The results of tests used to measure the performance of the target image mapping are summarized in Table 3. There were a total of seventy-five target sites recorded in this series of tests. A target site may be in two ROIs if the target lies across the border between the regions. Eight target detection conditions occurred in the analysis. These conditions consisted of targets which were in one or two ROIs, targets which were detected in one or two ROIs, and the level of offset between the actual target site and the detection site which varied from zero to two ROIs. The most accurate spray targeting is represented by conditions which have no offset between target site and detection site. When an offset occurs the level of weed control can be improved by extending the time the valve is open for a number of ROIs before and after the detected region. For example, if the valve control is set to spray two ROIs before the target and two ROIs after, the total coverage would be five ROIs rather than one ROI. This would ensure that the target is sprayed even when an offset condition occurs. The target was accurately detected with no offset condition 31% of the time in this test. Eight percent of the time the system sprayed two adjacent ROIs when only one contained a target. When the target was located in two adjacent ROIs the system correctly sprayed both ROIs 34% of the time and only sprayed one of the two ROIs 56% of the time. If the IISS was set to spray $^{+}/\text{-}1$ ROI (in the direction of travel) then the target would be sprayed 97% of the time.

Table 3. Performance Results for the Intelligent Intermittent Spray System

CONDITION	OCCURRENCE
1 target region, 1 detected region, no offset	2
1 target region, 1 detected region, 1 region offset	4
1 target region, 1 detected region, 2 region offset	1
1 target region, 2 detected regions, no offset	6
2 target regions, 1 detected region, no offset	35
2 target regions, 1 detected region, 1 region offset	1
2 target regions, 2 detected regions, no offset	21
2 target regions, 2 detected regions, 1 region offset	5

The results from the spray depositions test are shown in Table 4. Lower spray deposition was achieved when the IISS used weed activated spray control rather than conventional (full coverage) spray control. The only exception was in region 8 at 8.0 km/hr. On the average the spray deposition with the IISS operated in the weed activated mode was 57% of the conventional continuous spray system. The higher deposition achieved with the conventional spray control is likely to be the result of spray overlap between adjacent regions. Since all regions are being sprayed with the conventional method, a target in a specific region would be sprayed by the nozzle set for that region, plus the over spray from nozzles set for the adjacent regions. The deposition would also be increased by fall-out from the spray streams targeting ROIs further out. An additional factor which could result in lower deposition when using the weed activated control is the variance in the spray stream path due to wind influences. It was observed during the testing that a light wind (1 to 3 km/hr) was enough to shift the spray stream into an adjacent ROI. Wind would have less of an impact with the conventional spraying method since all of the spray streams would shift, so that a region would be sprayed by the spray stream originally targeting the adjacent region. The deposition might be increased by spraying +/.1 ROI as discussed previously or by using a nozzle with a higher flowrate.

Table 4. Percent Of Conventional Spray Deposition Achieved Using Weed Activated Control

		DEPOSITION (% of Full Coverage)		
SPRAY ROI	DISTANCE (m)	3.2 (km/hr)	8.0 (km/hr)	12.9 (km/hr)
1	0.3	90%	89%	73%
2	0.6	51%	61%	58%
3	0.9	45%	47%	44%
4	1.2	67%	64%	15%
5	1.5	60%	61%	41%
6	1.8	54%	64%	26%
7	2.1	40%	40%	33%
8	2.4	97%	101%	48%

The IISS system uses substantially lower amounts of spray material compared with a conventional spray system when the weed population is sparse. In the tests conducted here the IISS achieved an average spray deposition 57% of that applied by a conventional spray system while using less than 4% of the spray material used by the conventional system. If adjacent ROIs (both perpendicular to and parallel to the direction of travel) were also sprayed by the IISS the average spray deposition should be equivalent to that of a conventional spray system while still using less than 10% of the spray material used by the conventional system.

CONCLUSIONS

The technical feasibility of developing an intelligent intermittent spray system (IISS) for use by the California Department of Transportation in the control of vegetation along the shoulders of roadways was studied. To evaluate the feasibility, a prototype intelligent intermittent spray system (IISS) was developed. The prototype IISS consisted of two fundamental elements: 1) a computer vision system, and 2) a rapid-response intermittent spray system. This study indicates that it is feasible to use a computer vision system to automatically detect the presence of green plant material and to use a rapid-response intermittent spray system to efficiently apply chemical herbicides only to the targeted plant material. Results indicate that by using the IISS a substantial reduction in herbicide applied to non-plant material could be achieved. Implementation of this technology should allow the California Department of Transportation to reduce the financial resources spent on chemical herbicides and to reduce the amount of chemical herbicides released into the environment.

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