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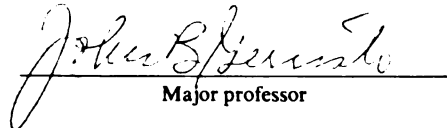
Vision Guided Robotic Tractor: The
Development And Operation Of An Engineering
Prototype

presented by

Bernard Wayne Fehr

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Agric. Tech. & Sys. Mgt.


Major professor

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VISION GUIDED ROBOTIC TRACTOR:
THE DEVELOPMENT AND OPERATION OF
AN ENGINEERING PROTOTYPE

By
Bernard Wayne Fehr

A DISSERTATION

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ABSTRACT

VISION GUIDED ROBOTIC TRACTOR: THE DEVELOPMENT AND OPERATION OF AN ENGINEERING PROTOTYPE

By

Bernard Wayne Fehr

An investigation was made into the practical use of color machine vision to guide a small tractor, expected benefits to include improved: 1) operator performance, 2) field efficiency, and 3) safety. A technological approach was used to assemble a Vision Guided Robotic Tractor (VGRT) that could follow a crop row. The VGRT consisted of a master computer which received video imagery of the path of travel. From this imagery, the master computer determined a control signal used to steer the tractor. The steering control signal was sent from the master computer, via a bi-directional parallel interface, to a slave computer. The slave computer monitors the functions of the tractor and receives the control signal from the master computer. The slave computer uses the control signal to stop or start tractor motion as well as determine positioning for the front wheels.

The VGRT was tested for its ability to follow well defined lines, lines with noise, and crop rows in a field. Line following was done in varying light and temperature conditions. Two types of line followers were developed:

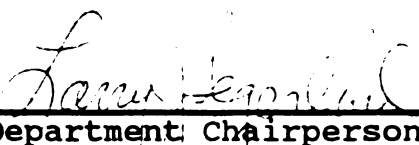
1) contrast within the color band of best discrimination, and 2) self-calibrated to the color of the desired line. Both methods utilized floating windows to enhance rate of position update performance. The steering performance of the VGRT was compared to the steering performance of human operators on the same tractor. The development of the VGRT even included a "learn" mode whereby the VGRT could assimilate distance and direction information necessary to repeat a left or right hand headland turn.

The results of the study produced a relatively inexpensive VGRT that could follow well defined lines at speeds up to 9.5 km/hr, and crop rows at speeds up to 4.0 km/hr. The VGRT could make either right or left hand headland turns, locate and follow parallel lines. The steering performance of the VGRT was comparable to that of human operators. The operation of the VGRT was also simple enough for inexperienced operators to master use of the system in approximately one hour of self instruction.

Approved:



Major Professor



Department Chairperson

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Bernard Wayne Fehr
1990

DEDICATIONS

To, Susan Fehr, my Wife who was the reason for finishing this, and getting on with life,

To, Walton and Mida Fehr, my parents who gave me the motivation to start this, and the discipline to complete it,

To Mrs. Hix and Miss Beer, teachers who, many years ago, were the beginning of all this,

To Les Sheets, who once gave me enough rope to hang myself and we both found out it wasn't long enough,

To Norm Reese, the one person in the Agricultural Engineering department at MSU who is truly qualified to hood me at graduation,

To Mary Carlson, a bright ray of sunshine at MSU Agricultural Engineering who truly can be counted on to pleasantly and efficiently get things done,

To the ROTC Department at MSU in the charge of Sergeant Major Waters, the one department on campus concerned enough to give me appropriate space in which to work,

To Bob and Joan Wendt, my in-laws, some very special people who provide number one (see above),

To Brian and Brenda Robertson, Bill DeGraff and Dr. Linda Donoghue, very good friends who helped keep this whole thing in perspective,

To the Millers; Henry, Betty, Carol, and Elaine, some very special people who gave me back the way of farming that I have known and loved,

To Norm Shoopman and Chuck Walters, who gave me my first inspiration in electronics,

To Mr. Ferree who instilled in me a deep desire to know my significant digits, and to Mr. Geshiwlrm who taught me the "nuts and bolts" of things.

Soli Deo Gloria

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Solvitur ambulando

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LIST OF ABBREVIATIONS

adc = analog to digital converter
cm = centimeter
d = dimensional
df = damping factor
eprom = erasable programmable read only (memory)
F (OF CAMERA) = F/STOP
HSI = Hue, Saturation, Intensity
m = meter
k = kilo (byte)
km = kilometer
nf = natural frequency
nm = nanometer
NTSC = National Television System Committee
po = percent overshoot
ram = random access memory
rt = rise time
sd = standard deviation
VGRT = Vision Guided Robotic Tractor

CHAPTER I

INTRODUCTION

1.0 INTRODUCTION

The rapid advance in technology is starting to catch up to agriculture. As the market for farm products becomes worldwide and more complex, and profit margins decrease with the rising cost of machinery, farmers find that they have to "farm smarter," not just "farm harder." In order to earn more money, a farmer will try to farm larger amounts of land requiring an increased capital investment in tools. These tools would certainly include larger farm machinery, but would also include greater use of farm management services and possibly even a home/farm computer. Agriculture is rapidly entering the 21st century and farmers need to keep pace with computerized advance.

Unfortunately, new technology has yet to reach the point where it can protect the farmer from the dangers of operating large powerful equipment. The safety aspect of farming continues to be of vital importance. As an occupation, agriculture continues to rank as the most dangerous in the nation; the operation of agricultural machinery is the most dangerous component (Doss, 1988). Operating larger equipment requires increased amounts of concentration, but the attention span of the human operator

remains the same. New technology should be used to improve safety by aiding the operator in basic field operations. Murphy (1988) expounds on the development of tractors and mechanization in agriculture and the quest for a guidance system to augment human capabilities.

A recent farmer survey has shown that human error is one of the main reasons for errors which result in accident. Fatigue was listed as having the greatest adverse effect on operator performance (Smith, 1987). A tired operator may make an error in judgment which would not be made under more alert operator conditions. Perhaps technology can be used to reduce the stress of operating equipment so that the operator can remain alert longer and make fewer dangerous mistakes. Technological aids could also free the operator from monotonous functions so that more time could be allocated to efficiently managing the field operation. Palmer and Matheson (1988) estimate that as much as a 10% reduction in cost of crop production could be realized by improving the navigation accuracy of field equipment. It would seem that farming is ready for improved technology. But, is improved technology ready for farming?

Goody (1982), in his book "The Intelligent Microcomputer" likens the activities of the microprocessor and peripheral chips, which are the heart of today's computers, to the basic sensory and decision-making

functions of a human. Perhaps a computer, which can mimic certain functions of a human, could be useful in helping the farmer to more safely and effectively operate farm equipment. The computer would seem a natural device to take over some of the monotonous tasks that now belabor the farmer. Chief of these tasks is the repetitious and highly demanding operation of field machinery. Driving a tractor back and forth across a field requires constant attention which has to be split between steering the tractor and monitoring the equipment the tractor is powering. A study done by Kaminaka, Rehkugler, and Gunkel (1981) shows the degradation in steering accuracy that results from monitoring a towed implement. A useful technological aid based on a computer could relieve the tractor operator of the monotony of steering the tractor.

One of the advantages a computer has over a human is that the computer can repeat the same operation many times for extended periods with no degradation in performance. The human operator, while poor at repetitious tasks, is better than the computer at making complex and relatively infrequently occurring decisions. By applying the theory of speed-load stress, Becker, Shoup, and Sinden (1983) showed that guidance may be the single most significant load on the mental facilities of an operator performing a field operation. Allowing a computer to take over the demanding repetitious tasks, such as steering, while leaving the complex but less frequent tasks to the human

operator would offer an improvement in both field efficiency and safety for the farmer.

Many guidance systems have been developed for tractors which have an inherent defect preventing them from being truly successful in a variety of situations. Most of the present guidance systems sense the tractor position from a point that is in direct proximity to the tractor. That is, the sensing mechanism determines the steering response of the tractor from a point that is somewhere near the front of the tractor, or in one extreme case, from behind the tractor (TRI-R Innovations, 1988)*. These systems may be contrasted with the human operator who looks ahead of the tractor to determine the steering response. This ability to "look ahead" provides an anticipatory mode of operation which is inherently stable.

Using an anticipatory guidance method, the operator can discern whether the tractor is going to deviate from its intended course before it actually does so to any great extent. The human operator can anticipate that, at the present heading, the tractor will start to leave its proper course. On the other hand, when determining the steering response from a point too near the tractor, the tractor actually has to leave the proper course before the sensing device can determine that a steering error has occurred.

* Any mention of a brand name throughout this paper does not necessarily constitute an endorsement of that product.

Fehr (1986) discussed the effect of moving the steering reference point and the improvement in accuracy realized by providing an anticipatory mode of operation.

One solution to the problem of providing an anticipatory guidance system for agricultural tractors lies in using machine vision. A video camera positioned to provide a forward field of view coupled with a computer could mimic the function of the human operator. Gerrish and Surbrook (1983) studied the potential accuracy of using machine vision guidance to steer a tractor. They showed that present technology for a camera, and computer, is accurate and fast enough to provide steering information for a row-crop operation. Based on theoretical work it would appear that vision technology is indeed ready for agriculture.

1.1 GOAL OF THIS RESEARCH

The goal of this research effort is to evaluate vision technology in the agricultural environment by fabrication and testing (as opposed to mathematical analysis and modeling). The success of this research project will be measured more by the performance of a working prototype rather than by analysis on paper.

A performance-oriented approach will be used to develop a test tractor to follow high-contrast lines or crop rows using computer vision as a sensor. An important

portion of the research effort will be directed at developing a system that is reliable. This system will be used to evaluate the ability of machine vision to guide a tractor. The main thrust of the research will not be to develop new algorithms to distinguish lines (hereafter lines may refer to constructed test lines or actual crop rows in a field), but to develop a discrete-control method of following a well-defined line using feedforward techniques. The ability to follow a line will be evaluated by introducing "noise" into the line, by "ringing" the system (using a step input), and by comparing tractor performance under computer control with performance under human control. To further emulate the agricultural setting, the ability of the tractor to negotiate headland turns will also be studied.

1.2 OBJECTIVES OF THIS RESEARCH

To accomplish the above goals the following objectives were developed to direct the study. This research project will be completed when the following objectives are undertaken and accomplished or proved unfeasible.

- 1) Procure an affordable vision system and install it on the test tractor.
- 2) Develop the system to follow a well defined line.
- 3) Develop the system to undergo a 180 degree turn, locate a parallel line and follow it.
- 4) Make the system "user-friendly".

1.3 LIMITATIONS OF THIS RESEARCH

Restricted funding and equipment availability limited the research to development on an electric lawn tractor. This reduced the testing of the unit in actual field conditions. The short wheelbase of the lawn tractor limited field speeds to about four km/hr. Test conditions were created both indoors and out of doors to evaluate the system.

CHAPTER II

LITERATURE REVIEW

2.0 INTRODUCTION

The amount of literature relating to vehicular guidance is becoming voluminous, an indication of the great amount of effort being applied to this field of study. This research venture is yet another step in the direction of complete autonomous vehicle operation. At this stage of technological development, it is felt that guidance should be employed to assist an operator. The human operator would still be on the vehicle but could now free up his attention to devote more time to other tasks. The advantage of having an operator on board is reflected in guidance controllers of a reduced complexity, and human intervention in the event of a guidance system failure.

The automatic guidance system developed for this study was further simplified by the nature of its intended use. Following crop rows or crop edges implies a relatively great deal of 'a priori' knowledge. The crop rows or crop edges are relatively straight, of a high contrast nature (vegetative material and soil background), and are the intended path of travel for the vehicle. The vehicle in this case would be a row-crop type tractor or harvester such as a combine.

2.1 REVIEW OF GUIDANCE IN AGRICULTURE

Young in 1976 published a monograph which summarizes the developments relating to guidance of an agricultural tractor to that date. The monograph began with an overview of different methods of guiding the tractor. Young's survey of guidance methods is still a definitive work.

To summarize, Young (1976) provided the following outline of guidance methods:

Indirect vehicle guidance by man

- a. Guidance by master vehicles
- b. Guidance by radio control

Vehicle guidance on directrixes

- a. Guidance with a directrix generated by the previous operation
 - 1) Guidance by means of mechanical contact
 - 2) Guidance by means of non-contact scanning
 - 3) Guidance by means of mechanical contact or non-contact scanning and an additional angle measurement
- b. Guidance by a directrix installed in the field
 - 1) Guidance by a mechanical conductor device
 - 2) Guidance by a conductor cable using alternating current
 - 3) Guidance by a light beam
- c. Guidance by a directrix calculated with the aid of fixed points

Vehicle guidance by image recognition

Vehicle guidance by man with semi-automatic steering
(p. 3)

As Young explained the different systems that were possible for automatic guidance, he indicated that the methods involved were to be an aid to the tractor operator, not a replacement for the operator. More than 10 years later Young's work seems amazingly prophetic. He predicted that with the advent of increased computer power in smaller packages, image recognition guidance will be feasible. This type of guidance would not only be able to follow the directrix, but would also be able to find it as well. This ability would be a significant improvement over previous methods that could only follow the directrix.

Since 1976 much new work has been accomplished in the category of agricultural vehicle guidance. In his 1981 study of a robotic lawn tractor, Squires discussed the classification of guidance systems into three basic types. These three groups were: semi-automatic, automatic command, and automatic preset.

The semi-automatic system could remove the operator from a hazardous location, but did not decrease the attention required for the steering task. The semi-automatic system could include radio control and master-slave arrangements. The automatic command system required highly accurate component systems to provide steering control from a remote location. The automatic command system resulted in a relatively expensive system that required off-vehicle location of control systems. The third guidance system, automatic preset, had the advantage

of a steering control system that was completely contained on the vehicle. Automatic preset also had the advantage of relieving the operator of some of the steering task.

McMahon (1982) listed four reasons to justify the development of automatic steering: 1) reduced fatigue, 2) increased vehicle speed, 3) increased machine output by allowing the operator more time to monitor machine performance, and 4) reduced wasteful implement overlap. These are all factors improving the operator's field efficiency.

In his development of an automatic steering controller for an apple harvester, McMahon (1982) also detailed the major components of what should comprise an automatic steering control system. The steering system was broken down into two main parts, a controller and sensing system. The controller received guidance signals, processed the signals, and provided a controlling signal to the machine. McMahon further explained that controllers could be of two types, analog or digital, and that the sensors also could be of two types, contact or non-contact.

In his explanation of sensing systems, McMahon discussed the advantages and disadvantages of the two main categories of sensors. Typical contact-type sensors were mechanical, which means their successful operation required periodic adjustment. Moreover, contact-type sensors wore and required periodic replacement of parts to continue

proper operation. Contact from the sensor to the object may also damage the object to an unacceptable degree. In some extreme situations the amount of contact force may prevent a contact-type sensor from even being considered for use, such as in sensing cereal grains.

In contrast, McMahon explained the advantages of using a non-contact-type of sensor. By its very nature of maintaining some distance between itself and the object that it is sensing, the non-contact sensor avoided most of the problems associated with the contact-type sensor. The potentially more complex non-contact sensor can be provided with better mechanical protection than can the more vulnerable contact sensor.

In my masters thesis (Fehr, 1986) I added a new concept to automatic guidance systems by developing a dual mode guidance system for a row crop planter. Previous guidance systems in agriculture typically utilized only one mode of guidance. If this single mode failed to detect the directrix, the vehicle became confused and required operator intervention to restore the steering control signal.

The guidance system developed by me utilized two modes of guidance. If one mode (the primary mode) lost its guidance reference a second mode was available to provide guidance information. The operator need not be aware of which system was providing guidance information, only if the event occurred where both systems were confused. This

guidance system also used a combination of contact and non-contact sensing showing practical applications of both methods.

My thesis, also described how I used a microprocessor in a multi-tasking mode. Use of programmable peripheral chips changed the role of the microprocessor to more of a supervisory mode of operation. Instead of the microprocessor being directly in charge of a few tedious tasks that resulted in poor use of the power of the microprocessor, it delegated these tasks to other parts of the computer. With this supervisory mode of operation, the microprocessor's power was much more efficiently utilized resulting in a more powerful guidance computer with only a small increase in complexity.

Murphy (1988) offered some interesting insight into the evolutionary development of the guidance technology used in agriculture. First, he explained the developments that increased the physical abilities of the operator, chiefly through the use of hydraulics. Later in the development of agricultural technology the emphasis shifted to enhancing the operator's mental capabilities. By providing engine speed controls, draft and depth controls, the operators field efficiency was improved. Ultimately this has led to the development of guidance systems for agriculture. With the help of a guidance system, the operator can now control large implements at high speeds,

another way to improve his field efficiency.

In his development of an ultrasonic-based guidance system for a tractor, Murphy brought out other interesting aspects of guidance in agriculture. An index relating to the difficulty of tracking on a row has been devised to quantify the degree of diligence required in performing a given field operation. Studies of this sort have shown that after operator fatigue, one of the greatest contributors to poor steering accuracy resulted from the operator having to look behind to monitor the implement and look ahead to steer the tractor. This awkward, but necessary, arrangement caused a reduction in speed as well as a decrease in steering performance.

As Murphy progresses to a discussion of guidance specifics he first mentions the aspect of safety. He discusses some established guidelines that relate to protecting the operator, the implement, the vehicle, and the surroundings. Automatically guided vehicles were classified into two types, one type with operator assist and one type that would have no operator on-board. Regardless of the type of system, the vehicle should have the capability for manual guidance in public areas or where automatic guidance provides too great a risk. In any case, the vehicle should also have the ability to revert to manual control and/or shut down in the event of a failure. Safety would require that the steering wheel remain stationary when in automatic mode, and always be available

to the operator in an override mode for emergencies.

Murphy then discussed steering control algorithms. These algorithms would include speed-dependent and non-speed-dependent aspects of controlling the tractor implement combination. Work was also done on different types of steering arrangements. This would include, front axle steering, rear axle steering, and articulated steering. The consensus is that all three types of steering could be adequately controlled for field operations.

Murphy also contrasted proportional hydraulic steering control with digital hydraulic steering control. Murphy used the digital mode of steering and arranged a set of networked microprocessors to provide the control signal. This network of microprocessors was another method of distributing the processing load. One microprocessor acted as the master of the system, the other microprocessors were slaves which were controlled by the master.

In summary, Murphy drew the following relevant conclusions about automatic guidance:

1. Safe and effective control of agricultural vehicle guidance is possible using automatic methods.
2. A microprocessor provides the speed and programmability required for automatic guidance control in agricultural operations.
3. Non-contact sensors with no moving parts are desirable for automatic guidance control because they are less fragile than mechanical contact sensors. (p. 11)

It would seem that the necessary parts of an automatic steering controller have been well established, as well as the advantages and disadvantages of various sensing methods. It now remains for the development of sufficiently complex controllers which will take advantage of the best sensing methods to provide a reliable steering control signal. An overview is given of these theses as the best way to present the previous works relating to guidance in agriculture in an expeditious manner. For more in-depth information these theses can be studied as well as the numerous citations that generated the discussions.

2.2 VISION GUIDANCE IN AGRICULTURE

The first investigation of the use of a vision system to provide a steering signal for a field operation is from Gerrish et al. (1983), Gerrish, Stockman, Mann, and Hu, (1986). This study indicated that then state-of-the-art technology in video cameras, video digitizers, and computers were fast and accurate enough to provide sufficient control signals to steer a tractor in a row-crop application. It now remained for the reduction of this theory to practice. Fehr and Gerrish (1989) produced an operational Vision Guided Robotic Tractor (VGRT) that could follow corn rows at speeds up to four km/hr.

Reid and Searcy (1988) worked on a parallel effort to Gerrish et al. in developing an operational vision guided

tractor. Reid (1987) used a slightly different approach in his vision-based steering control system. He used a monochrome camera with an optical filter to reduce the computing overhead. The optical filter limited the light received by the camera to the near-infrared portion of the light spectrum. The received light was in the 850 nm wavelength portion of the spectrum with a pass band of 100 nm. Reid's reasoning was to take advantage of the increased reflectance properties of soil and vegetative material in this light wavelength.

Reid then proceeded on a method to distinguish the crop material from the soil background from which to then extract a control signal. A Bayes classifier for a two class problem was used to find the optimum threshold to segment the image into object (plant material) and background (soil). Run length encoding (RLE) was used to reduce the memory storage requirements of a thresholded image. The transition points between runs represented boundaries between plant material and soil. The start and stop points of the runs (corresponding to the location of plant material) were averaged to provide a representative crop canopy center.

Reid then used one of two methods to quantify the line associated with the crop row. The Hough transform (Reid and Searcy, 1986) was used to define the line of the row, or a method of row clustering was used. Either method

produced a set of lines corresponding to the crop row in the ground plane. From these lines Reid then developed a control signal for steering the tractor. Like the method used by Gerrish and Surbrook, Reid defined steering error in two terms, heading error and offset error. By comparing the heading of the tractor and the offset position of the tractor to the lines formed from the crop rows, which are extended to the vanishing point, a steering heading was determined for the tractor.

Reid's vision guidance system had some similarities and many differences with respect to the vision guidance system described in this study. He used a monochrome camera in a slightly different portion of the light spectrum and placed the camera on the front of the tractor instead of over the rear axle. Reid's method of determining the steering control signal for the tractor also has a much higher computational overhead than what was used in this study. The vision guidance system in this study never quantized heading error and offset error as two separate entities. Both Reid's guidance system and the vision guidance system developed here used two computer systems in a master and slave arrangement (Brandon, Searcy, and Babowicz, 1989).

From the many examples of automatic guidance systems found here and in the literature it would seem that robotics, in the form of automatic guidance, is firmly entrenched in agriculture. As future efforts continue in

the development of robotic guidance systems it may be well to remember the words of Isaac Asimov (1950):

THE THREE LAWS OF ROBOTICS

- 1) A robot may not injure a human being, or through inaction, allow a human being to come to harm.
- 2) A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.
- 3) A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

Handbook of Robotics
56 Edition, 2058 A.D. (p. i)

2.3 NON-AGRICULTURAL VISION GUIDANCE - ROAD FOLLOWING

Outside of agriculture, many other efforts are being undertaken to study vision guidance. The equipment and type of algorithms involved in these projects differ markedly from those used in this agricultural related research project. One similarity, however, is that these non-agricultural vision guided vehicles use vision equipment that is self-contained on the vehicle. A representative sample of some of the research being conducted is given here.

In the Federal Republic of Germany, research has been done on a vision guided high speed vehicle (Dickmanns and Zapp, 1987). This vehicle was to operate in the relatively

controlled road situation of an autobahn. The vision system used was two forward looking black and white CCD cameras. One camera had a wide angle lens, the other camera a telephoto lens for looking farther ahead. These cameras were mounted on a movable base. The computer system involves the use of multiprocessors to split the image processing up among as many as 14 processors.

To follow a road, Dickmanns, and Zapp (1987) outlined five necessary functions that the autonomous system had to perform. The functions were:

- 1) Detection of the road and its parameters like curvature, lane width, surface state, presence or absence of obstacles (static objects).
- 2) Recognition of relative position in the lane and of position and speed relative to other moving objects.
- 3) Correct interpretation of traffic information like road markings (e.g. lines, interrupted or not), traffic signs (e.g. speed limits) and local warnings.
- 4) Safe and efficient control of the vehicle depending on the actual state resulting from 1 to 3 above.
- 5) Easy human interface for both switching from human to autonomous control and back and for human decision taking on request of the automatic system (warning functions). (pp. 1,2)

This system was placed in a van and fully equipped for automatic control. A test road scene was projected in front of the vehicle at simulated speeds of from 30 to 60 km/hr.

Road following work has also been done at Carnegie

Mellon Institute which includes the use of adaptive color classification and shape tracking (Wallace, 1987). In this research a van was equipped with a color camera mounted on a movable base that used vision to track the shape of the road through the image sequence. The basic problem was to segment the image into road (the navigable portion of the image in front of the vehicle), and shoulder (all other non-navigable portions of the image).

To operate a road following vision guided vehicle successfully in spite of all the color and shape inconsistencies encountered in a road situation the following assumptions were developed (Wallace, 1987):

1. Local Ground Plane. We assume that the roadway around the vehicle lies in a plane, or at least nearly so much so that the difference is unimportant for steering in situations we encounter. Furthermore, we assume that the one-to-one mapping from image points to ground plane points is known.
2. Obstacle freedom. The road in front of the vehicle is assumed to be obstacle free, so that the location of the road is all that is necessary for the robot to move forward without collision. In a practical system, the detection and avoidance of obstacles will be left to other modules running concurrently with the road following module.
3. Shape constancy. Although we allow the colors and textures of road and shoulder to vary wildly, the basic shape of roads and shoulders remains constant. Also, the program described here has no knowledge of intersections or road shapes other than the simple case of a locally straight road bounded by parallel lines.

4. Shape continuity. The position of the road changes only slightly from one scene to the next. More precisely, if the robot senses scenes of the road arbitrarily close together in time, then the difference in road position between scenes becomes arbitrarily small.
5. Dead reckoning. From one image to the next, an estimate of the vehicle's motion is known. This estimate is assumed to be bounded.
6. Colors distributed normally. The measured color features of objects are assumed to be statistical phenomena modelable by multivariate normal distributions. (p. 259)

A test situation was video taped of a one km curving asphalt roadway. The roadway had sections in direct sunlight and sections in the shade of trees. The imagery was further confused by pot-holes, color gradations in the road, and seasonal variations such as snow. A description of the success of the vehicle in following the road is somewhat vague. Failure modes of the vehicle were classified when a successful completion of the test section of the road was not completed.

This vehicle has since been developed to include the use of artificial intelligence in the form of neural networks to provide steering feedback control (Touretzky and Pomerleau, 1989). These neural networks use a method of back propagation to "learn" the proper algorithm to solve the presented problem and associated solution. The problem and its solution are presented, over and over, to the neural network which alters its weights when it reaches the correct solution. The neural network method has the

advantage of being able to attempt to resolve problems which it has never seen before, but which are similar to problems with which it has experience.

These non-agricultural autonomous vision guided vehicles work in an outdoor environment similar to the environment of the vision guided tractor presented in this dissertation. Similarities would include changing light conditions as well as color variations in the scenery surrounding the intended path of travel. The major differences would probably be in the computer systems, involved in the imaging systems and the types of algorithms used to solve the path following problem. The road following vehicles have more complex computer systems and use much more complex algorithms than does the tractor guidance system.

2.4 EDGE DETECTION

Of all the computer vision operations used to attempt to follow some target path such as a road or crop row, one operation is basic to most methods. The operation of edge detection is usually used to note when something in the scene changes which might be significant in detecting the desired path of travel. An edge can be described as a discontinuity or abrupt change in grey scale value or color in the scene (Levine, 1985). This abrupt change in grey scale or color could be the difference between the grass at the edge of the road and the asphalt of the road, or the

difference between the soil of the field and the vegetative material of the crop row.

Edges can be used as a clue to the shape of the object and the object may contain edges in any orientation. The orientation of the edge and the significance (rate of change of grey scale or color through the edge) of the edge can also be clues used to gain information from the edge. Edges that are nearly parallel to the supposed direction of travel could be a good clue as to the edge of the road, similar to that of the broad edge of the crop row in a field. Edge detection may be necessary to locate these areas of interest to determine a steering response.

Edge detection usually consists of scanning a matrix that contains the edge operator across the pixel array of the image. The edge detection matrix may either be one or two dimensional depending on the complexity of the target edges and their orientation. The dimensions of the matrix may also be varied to alter the size of the edge that is being viewed for as well as to reduce the effects of noise in the image.

Perhaps the most simple of edge detectors examines the difference between two pixels. A simple two element matrix is scanned across the image. At each new location the difference in grey scale or color between the two pixels is noted. When the difference is great, it is a good indication of the presence of an edge. Such a detector

works well for very ideal edges, but ideal edges are rarely found in natural scenes. As mentioned, the size and orientation of the matrix may be changed as well as the detection operation to improve the response of the edge detection to less ideal situations.

Edge detection can be further enhanced by first preparing the image. The usual method is to segment the image into object and background. With a two class system it is very easy to locate and derive information from the edges as there is little or no noise in the image. Thresholding is an easy method used to segment the image.

To threshold an image, a histogram of the light intensity levels must first be taken. Each pixel in the image has an associated light intensity value. The intensity levels represent each discrete level of light intensity that contains the range from cut-off (no light) to saturation (maximum light). One value per pixel if it is a black and white image, this would be its grey scale value. In the case of a red, green, and blue color image there would be three intensity values, one corresponding to each color value in the pixel. Thresholding can be based on one intensity value in the case of a grey scale image, or on one or more in the case of the color image.

The histogram represents a frequency of occurrence of each intensity level for the image. For an image that contains a clearly defined object and clearly defined background, the histogram should have two modes. One mode

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would correspond to the object and one mode the background. The more clearly defined the object and the background, the more definition these two modes have in the histogram. To segment the image, an intensity threshold is selected based on this histogram.

The threshold is selected from an intensity value that lies between the two peaks of the modes in the histogram. All intensity values below this threshold value can be set to cut-off (black) and all values above the threshold can be set to saturation (white). Now the image has only two classes in it, object and background. If the original image has good contrast, the object in the segmented image should bear the outline of the object in the original image. The segmented image now has clearly defined edges which can be examined for further guidance information (Levine, 1985).

2.5 COLOR DESCRIPTION AND PROCESSING

The apparent color of an object is due to the reflectance and absorption of portions of the visible light spectrum from that object to the human eye or video camera. Different colors are the combination of different wavelengths and intensities of portions of the visible spectrum. For most humans the visible spectrum ranges from 400 nm (violet) to 700 nm (red) (Searcy and Reid 1989).

Typically color is described by one of three methods.

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One method, commonly used in digitizing video equipment, is to describe the color based on the respective intensity values of the red, green, and blue components of the color. This method lends itself to being used in an additive mode to recreate the original colors. The additive mode involves the use of adding specific amounts of the three primary colors, red (R) (650 nm), green (G) (530 nm), and blue (B) (460 nm) (Kantowitz and Sorkin, 1983), to recreate the original color. With the use of these three primary colors all colors can be represented. The human eye appears to work on the additive mode of color representation (Lillesand and Kiefer, 1979).

The photographic process (film) uses a subtractive mode to capture colors. The primary color complements, yellow, magenta, and cyan, are subtracted in a specific order to maintain the integrity of the original color. Whereas the additive process contains a light source and adds the primary colors which then are emitted and received by the human eye, the subtractive process is passive and it is the reflected light (or transmitted light in the case of projected film) which is seen by the eye. In the subtractive process ambient light must first strike the film layers of the complementary colors. Depending on the amount of remaining complementary colors (after exposure and developing) the light that is not absorbed (subtracted) by the complimentary colors is reflected or passed and allowed to travel to the eye where it is registered as a

color (Lillesand and Kiefer, 1979).

The third method of color processing and rendition involves the use of hue (H), saturation (S), and intensity (I) to recreate the original image colors. Hue refers to the fundamental color, saturation defines the strength of that color, and intensity is the light level intensity associated with the color. This HSI method of reproducing color is probably more accurate than the RGB intensity levels method (Williams, 1988).

The RGB intensity method is actually three monochromatic values used to recreate the original color. This method can result in some ambiguity as to the original color because each monochromatic color (R, G, or B) must be treated with a different weight based on the response of the human eye. No matter how it is dealt with the RGB intensity method is only three grey scale renditions of the original color at different frequencies. The HSI method portrays the original color through the use of color descriptors (HSI) that can recreate more exactly the original color based on more factors than just grey scale intensities of three color frequencies.

2.6 RANGE FINDING

Range finding can be a non visual method to determine distances to objects in a given range of detection. This distance information can be used to both guide a vehicle

(Dunlay and Morgenthaler, August 1986) as well as avoid obstacles (Dunlay and Morgenthaler, October 1986).

Typically, range finding would use light or sound waves as the mechanism to determine the distance, since tactile sensing would be at a disadvantage in a mobile robot.

Range finding may have an advantage over intensity images in unstructured work environments. It can be argued that agricultural field settings are fairly structured and may not need range finding. This is true until the function of obstacle avoidance is deemed necessary for safe and successful operation of an automatically guided tractor in a field. Range finding may also provide help in locating rows or cut crop edges due to the dramatic change in height from crop to soil.

Whittaker, Turkiyyah, and Hebert (1987) list some of the elements of an unpredictable work environment that may also be relevant in an agricultural setting where range finding may offer an advantage.

Unstructured environments lack regular, obvious patterns that can be exploited to classify, recognize, and understand the surroundings. Cognition in these environments requires inferences based on intrinsic and often subtle characteristics of objects and their surroundings. Robots must discover structure in the environment rather than impose preconceived models and adjust their parameters as in rationalized environments such as factory work cells.

Dynamic environments evolve over time; they are discovered incrementally as task execution proceeds. The perceived world model rarely converges to a preconceived model (though some preconception is important as a starting point in perception). Such environments defy preplanning and present the need to continuously manage potential contingencies.

Achieving useful goals in these environments requires complete three-dimensional maneuvers without constraints such as planar actions or fixed orientations, hence the need for spatial reasoning capabilities not usually required in factory environments. It is also common that forceful interactions with the environment are required, ... (p. 1991)

Unlike visual intensity images of a scene which may be confusing due to the difficulty of extracting 3D information from a 2D representation (camera's image plane) of the scene, range finding utilizes the one physical phenomenon of spatial importance, that is, the geometry of the physical scene. Range data can provide information relevant to the following geometric items: angularity, orientation, extent, curvature, shape, and surface texture (Whittaker et al., 1987). Some of these items could be very useful in an agriculture setting.

Whittaker et al. (1987) further goes on to explain some of the more appealing advantages of range data.

Many scenes derived from unstructured work environments are not "interesting" in the sense that no one object is directly apparent to a viewer. The most expressive way of describing such scenes is by prescribing their geometry. Soil in an excavation pit is a good example of shapeless geometry where depth maps can be readily constructed from range images, but where intensity, color and regular geometry add little information. Depth maps can represent terrains and object surfaces efficiently.

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The inherent three-dimensional spatial geometry of most environments where robots work and the distinguished importance of the near field make desirable the use of a sensing model that provides direct, voluminous, dense, and accurate data for building models and planning actions. Emphasizing the near field and discounting the far is a natural consequence of finite-range sensors and provides a good way of separating the background from foreground objects most relevant to robot modeling and planning.

Many robots plan their actions based on distances in the environment (between objects, from surface to tool tip, etc.,). Range data enable fast, surface-relative tactics such as "fly-over", i.e. traversing over a surface while maintaining an objective standoff distance to cope with unanticipated surface variations. (p. 1992)

As the speed of receiving range data increases, it may become more useful as a guidance aid in agriculture as a supplement to a vision system such as in the Autonomous Land Vehicle (ALV) of Martin Marietta (Turk, Morgenthaler, Gremban, and Marra, 1987).

As previously mentioned range finding may use sound waves for detecting spatial information around a robot. The sound waves are generally in the ultrasonic frequency range and may be pulsed or continuous. This use of range finding (specifically known as SODAR, SONAR is for use in water, Polaroid, 1982) would probably take the form of obstacle avoidance due to the difficulty in achieving high resolution between small objects in the environment (Walter, 1987). However, techniques do exist to help improve the ability of ultrasonic sound to resolve objects that may make it more useful in obstacle detection (Gross, 1978). Range finding of an extreme nature may even use the

Global Positioning System of satellites for position information (Larsen, Tyler, and Nielsen, 1988).

Optical range finding, which can also be used for autofocusing, is of two basic types: active systems which require an active source of illumination and passive systems which do not employ their own source of illumination but rely on ambient illumination. There are disadvantages and advantages to either type of range finding (Wolpert, 1987).

Active systems have the advantage of being able to work well in situations of total darkness, or situations of less than optimal lighting conditions. They do however have a problem when objects, such as a window, are between the ranging system and the object. Passive systems are unaffected by windows but do have performance problems in low light situations, could not work at all in total darkness, and with objects that have poor contrast. A good ranging system may have a combination of both methods (Wolpert, 1987).

CHAPTER III

METHODOLOGY

3.0 INTRODUCTION

The purpose of this chapter is to describe the development of the Vision Guided Robotic Tractor system (VGRT) (Figure 3-1). The VGRT started with a conceptual mode of development which then proceeded to an operational mode of development. The conceptual mode deals with the development on paper of a prototype VGRT from available hardware. The operational mode is the functioning result and is composed of a hardware component and a software component.

3.1 TECHNOLOGICAL VS. ENGINEERING APPROACH

The technological approach to solving the problem of using machine vision to guide a tractor is both a pencil and paper approach as well as a hands on applied approach. It is more specifically the use of both of these methods on a continually alternating basis. This approach would be in contrast to the classical engineering approach of using pencil and paper until a complete path can be seen from problem formulation to solution. After completion of the engineering design phase, the project is then typically turned over to the applications approach and an attempt is

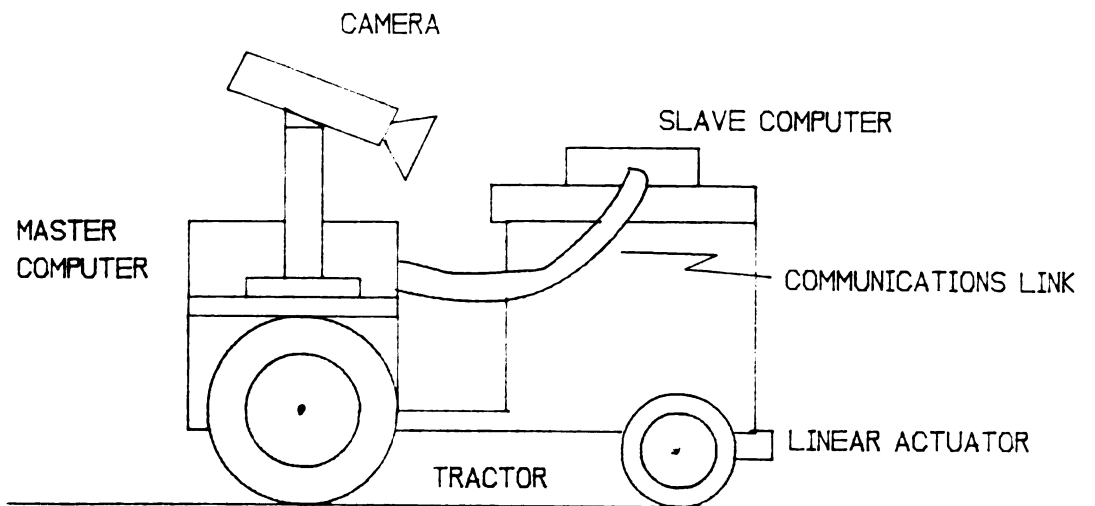


Figure 3-1. Side view of VGRT. This is a representative view of the completed VGRT showing the location of the major components.

made to verify the design by testing a prototype.

Each approach, technological or engineering, can be made to appear superior to the other. Engineering uses mathematics and other abstract processes as tools to solve the problem. This may produce a fine solution on paper that is impractical when it comes to actually trying to build a working model. The engineering design approach may, however, reveal fatal limitations that save the expense of building something that will quickly show the same fatal flaw. The engineering approach may produce a prototype that proves that a solution is feasible. The operation of the prototype however may not be very robust if it has been designed only for proof of concept.

The technological approach would use appropriate technology in a step-by-step approach to solve the problem. The big problem would be broken down into several smaller parts. These parts would be solved, recombined, re-evaluated and then presented as a solution to the big problem. As a smaller part is solved it can be used as a determining factor to decide if the potential still exists to solve the whole problem. With this approach, if a fatal flaw is found, some components may have to be discarded; but if a partial section works, then that part of the whole is already completed. The technological approach should produce a prototype that has a relatively high degree of robustness, this robustness being necessary to indicate

that the technology used did indeed solve the problem. Whereas prototype failure can be forgiven in an engineering proof-of-concept exercise, there is no such forgiveness in the technological exercise where the working prototype is the only proof admitted. By this definition of what the technology approach must accomplish also indicates that it must provide real-time position information to get the prototype to operate at real field speeds. The engineering approach may not provide this.

The technological approach is the solution of choice in this research project. The reason for choosing technology instead of engineering to solve this vision guidance problem is based on the author's current degree program and background which are both technology oriented. The question is: "Can technology solve the problem of using machine vision to guide a tractor?" It was believed from the inception of this project (1985) and to the present that available "off the shelf" technology would be sufficient to produce a working prototype of a vision guided tractor. This technology must be combined in a creative way to provide a solution, as opposed to creating new technology to solve the problem.

3.2 CONCEPTUAL MODEL

The problem of using machine vision to guide a tractor, and developing a working prototype was first viewed as a problem which can be broken down into component

parts. The conceptual solution to this problem would have a tractor with two computer systems arranged in a master-slave configuration (Figure 3-1, 3-2). The master computer would control the machine vision system and the slave computer would control the functions of the tractor. At the outset, I wanted to leave the master computer as free as possible to do image analysis of as yet undetermined complexity. The master computer can then spend its time deriving a steering control signal from the field imagery. The master computer would also be the source of software development for both computer systems.

The camera would be placed over the rear axle and mounted above one of the drive wheels (Gerrish and Surbrook, 1984). Such placement should give the camera the most lateral stability and still give it a forward view of the field scenery. The master computer's control signal would be presented to the slave computer, which would deal with the tedium of turning the steering wheels and/or starting or stopping the tractor.

In summary, the conceptual model of a working prototype VGRT would have the following characteristics:

Master computer:

- 1) Provide a supervisory role for dealing with failure modes.
- 2) Provide fast clock speeds for timely control signals (at least two position updates per second).

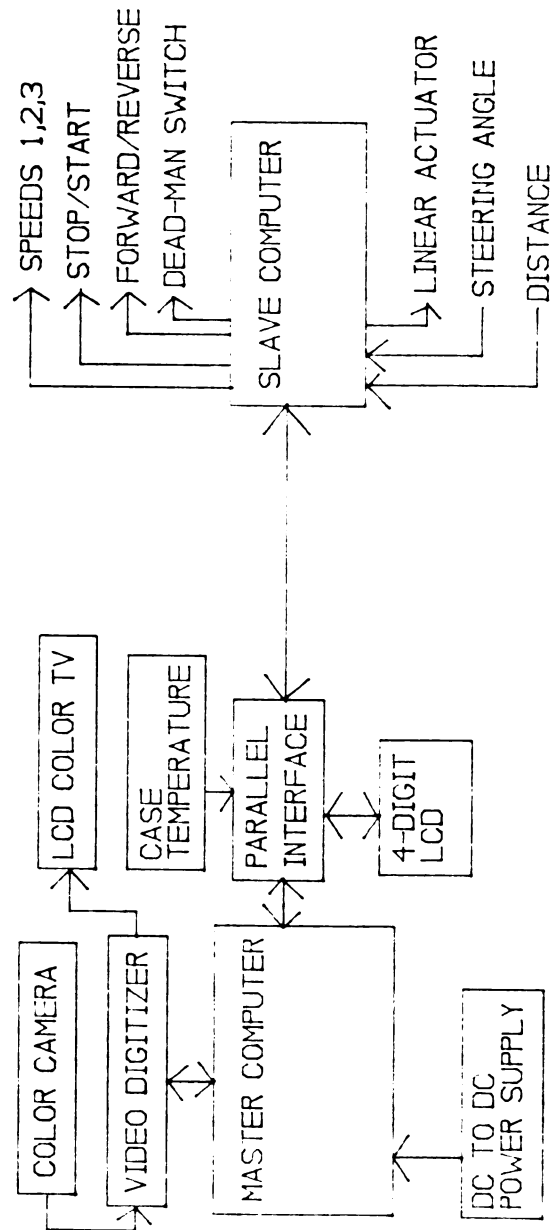


Figure 3-2. Block diagram of VGRT. This block diagram shows the interaction of the various components of the VGRT.

- 3) Provide means for developing software.
- 4) Provide capabilities for converting visual image information to a steering signal.
- 5) Provide a learn mode for headland turns.
- 6) Provide the overseer mode for starting or stopping the tractor.
- 7) Provide the interface (communications link) to slave computer.
- 8) Derive its power directly from the tractor batteries.
- 9) Consist of an Intel 80286 microprocessor based system.
- 10) Provide access to operational parameters (LCD).

Slave computer:

- 1) Provide direct control of direction and movement of tractor.
- 2) Provide distance traveled information.
- 3) Derive control of starting and stopping tractor only from master computer.
- 4) Provide interface (communications link) to master computer.
- 5) Derive its power directly from tractor batteries.
- 6) Consist of an Intel 8751 microprocessor based system.

Tractor:

- 1) Provide convenient use for this purpose (readily accepts computer control).
- 2) Facilitate testing (can be operated indoors or out of doors).

Camera:

- 1) Provide wide dynamic range.
- 2) Operate in color.
- 3) Utilize rugged solid state circuitry.
- 4) Produce an NTSC signal output.

The next phase of development will convert the conceptual model into the operational model.

3.3 OPERATIONAL MODEL

An operational model based on the conceptual model was developed using a technological approach to determine the feasibility of using machine vision to steer a small row-crop type tractor. This development was broken down into the following tasks: 1) acquire a tractor, 2) develop and install a slave computer system, 3) install video digitizing board in similar (to master) computer to test and develop vision algorithms, 4) acquire a master computer, develop DC to DC power supply for the master computer, install video digitizer board in master computer, and install master computer on the tractor, 5) develop and install communications link between master and slave computers, 6) develop system software, and 7) test

performance of system.

The operational vision guided tractor development is divided into two parts, the hardware and software portions of the completed prototype. Hardware refers to either mechanical, electrical, or electronic components while software refers to the programs developed.

3.4 THE TEST TRACTOR

The tractor used in the development of this VGRT was a GE ElecTrac lawn tractor donated by the Detroit Edison Company. The tractor has a three speed manual transmission with no reverse gear. Each mechanical gear has four electrical speeds to provide a total of 12 forward speeds, reverse is limited to two electrical speeds per gear. Reverse is obtained by reversing the polarity of the field winding of the drive motor. This tractor is a small scale model of a typical large field tractor and has many functions which make it comparable to a full size tractor.

There are many advantages to using a tractor of this size and type for development work. Being smaller, it is easier to work around. Having an electric motor for its motive force instead of an internal combustion engine allows for its use indoors, and due to its smaller size, smaller test areas can be used. The ability to test indoors safely is a major advantage as testing and development could proceed year around.

The initial testing of the vision system need not have waited for the procurement of an expensive full size tractor. If the system proved successful on the smaller tractor, then there would be sufficient reason to move up to a full size tractor.

From the work of Squires (1981), some of the necessary conversion components were already installed on the tractor. These included a linear actuator to steer the front wheels (Figure 3-3), the relays to actuate the linear actuator, and a metal box located on the hood of the tractor in which to mount the slave computer. The steering wheel had been removed for safety. Manual steering was done through a double-pole double-throw switch.

A 1K ohm wire-wound 270 degree potentiometer was installed on the rotating member of the front left steering king-pin (Figure 3-4). This potentiometer was implemented as a voltage divider to provide a change in voltage on its wiper arm that was directly proportional to the angle of the front wheels.

A toothed gear was added to the brake shaft of the transmission to provide distance pulses to a reluctance pickup. The brake shaft provided a direct link to the rear axle that was independent of transmission gear range. The result is a series of pulses that were directly related to rear wheel revolution.

The reluctance pickup used was a DI-MAG model 58424. This model provided a digital output that was compatible

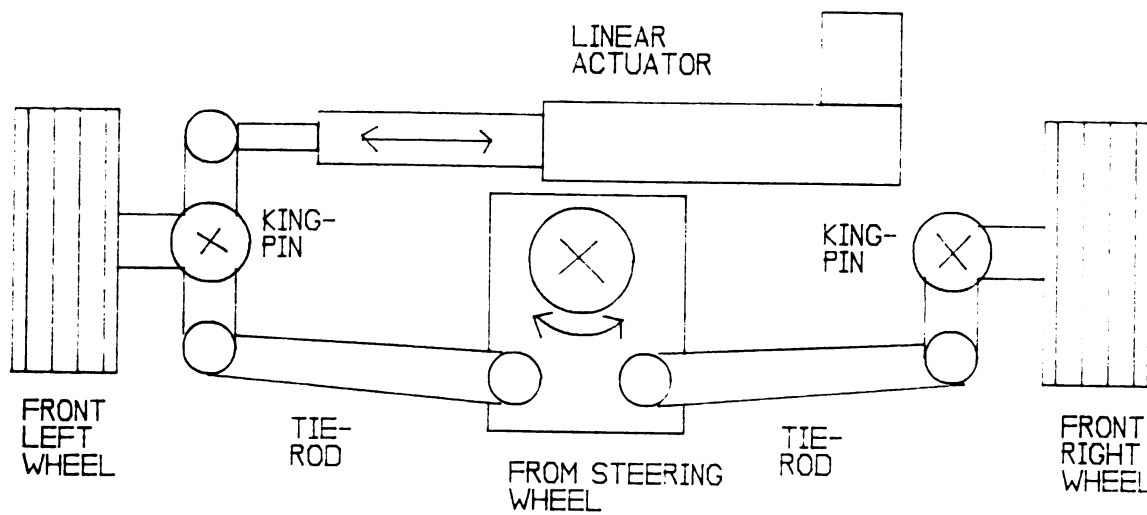


Figure 3-3. Top-down view of linear actuator placement. The linear actuator is used to turn the steering wheels.

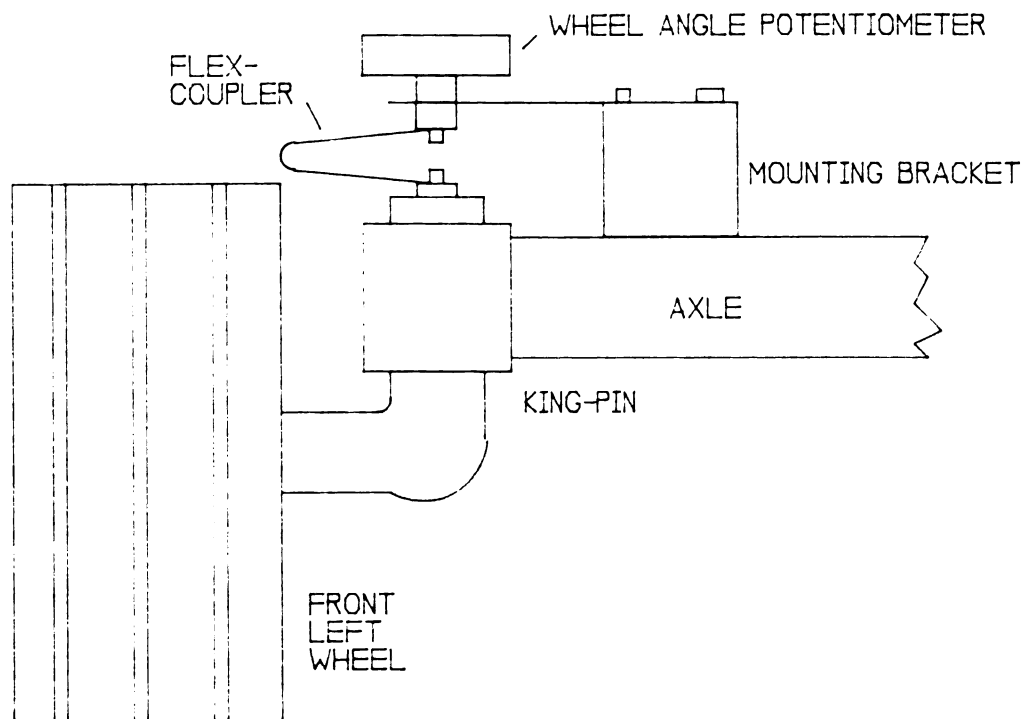


Figure 3-4. Front view of wheel angle potentiometer. The potentiometer provides steering wheel feedback to the slave computer.

with the input to the counter in the slave computer. Instructions with the reluctance pickup indicated that it should be mounted as close to the gear teeth as possible for best sensitivity. This proved to be a problem as the sensitivity was so great that vibrations in the mount used to hold the reluctance pickup caused false distance pulses. This problem was remedied by desensitizing the reluctance pickup through simply increasing the space between it and the teeth of the gear.

Another advantage of the electric tractor was the ease with which the slave computer could be placed in control of the tractor. Transistor buffers were used to increase the current gain of the microprocessor to the point where the current was sufficient to operate the relays that controlled the tractor. The last stage of the transistor current amplifiers (buffers) was an open collector wired OR configuration. This type of interfacing allowed for the control of the tractor by the stock speed and direction controls or by the slave computer (Figure 3-5). The slave computer could be either on or off for manual control of the tractor. With this configuration, the tractor could still be operated even if the slave computer was removed for development work or if a component failed.

3.5 SOLID STATE VIDEO CAMERA AND CALIBRATION

An Hitachi MOS type color camera (model VK-C3400A) was used as the video sensing device. This camera provided a

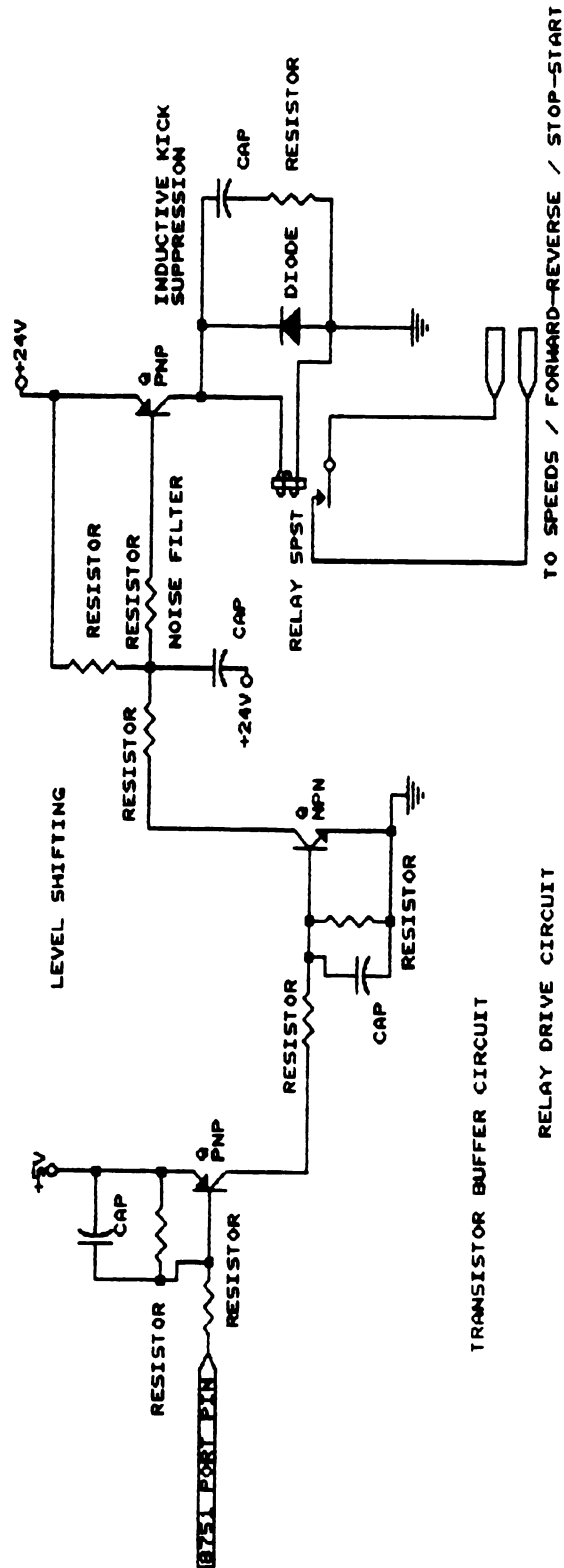


Figure 3-5. Electrical diagram of transistor buffers. These buffers provide an interface between the slave computer and the tractor.

2:1 interlaced, internally synchronized NTSC video image of at least 280 lines of horizontal resolution. The video output of the camera was coupled directly to the digitizing board. To provide the camera with the greatest lateral stability, while still providing sufficient field of view, the camera was mounted on a platform directly over the right rear wheel. A quartz-halogen light, which augments ambient light, was provided on the same platform to aid the camera in low light settings.

The Hitachi camera had an F of 1.2, and a variable zoom from 10.5 to 65mm. The camera was calibrated corresponding to the fixed zoom values as imprinted on the camera lens assembly. For calibration the camera was mounted 120cm up from the floor and at a distance of 178cm from a 122cm by 244cm sheet of 12mm plywood. The camera was placed so that its nadir was perpendicular to the plane of the plywood sheet with the X-axis parallel to the horizon. This arrangement produced a test setup that contained the full view of the camera on the plywood for all zoom angles.

For each imprinted zoom number the width of the field of view was measured for both the X and Y axes. The results of this calibration are listed in Table 3-1.

Table 3-1 shows the results of calibrating the Hitachi camera at the specified zoom angles.

Table 3-1. Results of camera calibration.

<u>Zoom Value</u>	<u>X(cm)</u>	<u>X(degrees)</u>	<u>Y(cm)</u>	<u>Y(degrees)</u>
10.5	122	34	94	28
15	88	26	70.	21
20	65	20.	53	17
25	51	16	42	13
30	41	13	32	10.
45	28	9	23	7
65	20.	6	16	5

The calibration of the camera was necessary to map the camera image plane coordinates onto the real world ground plane coordinates.

3.6 SLAVE COMPUTER

The slave computer is a single chip computer. The Intel 8751 controller type microprocessor has four eight-bit input/output ports, onboard 4K byte erasable programmable read only memory (EPROM), and 128 bytes of random access memory (RAM), and two 16-bit programmable counter/timers. The ports can be configured in any combination of in or out and are also bit selectable as to direction. If a bit is set to a high level, it is at a high impedance state. In this high impedance state, an

outside signal can drive the bit high or low and can be read as such by the 8751. This is how bits within a port can be set in or out. Generally the 8751 will drive a device with an active low level since the 8751 can source much more current than it can sink (conventional electron flow). The slave computer has port 0 set in, port 1 set out, port 2 bi-directional, and port 3 set primarily in with one bit set out. Port 3 is a special port. It can be used as an eight-bit bi-directional port or as the connection to special internal functions within the 8751. These internal functions include the timer/counters, interrupts, and serial I/O (Figure 3-6).

3.6.1 SLAVE COMPUTER HARDWARE

Port 0 of the 8751 microprocessor is devoted to an eight-bit analog to digital converter (ADC). The ADC is connected in a free-running mode with its output buffers always on. The analog signal input to the ADC is connected to the filtered output of the steering angle potentiometer. With such continuous free-running operation of the ADC, the 8751 is assured of a constant stream of new steering wheel position updates, as many as 2000 per second.

The potentiometer is positioned so that approximately straight travel corresponds to an ADC output of 124. Values below 124 indicate turns to the right and values above 124 indicate turns to the left. The complete

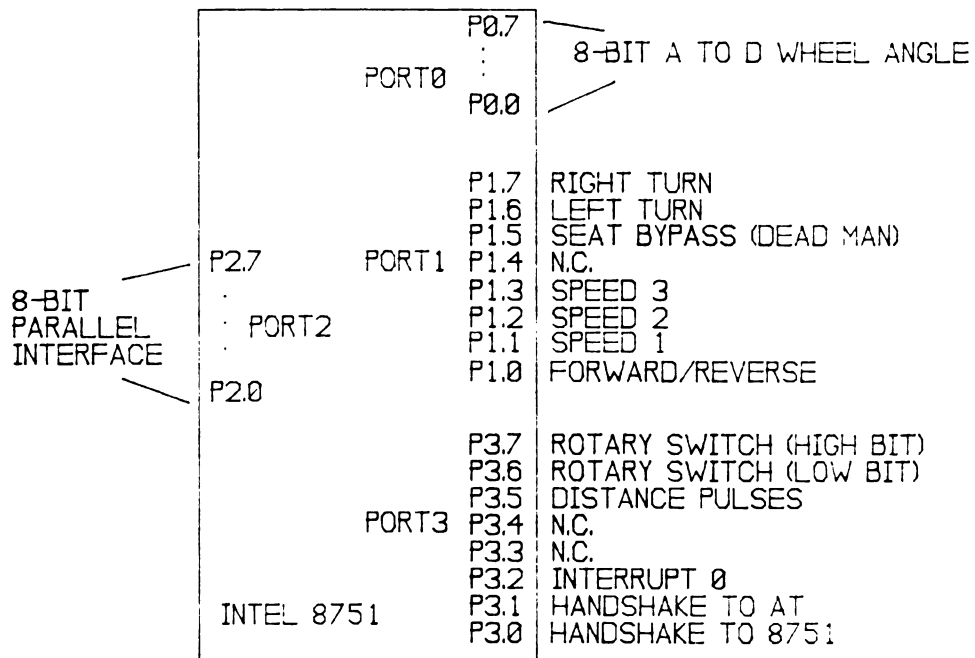


Figure 3-6. 8751 port listing. This figure provides a diagram of the various port connections of the 8751 processor used in the slave computer.

turning range of the front wheels is from 96 to 145 with one change in count corresponding to approximately a one degree change in steering angle.

Port 1 is used as an out port which controlled the seat dead-man switch; steering relays; speeds one, two , or three relays; and the forward or reverse direction drive motor control relay. Port 2 is used in a bi-directional mode of operation as the parallel communications link with the master computer. Port 3 is used on an individual bit basis. One bit is the input to counter 0. A second bit is the input for interrupt 0. A third bit is used as the communications handshake signal line received by the slave computer. A fourth bit is used as the communications handshake signal line which is sourced by the slave computer.

3.6.2 SLAVE COMPUTER SOFTWARE

Two Assembler programming languages are necessary for the VGRT. The control oriented instructions for the slave computer differ to a great degree from the much more flexible instructions for the master computer. The Assembler for the master computer also has many more features that make it rival a high level programming language in some respects.

The first software written for this VGRT was Assembler language for the slave computer. Test programs were written to see if the computer hardware and tractor were

functioning properly. These tests included starting and stopping the tractor in forward and reverse, turning the front wheels, changing the speed of the tractor, and counting distance pulses.

Two problems had to be solved in the software used to control the tractor. A dead band had to be determined for the steering wheels that would provide accurate steering but would prevent the wheels from chattering. A dead band of approximately two degrees provided a good level of steering accuracy but had some chatter. Increasing the dead band to approximately three degrees gave the tractor good steering accuracy, but with virtually no chatter.

The second problem deals with stopping the tractor while in reverse. Starting the tractor into motion requires closing a SPST relay that provides power to the shunt wound electric drive motor. Directional control of the motor is accomplished by a second DPDT relay that controls the polarization of the field windings. For reverse travel, this DPDT relay has to be energized to reverse the field polarity. The problem stems from this DPDT relay being in series with the SPST relay (in regard to the field winding, field and armature are in parallel); both relays could not be de-energized at the same time. The SPST had to first be de-energized, then the DPDT. If both relays were de-energized at the same time, inductive kick produced a large arc on the DPDT relay damaging the

contacts. A time delay between releasing relays of even 0.5 seconds is sufficient to prevent the problem.

This also brings up two more considerations when using computer control of the tractor. 1) The stock tractor controls have a built in delay to prevent too rapid a shift between forward and reverse. When the computers are operating the tractor, this built-in delay is bypassed and has to be provided by the software. 2) When using computer control, limits have to be provided to prevent the linear actuator from turning the steering wheels hard against their limits. The linear actuator has sufficient force to jam the wheels at their travel limit where they may remain mechanically stuck and require operator intervention to return to an in-between position.

After it was determined that the slave computer could operate free of interference produced by electrical noise from the tractor, work could continue on development of communications with the master computer. A communications exchange can only be initiated by the master computer. Only the master computer can start tractor motion. This prevents accidental tractor movement before both computers are up and running.

A characteristic of the 8751 is that at "reset" the counter/timer registers are set to zero. This is not a problem except when an error occurs in a communications attempt and the master computer resets the slave computer. A "reset" would have zeroed the accumulated distance and

give the master computer a false distance reading at the next communications interchange. This problem was remedied by reserving two RAM addresses as a scratch pad in which to save the two bytes of distance information. During initialization after a reset, the data in these two RAM addresses is now written into the low and high byte registers of the distance counter.

At power up, the distance values are random which is allowable since only elapsed distances are used. The distance information is updated in these RAM addresses during each subsequent communications interchange. When a reset occurs, the current distance information is reloaded into the counter allowing the distance count to survive the default reset to zero.

The slave computer executes a loop after initialization that provides for steering wheel response or communications interchange. The normal mode of operation for the slave computer is simply to monitor Port 2 for steering wheel positions. This mode is indicated by an inactive handshake line. At the beginning of its program loop, the slave computer checks for an active handshake line. If the line is not active, it reads the data from Port 2 which will tell it the setting to which the front wheels are to be turned. If a handshake line is active then the slave computer jumps to the communications interchange subroutine.

3.7 MASTER COMPUTER

The master computer is a general purpose, commercially available MS DOS based, IBM AT type system. The system chosen was a 6 or 12MHZ Intel 80286 based system using the Zymos "personal computer on a chip" (POACH) set. This type of system was chosen because it had a dual purpose. The computer was used as the master computer in the vision guided tractor; and was also used for software development. Essentially the computer could be operated independently of the tractor as a conventional personal computer. This was a great advantage as it was not necessary to procure a separate development system and programs could be stored and loaded from a floppy disk.

3.7.1 MASTER COMPUTER HARDWARE

The only significant modification to the computer was the removal of the standard 110v power supply and the installation of a custom built DC to DC converter power supply which allowed the computer to receive its power from the tractor batteries. Holes were also machined in the lid of the master computer to facilitate air movement for improved cooling.

The master computer contains a Hercules monochrome graphics adapter board, a floppy/hard disk controller, a custom built parallel interface board, 1M byte of RAM, and a video digitizer board. The 1M byte of RAM is split into

two 512K byte areas. One 512K byte area is used for program operations, the other 512K byte area serves as a virtual disk. Programs as well as editors, assemblers, and linkers can be loaded once from a floppy disk to the virtual disk and executed many times at a great improvement in speed. This was a great convenience factor for developing software.

The master computer was also used to develop and cross assemble the software for the slave computer. A separate custom built 8751 EPROM programmer was connected to the printer port of the master computer. The program code was transferred through the printer port to the programmer and then "burned" into the 8751.

3.7.1.1 CUSTOM POWER SUPPLY

A DC to DC power supply was built for the master computer to reduce waste power consumption from the tractor batteries. This power supply also supplies a filtered +12V for the solid state camera. The power requirements for the computer and camera were +12V at 750mA, +5V at 6A, -12V at less than 100mA, and -5V at less than 100mA. Series linear power supplies were used for the two positive supplies and the two negative supplies used inverting mode switching supplies.

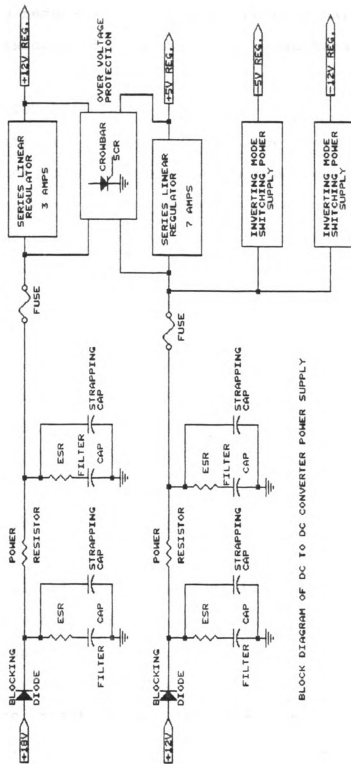
This custom power supply was built so that it would fit in the same location in the master computer case as the 110v AC power supply it replaced. The master computer case

was fitted with two cooling fans, one fan to draw ambient air into the case and one fan to exhaust hot air from the case. The slave computer only requires +5V at less than 200mA so a series linear power supply was used. All power supplies were fitted with ample heatsinking to reduce component heat levels.

Both the master and slave computer power supplies were subject to a great deal of battery supply voltage noise. This noise was the result of either starting or stopping the drive motor, or various relays engaging or disengaging. Proper isolation from the regulated to the unregulated sides of the power supplies had to be provided to prevent the noise from disrupting the computer's operation.

Two precautions were taken to improve isolation. A diode was placed in series with the positive supply lead from the batteries to the input of the power supply. This prevents the power supply filter capacitors from discharging back into the batteries when battery voltage momentarily drops due to drive motor startup. The second precaution was to use a modified pi-R filter after the diode (Figure 3-7).

The pi-R filter uses two filter capacitors, one on either side of a series resistor to reduce voltage fluctuations. The two capacitors source or sink current to try to maintain a steady voltage while the series resistor gives the voltage fluctuations a place to develop. The large filter capacitors were each strapped with a small



BLOCK DIAGRAM OF DC TO DC CONVERTER POWER SUPPLY

Figure 3-7. Electrical diagram of custom power supply. This power supply allowed the master computer to work directly from the tractor batteries.

capacitor to reduce the effects of the external series resistance associated with the large capacitors.

3.7.1.2 CUSTOM I/O BOARD

The custom I/O board provides three basic functions for the master computer system. One function is to sense the temperature inside the master computer case. The internal case temperature is monitored in the unlikely event that a component failure might cause a drastic and possibly harmful rise in temperature. Another function is the provision of a four digit display of user selectable information. This information could pertain to any of the operating conditions of the VGRT. During normal operation of the VGRT the monochrome monitor is removed, leaving the four digit display as the only means to view operating conditions.

The third function of the custom I/O board is the parallel communications link to the slave computer. This is an eight-bit bi-directional link with two handshake lines to the slave computer. To insure that the slave computer is operating in proper response to the master computer or in the event of a failure in communications, a slave computer reset signal line is also provided from the I/O board. To initialize slave computer operation or recover from a failure in the communications mode, the master computer can reset the slave computer to re-establish proper operation of the VGRT.

For ease of communication protocol and construction, I chose a parallel type interface for the communications link. A parallel communication operation would be less susceptible to errors and would provide faster data transfer rates than would a serial link. None of the clock frequencies in either of the two computers are temperature compensated. Therefore there was some risk, due to the potentially wide temperature range over which the VGRT might operate, that baud rates could change enough to cause data transmission errors in a serial link. With a parallel link that has handshake lines, there is no danger of this occurring.

The parallel link consists of an eight-bit bi-directional data bus, two handshake lines, and a ground reference bus. The handshake lines are used by one computer to indicate to the other computer that it is ready to send data or to acknowledge that data has been received (Figure 3-8). Each computer sources one handshake line and monitors the other.

3.7.1.3 VIDEO DIGITIZING BOARD

A 256 by 256 pixel, color NTSC video digitizing board (ATT ICB) provides the video input to the master computer. The RAM that contains the digitized images is located in the memory map of the master computer (the board is placed in the backplane of the master computer). By placing the

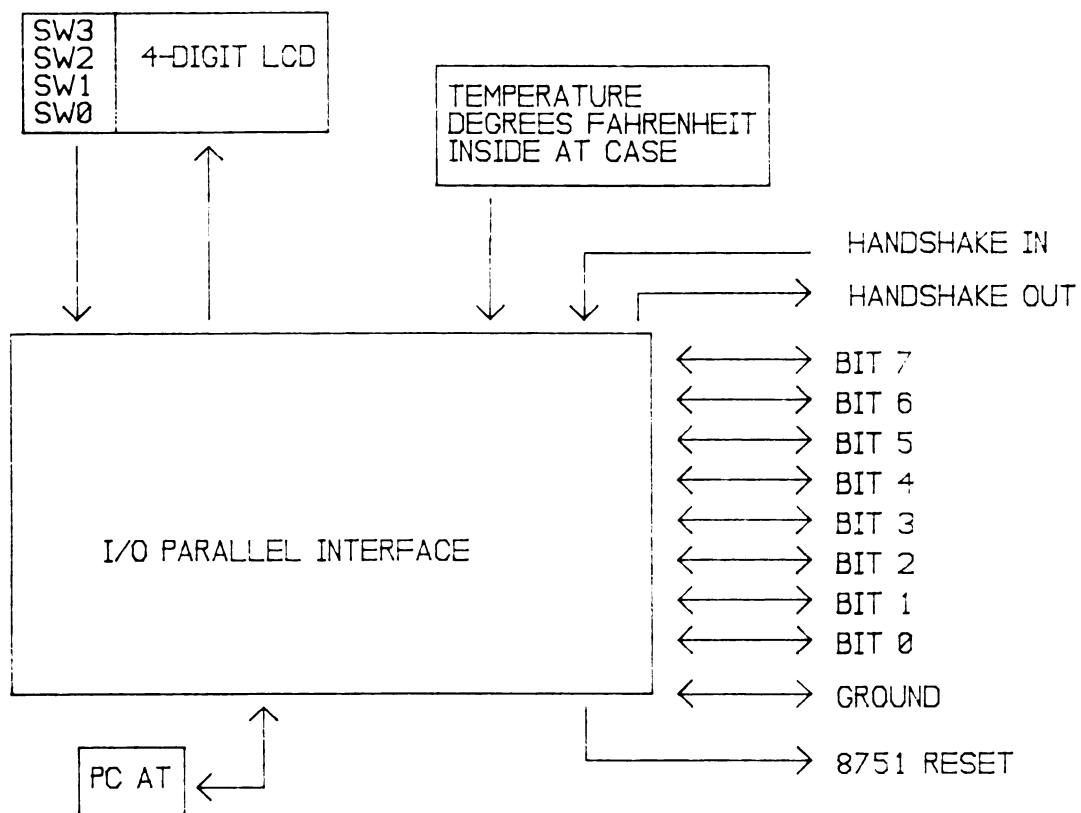


Figure 3-8. Block diagram of the custom I/O board.

video RAM in the computer's memory map, more Assembler programming instructions are available to manipulate the data. Each color band (red, green, and blue) is digitized on a scale ranging from 0 (cutoff) to 31 (saturated). Each pixel is represented by three values, one value for each color band. Due to the camera's recording format, the video image actually uses 256 by 200 pixels (4 by 3 aspect ratio) which requires 104K of RAM per digitized image. This RAM is physically located on the digitizing board and is available for memory access in two 64K blocks.

3.7.2 MASTER COMPUTER SOFTWARE

One of the major requirements involved in working with the VGRT is having sufficient computational speed to provide timely position information. Attaining maximum speed entails having as fast a computer clock speed as possible along with the most efficient form of programming. In this VGRT, one handicap is the 6MHZ limit on clock speed in the master computer, as imposed by the video digitizer board. (When trying to process the large amounts of video information 6MHZ is none too fast a clock speed.) In order to get the maximum performance from this clock speed, all programs are written in Assembler language.

Assembler language may be tedious but it offers the most compact, efficient programs and fastest execution times possible. The difference in execution time between

Assembler language and a high level language may be as much as three or four times depending on the language and how well it is compiled, (in one extreme situation the difference in execution time was two orders of magnitude of time slower for the same histogramming program written in Quick-Basic). Assembler language also has an advantage in dealing directly with the bit manipulations that are required for the video information and I/O control to the slave computer.

The software development for the VGRT proceeded in a logical manner from first learning how to control the video digitizer board to actually processing images in a near real time mode. When a high enough degree of confidence in programming skills was established, the video digitizing board was installed on the test tractor. Programming then continued with developing the VGRT.

The camera image plane contains a 2D map of the 3D real image. The 2D image is sent to the video digitizer. The image is mapped by X, Y coordinates for each pixel. The pixels can be considered to be in the first quadrant of a Cartesian coordinate system with the lower left corner of the image as the origin. Using this coordinate system permits easy mapping of the virtual coordinates of the image (as derived from the camera's image plane) to real coordinates as found on the real-world ground plane.

To derive control signals by which to steer the

tractor, the camera's image has to be mapped to real world coordinates. Since the camera is positioned so that it provides a low oblique view of the field image, its nadir is not perpendicular to the ground plane. This causes a perspective of the image that has to be corrected in order to derive real distances and angles (Figure 3-9).

3.7.2.1 INITIALIZATION OF CONTROL PARAMETERS

In order to convert virtual distances in the camera's image plane to real distances on the flat ground plane, the VGRT had to be calibrated based on the camera position. During testing, the constants associated with camera position were a user input so they could be changed for different tests. The master computer will query the user for the camera's height, angle of tilt below the horizontal, and the zoom angle. At this point, the master computer uses this information to determine the near and far edges of the camera's field of view in real distances (Figure 3-10). For all mapping of image plane coordinates to real world coordinates, only the tangent (or arctangent) function is used (Figure 3-11). The user can then select a control point distance (forward of the front axle) and enter it into the master computer. The master computer will then query for a steering gain value and a center pixel line value. The VGRT is now ready for operation (Figure 3-12).

The control point is used to determine where the

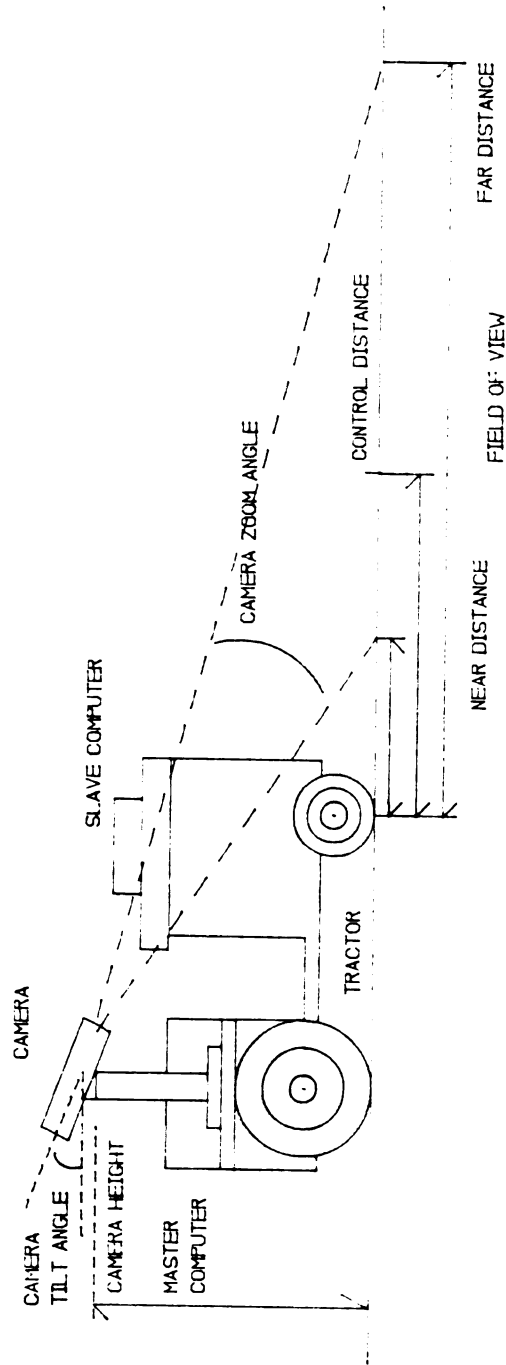


Figure 3-9. Side view of VGRT. Note camera nadir is not perpendicular to ground plane. When the camera nadir is not perpendicular to the ground plane a perspective error is introduced which must be corrected for.

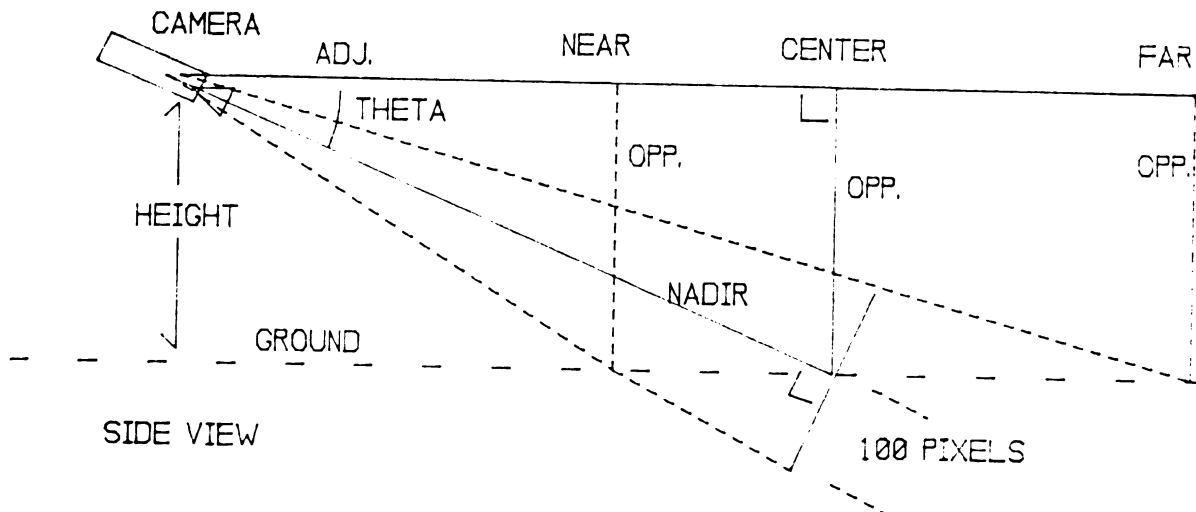
---- FLOW DIAGRAM ----

Initialization of constants for mapping image plane to ground plane. Only the tangent function is used.

This is executed once at beginning of program.

1. Enter camera height.
2. Enter camera tilt angle (below the horizontal).
3. Enter camera zoom number.

Look up corresponding X and Y zoom angles.



4. Find tangent of theta (camera tilt angle).
5. Opposite side equals camera height.
6. Using camera height determine adjacent side.
(camera height / tan of theta = adjacent side).
7. Now know opposite and adjacent sides in cm.
8. Determine nadir length (hypotenuse), in cm.
(Pythagorean theorem to determine hypotenuse).
9. Determine nadir length in pixels.
10. Opposite side now equals Y axis / 2 or 100 pixels.
11. Theta now equals Y zoom angle / 2.
(100 pixels / tan of theta = adjacent side).
12. Now know opposite and adjacent sides in pixels.
(adjacent side = nadir).
13. Now have a direct correlation of camera position constants in both real units (cm) and image (pixel) units.
14. Alternately add and subtract Y zoom angle / 2 to get near and far edge of window on ground plane.
15. The adjacent side is the respective near and far distance.
16. Enter a control distance between these two values.
17. Enter steering gain.
18. Enter lateral center value.
19. VGRT is now calibrated and ready for operation.

Figure 3-10. Flow diagram of guidance control parameters.

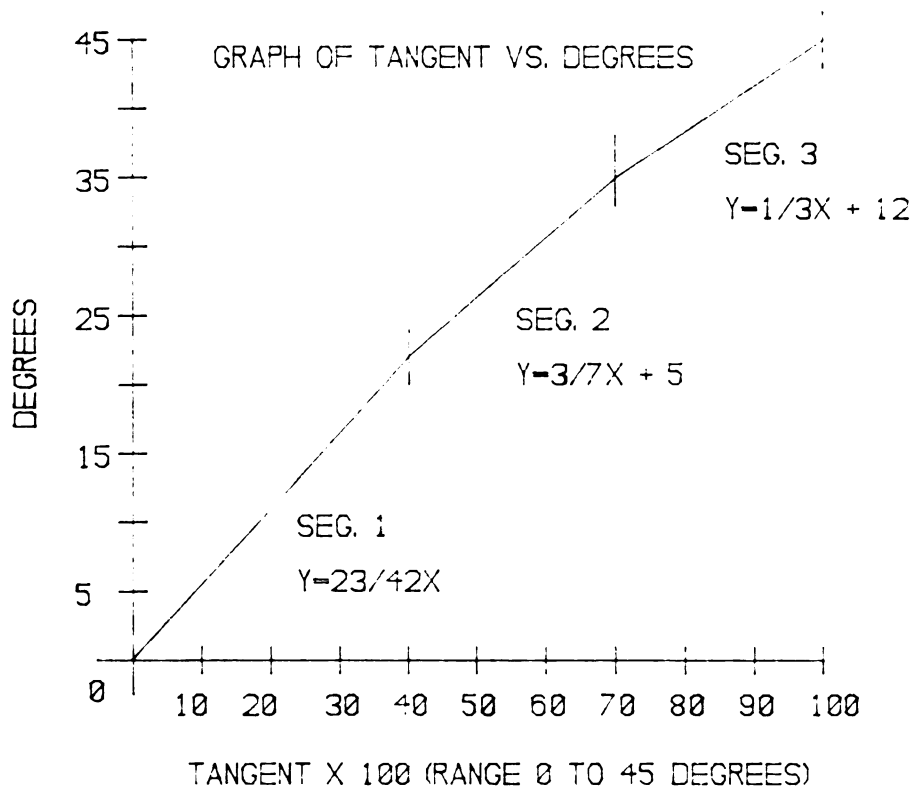


Figure 3-11. Tangent curve approximation. The tangent curve from 0 to 45 degrees is approximated by three straight lines for ease in computing tangent functions.

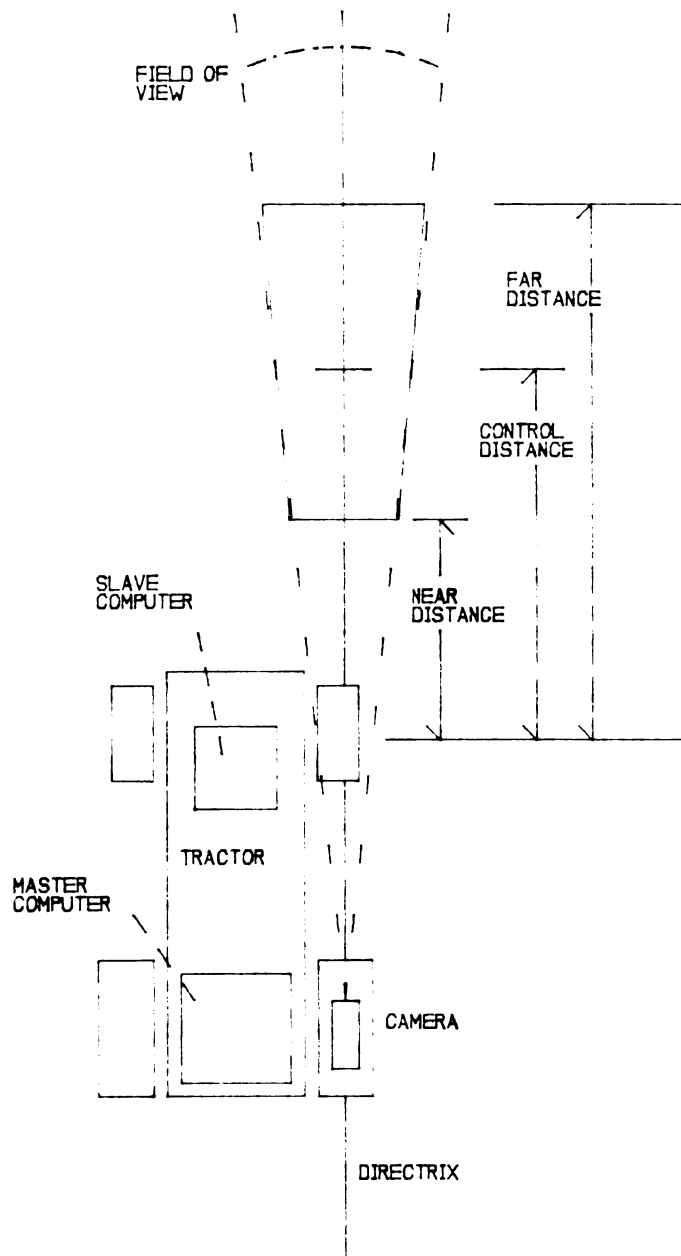


Figure 3-12. Top-down view of VGRT ready for operation. The various camera position constants have been entered and the near and far field of view values have been determined.

vertical center of the window will be in each image. The window will move horizontally back and forth as necessary on the pixel line that passes horizontally through the control point.

3.7.2.2 STEERING CONTROL

The control point located in the image serves as a reference to determine the angle to which the front steering wheels should be turned. All steering angles are either to the right or to the left of a center line, or if the tractor is traveling directly along the line, straight ahead. The center line is the vertical row of pixels that is parallel to the major axis of the tractor. If this pixel line is directly over the center of the row, or edge of the row, the tractor is traveling straight ahead with no steering correction required. When this pixel row and the center of the row start to diverge or converge then a steering correction is required to bring the tractor back onto course.

The angle at which to turn the front wheels is determined from one of the angles formed by an imaginary triangle (Figure 3-13). The three corner points of this triangle are: 1) the point at the intersection of the center pixel line and the front axle, 2) the point on the center pixel line that is the assigned control point distance ahead of the front axle, and 3) the control point as determined from the row edge or row center finder. The

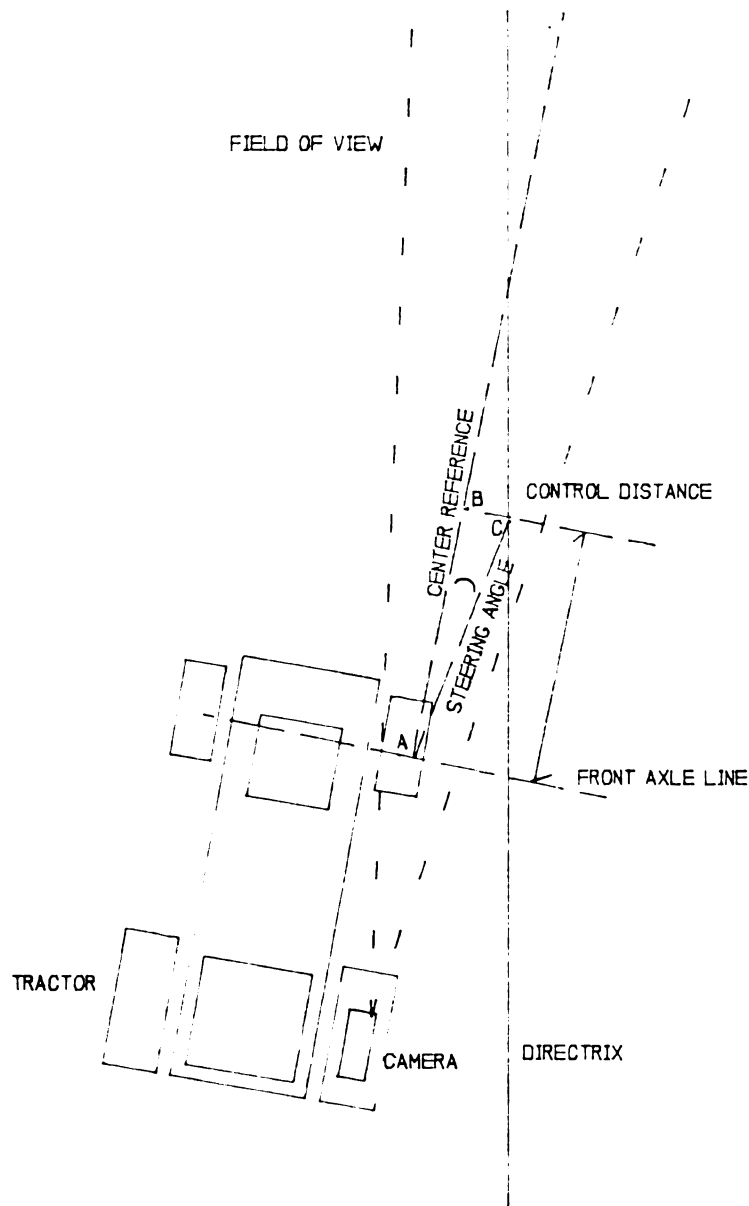


Figure 3-13. Diagram of triangle used to determine steering angle. This view shows the VGRT in an off-row situation and the resultant triangle formed to determine the angle at which to turn the front wheels.

angle formed by the center pixel line and the line from the control point distance on the pixel center line to the control point is a right angle. The angle formed by a line drawn from the axle point to the control point on the center pixel line, and the line drawn from the axle point to the control point determined from the row or edge point is the angle at which to turn the front wheels. In essence the front wheels are always aimed at the control point determined in the row or edge finder. When the steering gain is one, the wheels are actually aimed at that control point, when the gain is more or less than one than the wheels are turned more or less than that angle (Figure 3-14 to Figure 3-16). The amount of error from this method of mapping image coordinates to real world coordinates was less than 10 percent, based on a calibrated scene.

3.7.2.3 COMMUNICATIONS SOFTWARE

A communications interchange always follows the same pattern. Having only a single communications interchange procedure greatly simplifies the communications protocol. No information has to be exchanged to see which procedure to follow and this reduced the number of handshakes and the associated chance for error. To further reduce complexity, the master computer is programmed to be the only computer that can initiate a communications interchange. The interchange always starts with the master computer

----- FLOW DIAGRAM -----

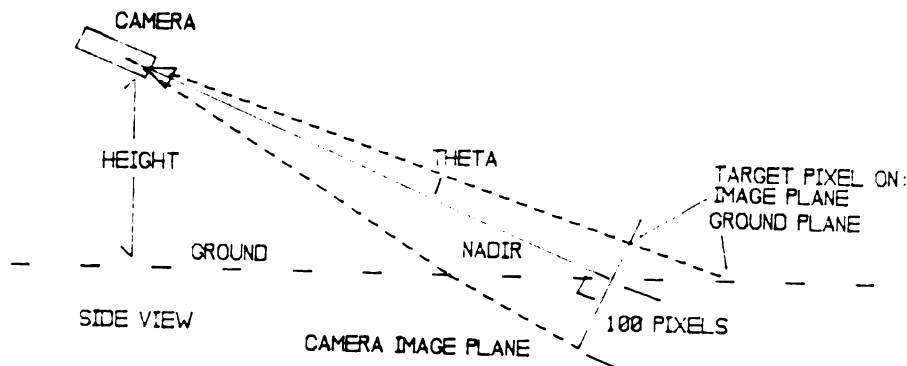
Steering angle, mapping Y coordinate value.

Only the tangent function is used.

This is executed once each position update.

Map image coordinates to real-world coordinates.

1. Run contrast mode or color discrimination mode row edge or center locator.
2. Now have X and Y coordinates of row (use Y value).
3. If above center subtract 100 to get absolute value of Y.
4. Determine tangent of theta.
(Pixels above center / nadir in pixels = tan theta).



5. Determine angle in degrees.
(Theta in degrees = arctan theta).
6. Convert this angle to real world angle.
(Camera tilt angle - theta = new theta).
7. Now have theta of real world angle to determine actual distance of located row point in front of front axle.
8. Determine real world distance.
(Camera height / tan of theta = distance in cm.).
(Subtract 99 cm to convert distance to front axle).
9. If Y is below center add instead of subtract 100 to get absolute value of Y, and add resultant angle in degrees to camera tilt angle.
10. Now have Y value in real world units.

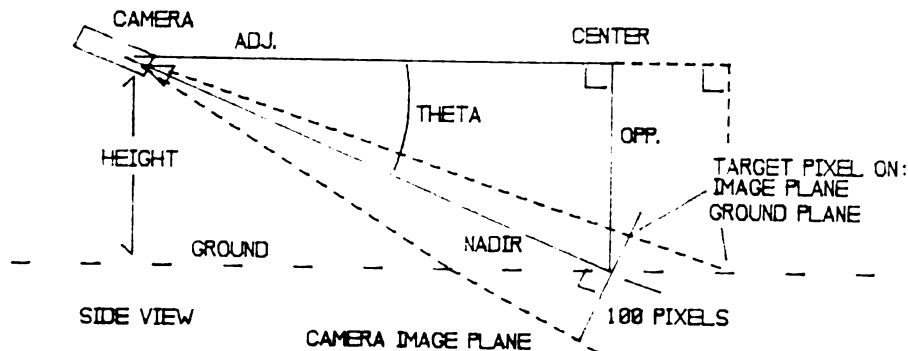


Figure 3-14. Procedure for mapping Y coordinate value.

----- FLOW DIAGRAM -----

Steering angle, mapping X coordinate value.

Only the tangent function is used.

This is executed once each position update.

Map image coordinates to real-world coordinates.

1. Have X image coordinate value from run of row mode locator.
2. Find absolute value of X from center.
3. Get camera zoom angle / 2 for X axis.
4. Determine tangent of this zoom angle.
5. Effectively move camera to ground plane to determine full width (127 pixels) of X row at this Y distance.
(Y length cm. * tan theta = full width in cm.).
6. Now know full width of X row in real world values.
7. Determine real world distance of X pixel coordinate value.
8. Use proportion to find actual X value in real world units.
 $((\text{pixel offset} * \text{full width in cm}) / 127 \text{ pixels})$
= displacement from center in cm.
9. Now have X and Y coordinates of row edge or center in real world units.
10. Use these units to determine steering angle.

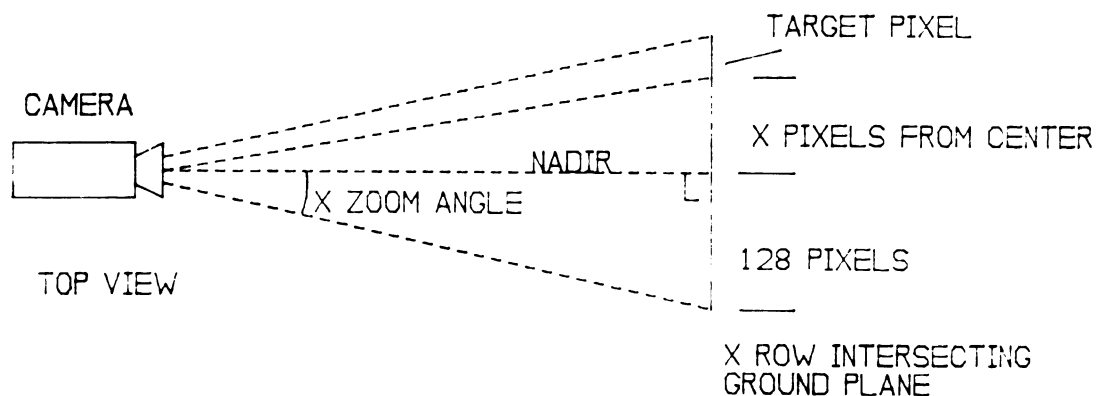


Figure 3-15. Procedure for mapping X coordinate value.

----- FLOW DIAGRAM -----

Determination of steering angle.

Only the tangent function is used.

This is executed once each position update.

1. Know now the X and Y values for the row center or edge in real world cm. values.
2. Use Y value in reference to the front axle.
3. Y value is adjacent side of triangle.
4. X value is opposite side of triangle.
5. The angle formed by the adjacent side and hypotenuse of this triangle is angle at which to turn front wheels when steering gain = 1.
6. Determine tangent of this angle.
(X value / Y value = $\tan \theta$).
7. Determine this value in degrees.
(θ in degrees = $\arctan \theta$).
8. Multiply this degree value by steering gain constant.
9. This degree value is either to left or right of center.
10. Now have angle to which to turn front wheels.

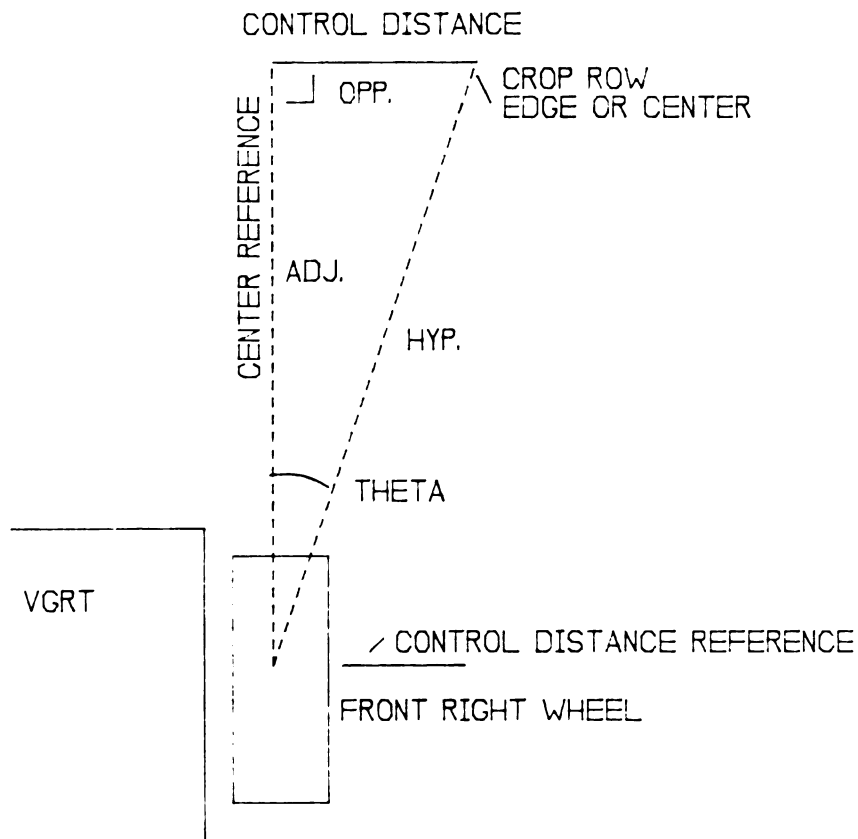


Figure 3-16. Procedure to determine steering angle.

sending a control word to the slave computer. This control word tells the slave computer to start or stop the tractor and how fast to move the tractor. The slave computer then responds and sends to the master computer the two bytes of distance information.

One weakness in this communications interchange is that no verification is made by one computer to guarantee that the data are received correctly by the other computer. However, use of the system has shown that if both computers successfully complete their respective transmission and reception of data, then no error had occurred. "Watchdogs" are used in the master computer to monitor the handshake line from the slave computer. If an error occurs in the communications protocol, a watchdog is activated causing the master computer to stop the present communications interchange and reset the slave computer. At this point the master computer initiates another communications interchange. Redundancy in the communications attempt, when an error is detected by a watchdog, is the method used to resolve errors in communications (Figure 3-17 to 3-19).

3.7.2.4 ROW CENTER, OR EDGE DETECTION SOFTWARE

Two types of row or line follower software were developed. The first type uses contrast within the image to determine an edge to follow. This method was fairly simple to implement and provides a means for developing the

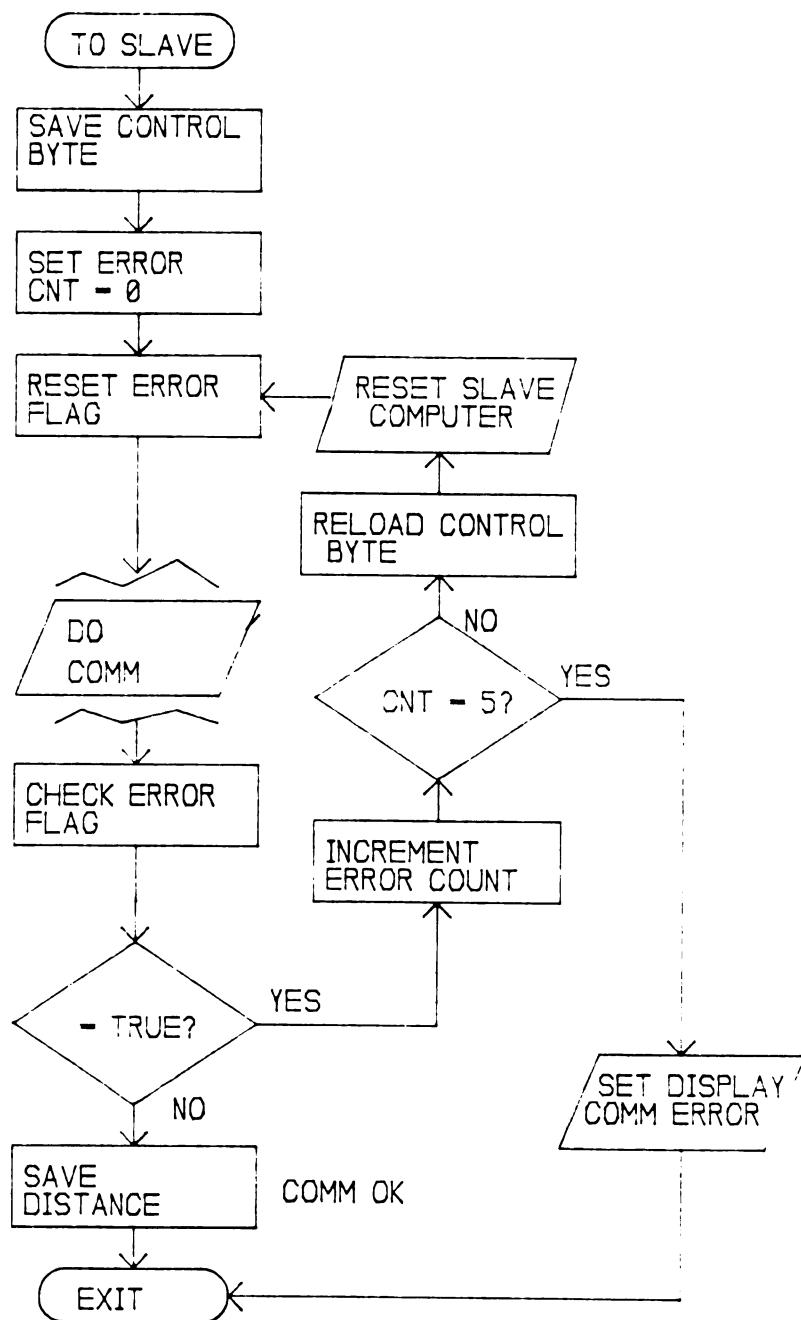


Figure 3-17. Flow chart of communications exchange. This flow chart shows the redundant communications attempts if one attempt is not successful.

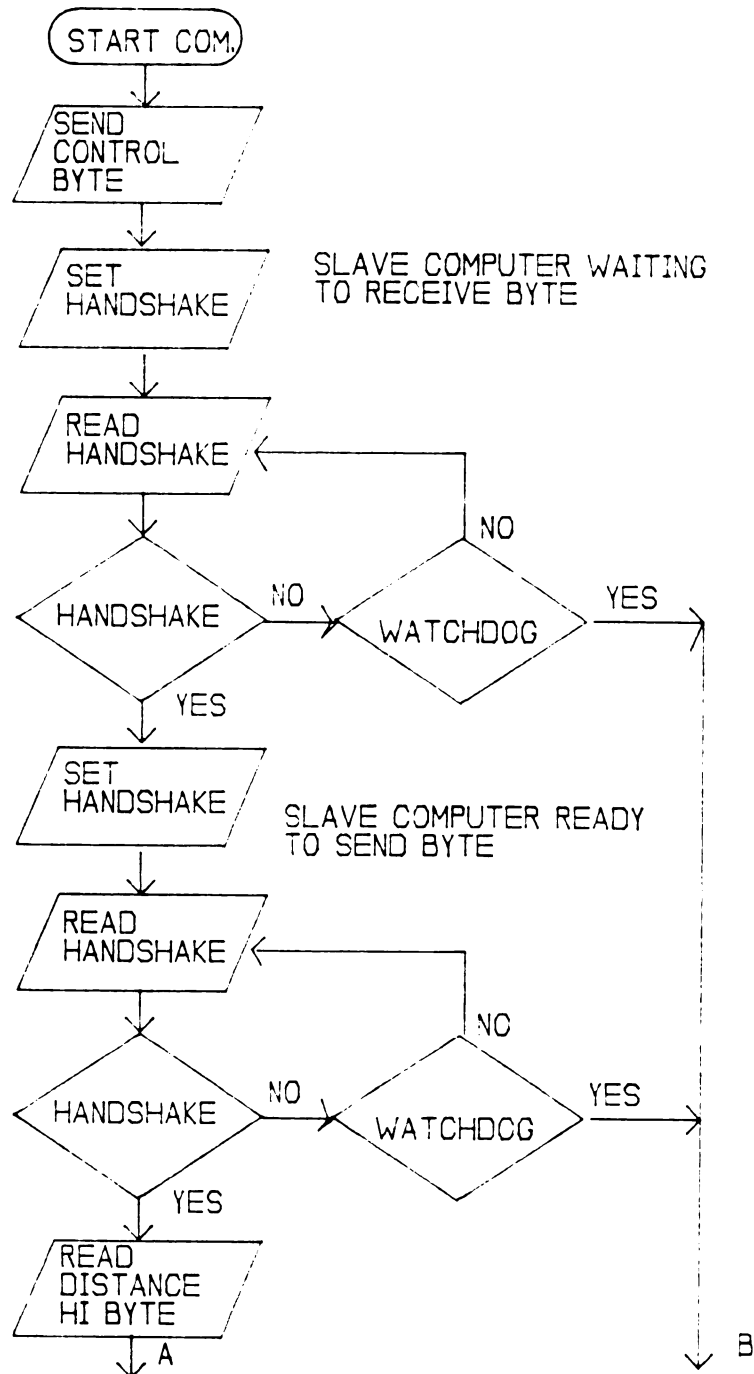


Figure 3-18. Communications procedure with slave computer. This flow chart shows the order of the data exchange and where the watchdogs are used to resolve missing handshakes.

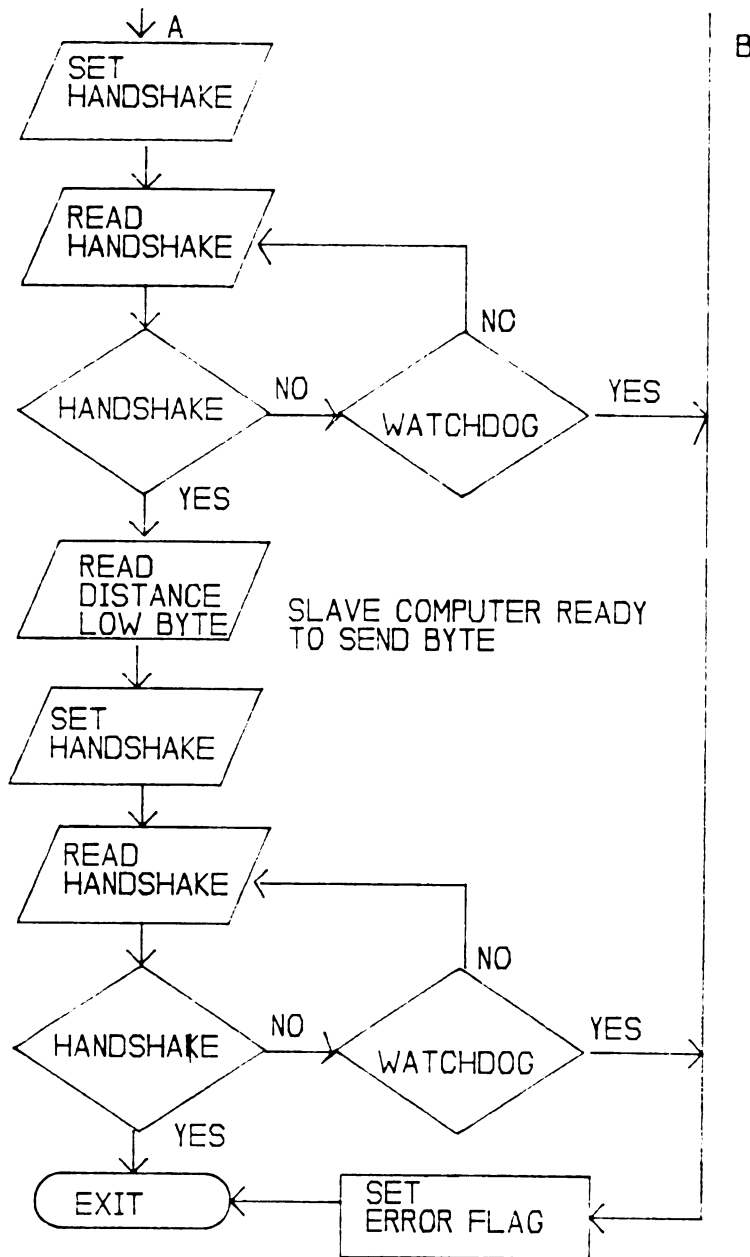


Figure 3-19. Communications procedure with slave computer, continued.

steering control software. The second method actually calibrates itself to a particular color and finds the average center of the row or line to follow. Whereas the first method was used to test the basic performance of the guidance system and develop the steering control software, the second method increases the robustness of the system and provides a means to actually follow a crop row (Figure 3-20).

3.7.2.4.1 CONTRAST MODE ROW FOLLOWER

The contrast row follower requires a bi-modal distribution in the image histogram. A histogram is taken of the window area to find the color band with the best discrimination. A smoothing filter is passed over each color band's histogram to reduce noise and accentuate trends. The filter adds one-half of the target value plus one-fourth of the previous value and one-fourth of the successive value. The sum of these values is placed in a new histogram at the same respective location to prevent the new values from confounding the old values.

After smoothing, each new histogram is tested to find which color band has the lowest valley between the two peaks. The color band with the lowest valley is selected as the color band to use for locating the edge. The color band with the lowest valley should provide the best contrast between the row (object) and dirt (background) (Levine, 1985).

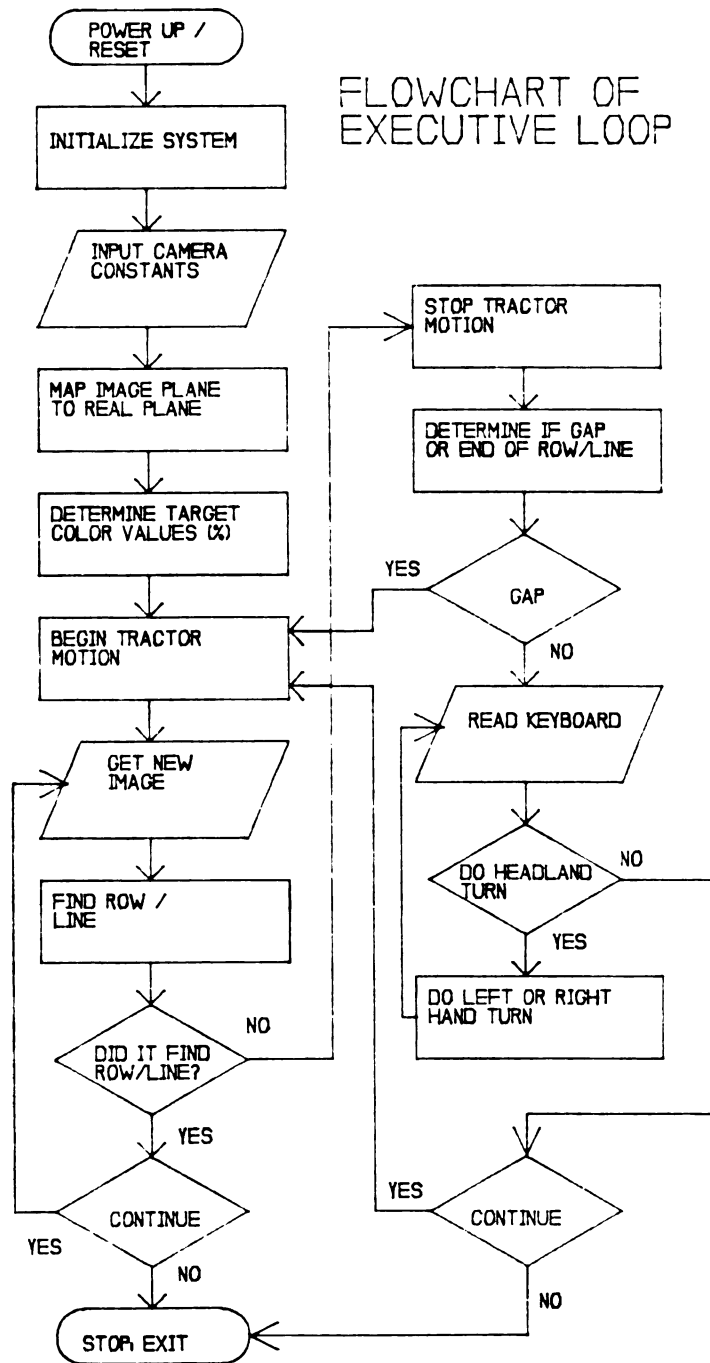


Figure 3-20. Flow chart of executive loop. This flow chart shows the order in which guidance control software is executed.

The color scale corresponding to the valley is used as the threshold to classify pixels into object or background. Values on one side of the threshold are object, values on the other side are background. The important issue is not which side of the threshold is object and which is background, but rather to find the boundary between them.

Next a raster scan is used in the window area to locate the edge of the row. Scans go from left to right and stop when a pixel is located that is on the opposite side of the threshold from the first pixel in the scan line, or the other side of the window is located (Figure 3-21). For each scan line that crosses the threshold, the X coordinate of the pixel is saved to help in determining the location of the edge. After the scans are completed for the window (typically 16 scans), all the X values from scan lines that crossed the threshold (but not scan lines that stopped at the opposite side of the window) are added together and an average is calculated. This X value, coupled with the Y value corresponding to the center of the window, provides a single coordinate point of the row edge (left side of the row). This point is used both as the control point for steering the tractor and as the center of the next window. When the coordinate point is used as the control point for steering it is on the real, ground plane and when it is used as the center for the next window it is on the virtual camera image plane. This method allows the window to float with the steering control point.

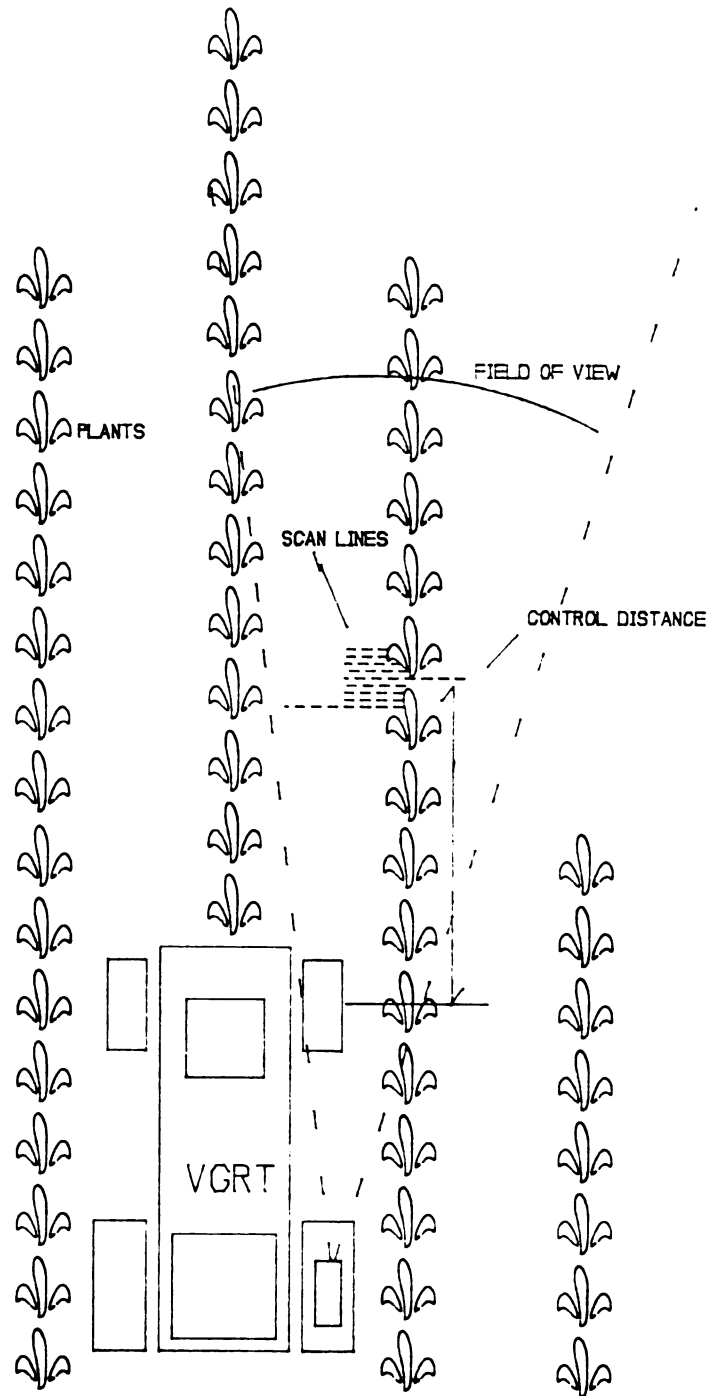


Figure 3-21. Contrast mode row following. View of VGRT and use of scan lines in contrast mode to determine row edge.

The contrast edge follower is fast and easy to use because no calibration is involved. During normal operation, a new histogram is taken for each new window. This provides a threshold that is consistent with the light levels in the window portion of the image. Weaknesses of the contrast follower require a relatively high degree of contrast between object and background and that the contrast only occurs at the boundary between the two. Contrast that occurs elsewhere in the image is considered to be noise and, in large amounts, can confuse the edge follower and provide a false control point. Noise can be in the form of shadows that fall across the edge or variations in the color of the edge and background. One precaution to note: no significant portion of the histogram can be either in cut-off or in saturation. This last item is principally dependent on the light adaptation and dynamic light range of the camera.

3.7.2.4.2 COLOR DISCRIMINATION MODE ROW FOLLOWER

The color discrimination row follower more fully utilizes the advantages of having three color bands than does the contrast edge follower. Whereas the contrast follower uses only one of the three color bands at a time, the color discrimination follower uses a combination of all three bands all of the time. In a row situation, color can be a simple clue in identifying the plant row from the

background dirt. The added complexity of having a color video digitizer may be offset by having relatively simple row detection algorithms than would be the case with the inherently simpler monochrome video digitizer.

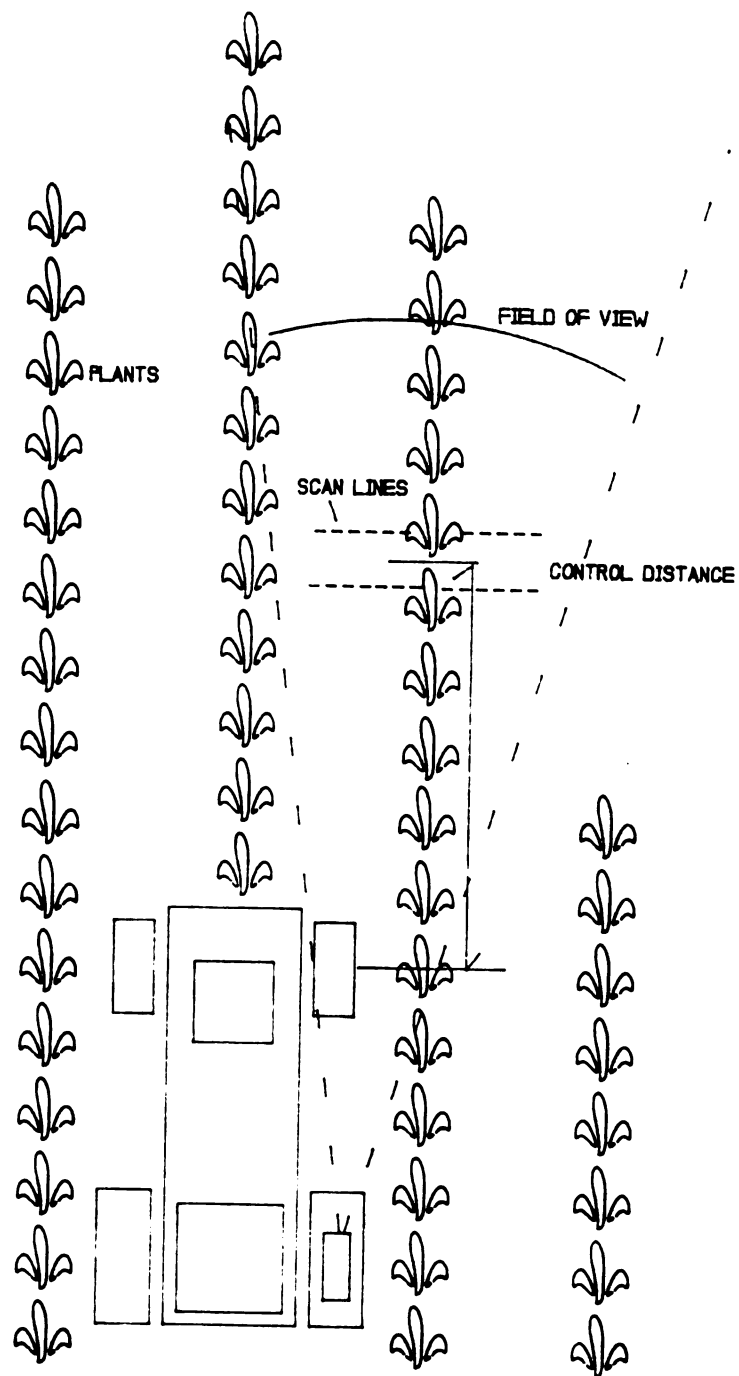
The color discrimination row follower is based on a calibration sequence that determines the percentages of red, green, and blue in the target color. When initializing the program, a still image is taken in which the target color must be located in the lower center of the field of view. First a histogram is taken of the lower area of the field of view. A threshold is determined as previously described and the background is set to a zero value. An average color intensity is determined for each color band based on the remaining target color. These average intensities are then converted to a percentage of the whole color. The target color is determined by a mix of percentages of the three colors that compose it. By converting to a percentage basis, changes in light level have a reduced effect on altering the apparent color of the row. This can reduce the confusion that shadows cause to the VGRT.

Tolerance limits of plus and minus ten percent (of the average percent value) are set for each color band based on the percentages determined in the calibration sequence. Each pixel that is tested in an image is converted to a percentage of its composite colors. These percentages are tested to see if they fall within the tolerance limits of

the calibration colors. Each color band can have a score of one or two. A one indicates that it is completely above or below the calibration limits, a two indicates that it falls within the tolerance limits. For all three color bands, a total score can range from three to six with a score of six indicating a very good match.

Another improvement in the color discrimination row follower is the method of locating the control point. Instead of locating the edge of the row, a new method of finding the approximate center of the row is used. Scan lines at the upper and lower edge of the window start at the outside edges and scan in towards the center of the image (Figure 3-22). A scan line stops when it finds a pixel that has a score of five or six. This indicates that the pixel color matches the calibration reference colors well. If no color match is found, the scan lines stop when they meet in the center. All four scan lines have to find a valid color match in their respective pixels for the coordinates of these four pixels to be considered valid in determining the control point. The four X values are averaged to provide the X value for the control point. The Y value is based on the center of the window.

There is more computation time involved with the color discrimination row follower than the contrast edge row follower. Yet, color discrimination is generally less susceptible to noise and provides a control point that is



**Figure 3-22. Color discrimination mode row following.
View of VGRT and use of scan lines in color discrimination
mode to determine row edge.**

more immune to undulations in the row edges. Because the color discrimination row follower "looks" for a specific color, it is less prone to confusion by spurious areas of contrast. Varying light levels also do not confuse it because colors are converted to percentages. In the case of shadows, as long as they are not completely black, the row can be discerned despite them.

3.7.2.5 HEADLAND TURNS

Dead reckoning is used to guide the tractor through headland turns. Each turn can consist of one, two, or three segments. The operator must first teach the tractor the turn; then the tractor will repeat the turn whenever the operator wishes it to do so. Left and right hand turns are taught separately.

In the "learn" mode, the master computer sets the distance/direction arrays to zero and about once each second records steering angle and distance information in the array. When a turn is played back, the master computer monitors distance information from the slave computer. When a distance is reached that matches one found in the array, the front wheels are turned to the angle found at that distance. This continues until the length of the turn is completed. At the completion of the turn, the tractor stops and waits until the tractor operator initiates further action.

CHAPTER IV

RESULTS AND DISCUSSION

4.0 INTRODUCTION

Tests of the Vision Guided Robot Tractor (VGRT) were designed to evaluate the performance of the system as a whole. Tests started with the VGRT following a continuous line with varying forward tractor speeds, control distances, and position update rates. The continuous line tests were considered to be the easiest scenario for the VGRT and would establish what should be its best performance. As new, more difficult tests would be attempted, any changes in VGRT performance could be evaluated against the original benchmark performance tests.

Testing progressed to greater levels of difficulty by modifying the line which the VGRT followed. Spotted lines were used to test for performance following a less than ideal line. A step was introduced into a continuous straight line to test the time response of the system. Human operators' manual steering performance was used as a comparison for evaluating VGRT performance. The VGRT was tested on "fuzzy" lines, lines that could be compared with crop rows in a field. A "user friendliness" test was done with operators unfamiliar with the VGRT to test the ease with which they could master the system and operate it.

And finally, the VGRT was taken to the field to see if it could actually follow a crop row.

To record VGRT performance, a second video camera was placed at the back of the tractor and positioned so that it could record a downward-looking view of the right rear tire and the area on the ground directly behind the tire. When the tractor was in motion, the camera was set to record this view which contained the line the tractor was intended to follow (directrix) and distance marks which were made on the tire (Figure 4-1).

The tread face circumference of the right rear tractor tire was divided into thirds at which points white stripes were painted on the tire. These stripes passed within the field of view of the second video camera providing a fixed distance interval of 61 cm of tractor travel. To further expedite the measurement process of recording undulations (lateral deviations from the desired path) in the tractor's path of travel, a meter stick was mounted in the field of view. This meter stick was rigidly attached at the rear of the tractor and positioned 2.5 cm above the floor perpendicular to the line the tractor followed. With this arrangement, the second video camera could provide a record of the path the tractor traveled which would contain a "tick" mark at every 61 cm interval of tractor forward travel. At each mark the lateral position of the VGRT could later be read from the meter stick.

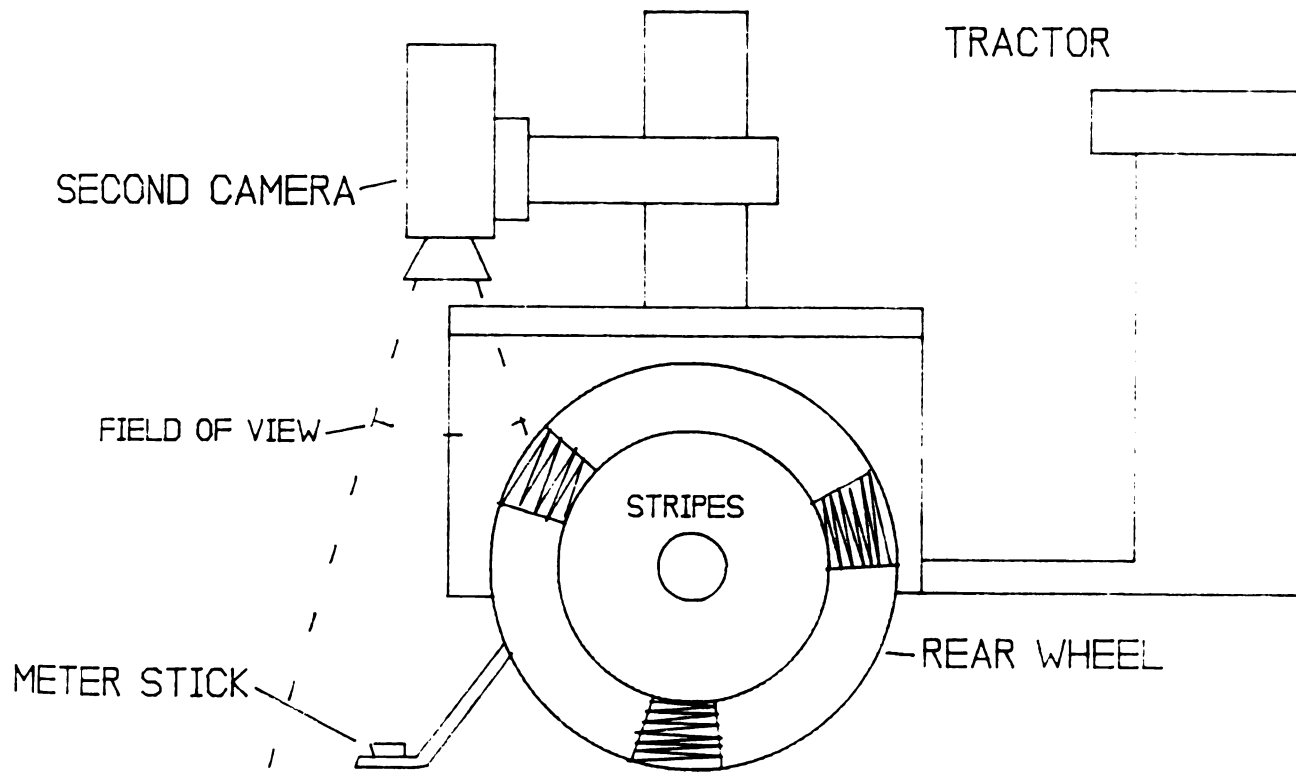


Figure 4-1. View of second camera placement, used to record tractor path of travel, and distance "tick" marks.

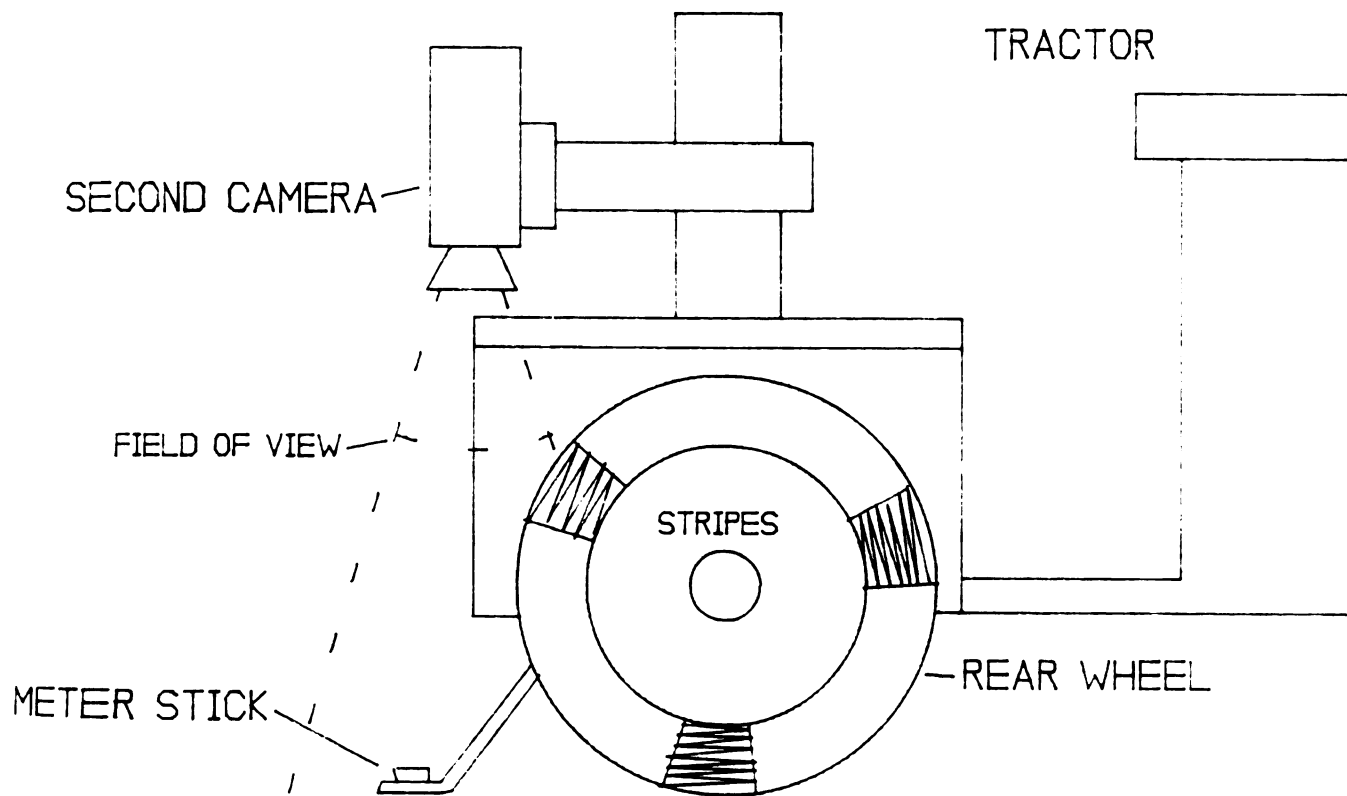


Figure 4-1. View of second camera placement, used to record tractor path of travel, and distance "tick" marks.

At a later date the standard 1.3 cm VHS video tape was played back to review the tractor's guidance performance. Every time a white stripe on the wheel would pass within the field of view a written record was made of the position of the line that the tractor was following with respect to the meter stick. These resultant meter stick values were plotted to give a visual representation of the tractor's performance. To quantify the tractor's performance, a standard deviation of the lateral tractor travel was determined from the meter stick readings.

Further testing was done on some of the individual components of the VGRT system to evaluate their effect on total system performance. The amount of free play in the steering system was determined. Factors affecting the position update rate were evaluated. Special attention was paid to the camera's ability to resolve colors under different light conditions. The last aspect of the VGRT testing, performance, is also one of the most significant for this research effort.

The other VGRT tests dealt with particular aspects of the total system performance; the last test was actually a test that continued throughout the entire evaluation of the VGRT. This tested the performance of the system as a whole. Was the system robust, or did it take a lot of adjustments to get it to work for one test, then more adjustments for the next test and so on.

As is naturally the case with most engineering

prototypes, there was some software and hardware development, and the subsequent elimination of bugs, as new tests were devised. The important question was: during a given test (or stage of development of the VGRT) was the performance consistent? Could the person conducting the test expect the system to work in spite of dramatic changes in ambient temperature, vibrations, repeated power-up cycles, and even handling by inexperienced operators?

4.1 CONTINUOUS LINE TESTS

A continuous line 3.8 cm wide by 46 m long was used as a basis to test what would be the best performance of the system. The test track was indoors and under fixed lighting so that the only variables in the VGRT system could be controlled at the tractor. This test was used to establish the basic performance characteristics of the VGRT. As later tests became more complex, comparisons in performance could be made to evaluate the ability of the VGRT to perform the more complex guidance tasks. All continuous line tests used the contrast edge-following mode of VGRT guidance.

4.1.1.1 FIXED STEERING GAIN TESTS

The first series of tests involved running the tractor at four different speeds, four different control distances, five different position update rates, and a fixed steering

gain. This test was to indicate the effect that control distance and position update rate would have on steering stability for a given speed. The speeds selected for the test were 0.6 km/hr, 1.8 km/hr, 4.0 km/hr, and 9.4 km/hr. These speeds gave roughly a doubling of speed for each increment in speed and were compatible with the gear ranges on the tractor. They also covered the speed range of the tractor from its slowest speed to its fastest speed.

The control distances selected were one, one and one-half, two, and three meters (ahead of the front axle). The position update rates were eight, four, two, one, and one-half per second. The results were divided by category into different position update rates. The VGRT was run once for each trial situation until it failed to follow the line the full distance. For a trial run to be successful the VGRT had to follow the line for the full distance. The results for computer control appear in Tables 4-1 to 4-5. Each result value in the table represents the standard deviation of the tractor's lateral displacement about the line in centimeters, (each datum was accurate to 0.5 centimeter):

Tables 4-1 to 4-5 indicate the change in VGRT line following performance when the position update rate is varied. N = at least 70 samples per test run. Lateral position accuracy to +/- 0.5 cm. The table results use standard deviation as the means to express variability. A "-" sign indicates an untried test.

Table 4-1. Steering Variability - 8 Updates/sec.

<u>Control</u> <u>Distance (m)</u>	<u>Km/hr</u>			
	<u>0.6</u>	<u>1.8</u>	<u>4.0</u>	<u>9.4</u>
1.0	1.8 cm	1.3		-
1.5	1.6	2.0	3.0	3.9
2.0	2.6	2.2	4.5	
3.0	2.2	3.5	4.9	

Table 4-2. Steering Variability - 4 Updates/sec.

<u>Control</u> <u>Distance (m)</u>	<u>Km/hr</u>			
	<u>0.6</u>	<u>1.8</u>	<u>4.0</u>	<u>9.4</u>
1.0	1.7 cm	2.1		-
1.5	1.9	3.2	2.5	
2.0	1.3	1.2	4.7	
3.0	3.3	3.2	4.5	

Table 4-3. Steering Variability - 2 Updates/sec.

<u>Control</u> <u>Distance (m)</u>	<u>Km/hr</u>			
	<u>0.6</u>	<u>1.8</u>	<u>4.0</u>	<u>9.4</u>
1.0	2.6 cm	2.4		-
1.5	1.5	2.3	6.5	
2.0	2.4	4.2		-
3.0	2.4	3.1	9.6	

Table 4-4. Steering Variability - 1 Update/sec.

<u>Control</u> <u>Distance (m)</u>	<u>Km/hr</u>			
	<u>0.6</u>	<u>1.8</u>	<u>4.0</u>	<u>9.4</u>
1.0	1.8 cm		-	-
1.5	1.9		-	-
2.0	5.3	8.0		-
3.0	4.9	6.4		-

Table 4-5. Steering Variability - 0.5 Updates/sec.

<u>Control</u> <u>Distance (m)</u>	<u>Km/hr</u>			
	<u>0.6</u>	<u>1.8</u>	<u>4.0</u>	<u>9.4</u>
1.0		-	-	-
1.5	5.1 cm		-	-
2.0	6.6		-	-
3.0	6.2		-	-

As previously noted, a test run was considered successful only if the VGRT could travel the full distance. A blank space in tables 4-1 to 4-5 indicate that the VGRT was not able to travel the full length of the line. Failure to follow the line was usually a result of the VGRT going out of control and losing the line as its control signal.

For comparison, five human operators were asked to drive the tractor over the same course. Each operator was told to drive the tractor with the line under the right front tire and to follow it as best as could be done. The human operators drove the tractor at each of the same four speeds and were allowed to select their own control distance. A steering wheel was installed on the VGRT for this purpose. The operators had no practice or minimal practice in steering the tractor and used their normal vision for steering, see Table 4-6 for results.

Table 4-6 provides a comparison between human operators and computer operation of the test tractor. N = at least 70 samples per test run. Lateral position accuracy to ± 0.5 cm. The table results use standard deviation as the means to express variability.

Table 4-6. Steering Variability - Human Operators.

<u>Operator</u>	<u>Km/hr</u>			
	<u>0.6</u>	<u>1.8</u>	<u>4.0</u>	<u>9.4</u>
1	0.7 cm	0.9	1.1	1.5
2	1.0	1.5	2.3	6.1
3	0.5	1.0	0.9	2.0
4	0.6	0.6	0.9	2.3
5	0.9	1.0	1.0	3.8

4.1.1.2 VARIED STEERING GAIN TEST

To test the effect of steering gain on tractor steering performance, the control distance and position update rate were held constant. The tractor was run at each of the four speeds with five different steering gain values. The following steering gains were used: four, two, one, 0.5, and 0.3. For each position update the steering error was determined in degrees then multiplied by the steering gain factor. The results of the test are as follows in Table 4-7:

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Table 4-7 shows the VGRT's change in performance for a change in steering gain. The position update rate was held constant. N = at least 70 samples per test run. Lateral position accuracy to +/- 0.5 cm. The table results use standard deviation as the means to express variability.

Table 4-7. Steering Variability -
Varied Steering Gain.

<u>Gain</u>	<u>Km/hr</u>			
	<u>0.6</u>	<u>1.8</u>	<u>4.0</u>	<u>9.4</u>
4.0	0.7 cm	0.7		
2.0	1.1	1.7	1.5	
1.0	1.5	2.0	3.0	4.0
0.5	8.7	8.7	9.7	9.2
0.3	12	12	15	17

4.1.2 CONTINUOUS LINE STEP TESTS

After exhaustively testing the VGRT system on a continuous straight line to establish basic parameters of performance, a step of 30cm was introduced into the line to "ring" the system. This step input would determine the natural response of the system and indicate the degree of stability in the steering control. The step tests were divided into three series, the first tested the ability of the VGRT to respond to both a right and left step and the second tested the ability of the VGRT to respond to a constant step at different speeds. The third step test,

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tested the ability of human operators to respond to a constant step at different speeds for comparison purposes.

The purpose of the first step test, that of introducing a left or right step into the line, was to determine if the VGRT responded in a similar manner to either step. This would give an indication of the effect of camera placement on VGRT response to steering corrections in either direction. The concern was to determine if an offset camera placement would have an affect on steering response that would differ from the left to the right side.

The second and third tests were to provide a comparison between VGRT steering response and human operator steering response. The results of these tests would indicate if the VGRT could provide a steering response to a change in course similar to that of a human operator.

To describe the results of these tests, four criteria were used. For a given test only one or more of the criteria may be used depending on the applicability of the criteria. Criteria are used sufficient to indicate the point of the comparison test. The four criteria are: rise time (RT) (10% to 90%), percent overshoot (PO), damping factor (DF), and natural frequency (NF).

For the purposes of this research effort and simplicity the VGRT is considered to be a second order control system. Due to the emphasis of this research (non

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math intensive) no mathematical verification is given for the decision to consider this order of control. This decision is based on observation of the results of "ringing" the system. The plotted results of ringing the VGRT system with a low steering gain (0.5) indicate a response that could be adequately described by a second order system (Figure 4-2). It is felt that a higher order system is both unnecessary and would needlessly over complicate the mathematical analysis of the results.

4.1.2.1 RESULTS OF RIGHT AND LEFT STEP

For the left versus right step test the VGRT's speed, update rate, and control distance were held constant. The steering gains used were: 0.5, 1.0, and 2.0. The speed was 0.6 km/hr, eight updates per second, and 1.5 meter control distance were used. The results for the three steering gains are as follows (see Figures 4-2, 4-3, and 4-4):

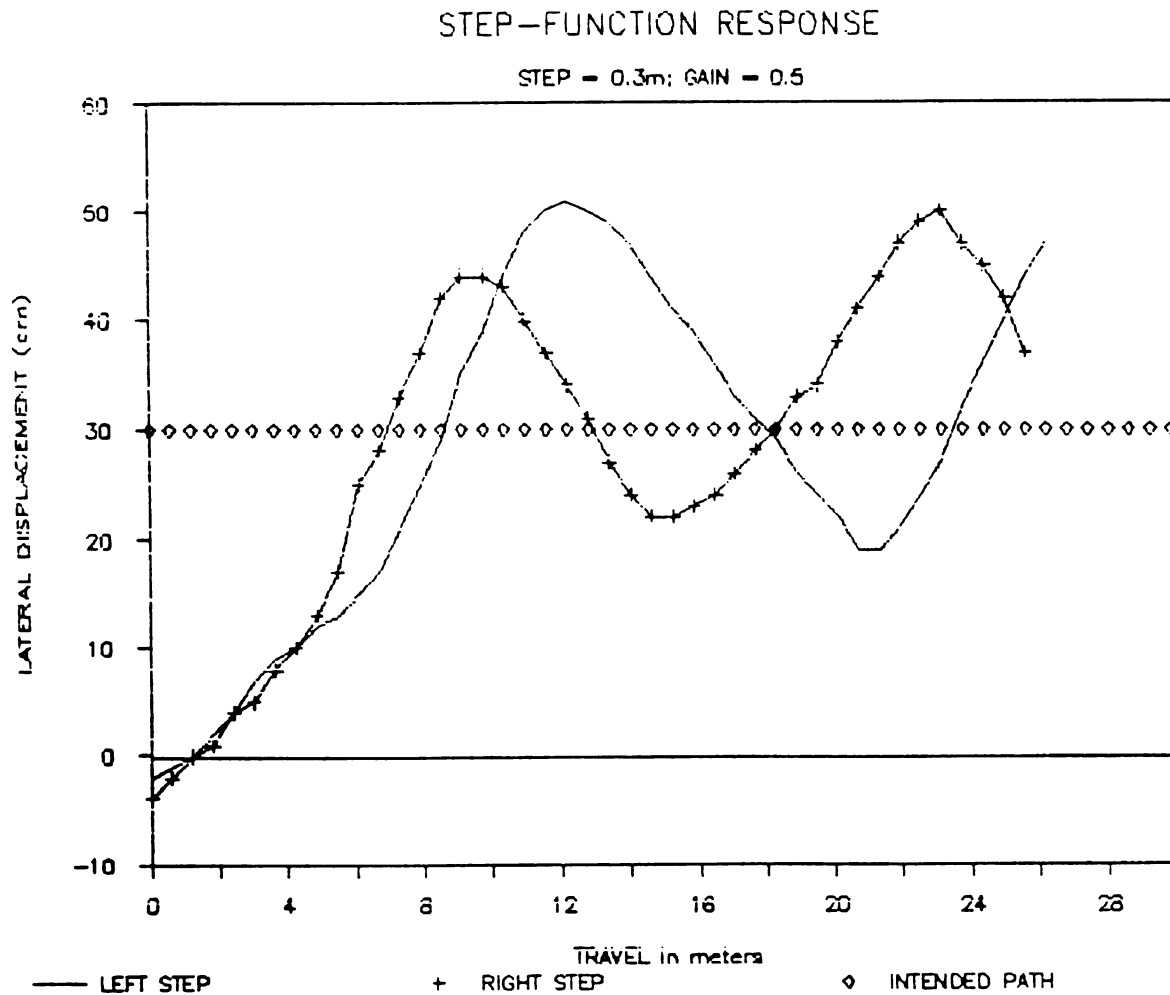


Figure 4-2. Graph of steering response, right and left step. Gain = 0.5

Test run left: DF = 0.2, NF = 0.07HZ, PO = 50%

Test run right: DF = 0.3, NF = 0.09HZ, PO = 40%

N > 40.

**DF = Damping Factor, NF = Natural Frequency,
PO = Percent Overshoot.**

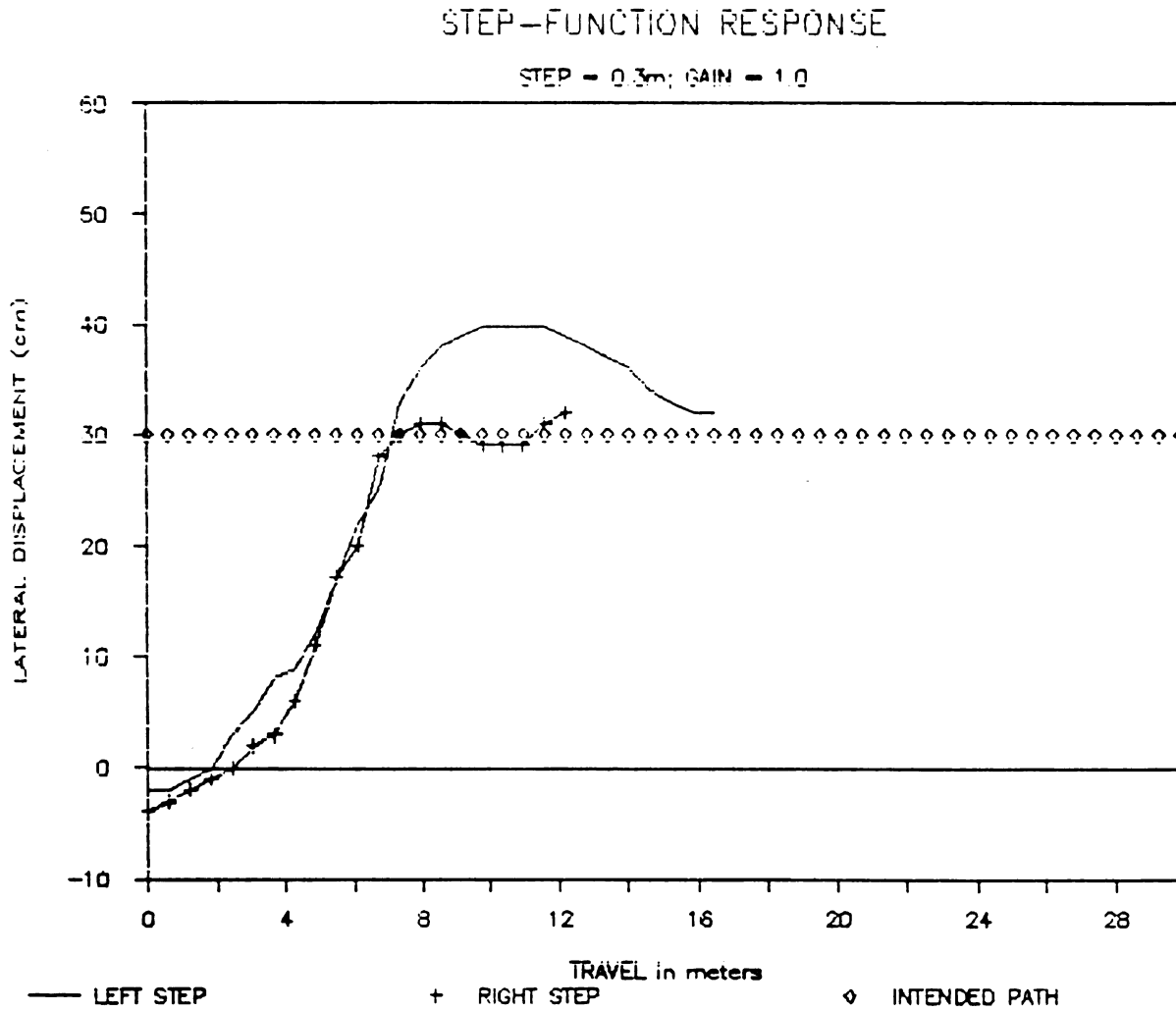


Figure 4-3. Graph of steering response, right and left step. Gain = 1.0

Test run left: DF = 0.3, RT = 24 seconds

Test run right: DF = 0.7, RT = 19 seconds

$N > 20$.

DF = Damping Factor, RT = Rise Time.

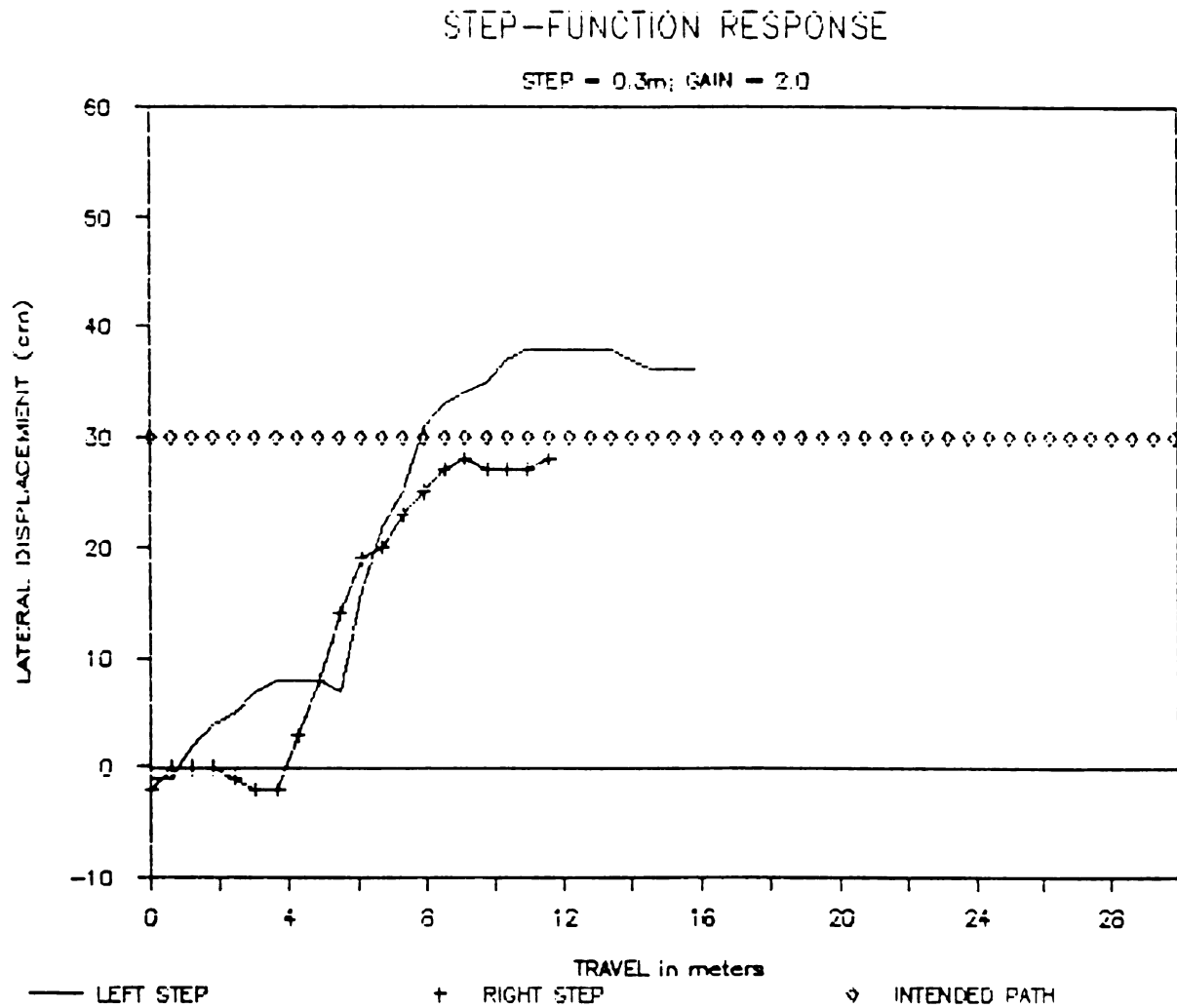


Figure 4-4. Graph of steering response, right and left step. Gain = 2.0
 Test run left: DF = 0.7, RT = 20. seconds
 Test run right: DF = 0.7, RT = 20. seconds
 N > 20.
 DF = Damping Factor, RT Rise Time.

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4.1.2.2 RESULTS OF COMPARISON STEP TESTS

The VGRT was run at three different speeds with position update rate (8 per second), control distance (1.5M), and steering gain (1.0) held constant. For comparison, five human operators were asked to operate the tractor over the same 30cm right step. The results are as follows in Tables 4-8 to 4-10:

Tables 4-8 to 4-10 show the results of the test tractor being rung with a right step wave. The tables provide a comparison between human operators and computer control. N = at least 16 samples per run. Lateral position accuracy to ± 0.5 cm. DF = damping factor, RT = rise time, and PO = percent overshoot.

Table 4-8. Step Comparison Tests.

<u>Operator</u>	<u>SPEED 0.6 Km/hr</u>		
	<u>DF</u>	<u>RT</u>	<u>PO</u>
VGRT	0.7	15.3s	3
H1	0.7	8.5s	3
H2	1+	11.9s	0
H3	1+	13.6s	0
H4	1+	17.0s	0
H5	1+	15.3s	0

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Table 4-9. Step Comparison Tests.

<u>Operator</u>	<u>SPEED 1.8 Km/hr</u>		
	<u>DF</u>	<u>RT</u>	<u>PO</u>
VGRT	0.7	4.8s	3
H1	1+	3.0s	0
H2	1+	3.6s	0
H3	1+	6.0s	0
H4	1+	7.2s	0
H5	1+	6.0s	0

Table 4-10. Step Comparison Tests.

<u>Operator</u>	<u>SPEED 4.0 Km/hr</u>		
	<u>DF</u>	<u>RT</u>	<u>PO</u>
VGRT	0.7	2.3s	3
H1	1+	1.5s	0
H2	0.4	0.8s	22
H3	1+	4.0s	0
H4	1+	2.8s	0
H5	1+	2.0s	0

4.1.3 RUNOUT TESTS

A steering runout test was done on the VGRT to show that it could not have "accidentally" followed the line

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consistently and with the type of accuracy indicated in the previous tests. Along with the runout tests, the free play in the tractor's steering system was also determined. The runout test consisted of starting the VGRT on the line using the vision guidance system to align the tractor to the line. The tractor was allowed to travel down the line until it reached the beginning of a three meter section of the line. At the beginning of the test section the camera was shut off and the tractor allowed to travel blind for the three meters and then the tractor was stopped. After stopping the tractor the lateral offset of the tractor's position from the line was measured.

4.1.3.1 RESULTS OF RUNOUT TESTS

Six test runs were made over the three meter test section of the line. The tractor was traveling at 0.6 km/hr with a 1.0 meter control distance at eight updates per second. The results are in centimeters of lateral deviation from the line to either the left or the right. The results (Table 4-11) are as follows:

Table 4-11 shows test tractor runout test results. Runout indicates that the tractor could not have accidentally followed the three meter line.

Table 4-11. Results of Runout Tests.

<u>Run</u>	<u>Deviation</u>	<u>Side</u>
1	64cm	Left
2	57cm	Right
3	54cm	Right
4	57cm	Left
5	55cm	Right
6	52cm	Right

By measurement the VGRT was found to have 20 to 22 degrees of steering wheel play, i.e. 20 to 22 degrees of rotation of the steering wheel to take the slack out of the steering system. This steering wheel play is with the front wheels locked against rotation. The front steering wheels have three to four degrees of free play when locked against the steering linear actuator. This steering free play is a reflection of the amount of play in the steering gear, ball joints, front axle bearing, etc. Stop to stop travel of the front wheels (50 degrees) represented one turn of the steering wheel. The linear actuator could move the front wheels lock-to-lock in two seconds. While the human operators had a steering system that had more free play, they also had the advantage of both a variable rate

of steering response and variable control distance.

4.1.4 VGRT TILT TESTS AND RESULTS

To determine what effect camera platform tilt has on steering heading, for a constant VGRT heading and offset, a jack was used to tilt the VGRT. The VGRT was aligned with a continuous line and then not moved while a jack was used to alternately lift one side of the VGRT or the other side. As the VGRT was raised the steering angle (heading in degrees) was noted. The steering gain was set to 1.0 and the control distance was 1.5M. Table 4-12 indicates the results of this test.

Table 4-12 shows the change in heading for a specified tilt of the VGRT about its major axis.

Table 4-12. VGRT Tilt Test.

<u>Side Raised</u>	<u>Degrees of Tilt</u>	<u>Heading</u>
Left	0	128
	2	128
	5	128
	8	128
	12	128
	0	128
Right	0	128
	2	128
	5	128
	8	129
	12	129
	0	128

4.1.5 PIXEL WIDTH OFFSET TESTS AND RESULTS

A determination of the effective pixel width was made at the 1.5M control distance. The VGRT was set to eight position updates per second, 0.6 km/hr, 1.5M control distance, and steering gain was 1.0. The VGRT was positioned to follow a straight, continuous line and the

lateral position with respect to the line was measured for different center positions.

The width of the camera's field of view in pixels is 256 pixels. The center of the field of view at the control point is usually set to 128. This center value can be varied to alter the VGRT's offset with respect to the row or line. Four different center values were used and their respective offsets measured, see Table 4-13.

Table 4-13 gives an effective pixel width at the real ground plane and VGRT offset for different center values.

Table 4-13. Results of Pixel Width Tests.

<u>Center value</u>	<u>Offset (cm)</u>
128	5 - 8
130	10 - 13
132	13 - 15
134	18 - 20

This would indicate that a pixel has an effective width of two to three centimeters at a control distance of 1.5M.

4.2 INTERMITTENT LINE TESTS

The next phase of testing was a start in the VGRT testing that would begin to approximate a row crop situation. An intermittent line was used to investigate

the change in VGRT performance to a less than ideal line following situation. The same contrast mode edge-following program was used but now the line had gaps placed in it. The gaps in the line simulated the gaps between plants in a crop row.

4.2.1 INTERMITTENT LINE TEST RESULTS

For the intermittent line test, tractor speed, update rate, steering gain, and control distance were held constant. The 46 m test line was made up of five-by-eight cm rectangles of paper (Post-It notes). The papers were placed with their major axis in line with the line and the gap was measured from the end of one paper to the beginning of the next paper. The tractor speed was 0.6 km/hr, the control distance was 1.5 m, the position update rate was eight per second, and the steering gain was set at one. The results (Table 4-14) are as follows:

Table 4-14 shows the performance of the VGRT when following a line with gaps introduced into it. N = at least 70 samples per test run. Lateral position accuracy to +/- 0.5 cm. The table results use standard deviation as the means to express variability.

Table 4-14. Steering Variability - Intermittent line.

<u>Speed (km/hr)</u>	<u>Gaps (in cm)</u>				
	<u>8</u>	<u>15</u>	<u>23</u>	<u>30</u>	<u>38</u>
0.6	1.4 (cm)	2.7	4.0	3.8	4.0

4.2.2 FUZZY ROW TESTS AND RESULTS

A row resembling an actual crop row was painted on concrete to further test the VGRT in a situation more closely resembling that of an actual crop row. The row was green in color and made of "leaves" that were approximately 13 to 15 cm long by five to eight cm wide. The row was 23 m long (Figure 4-5). The two types of row followers, contrast mode, and color discrimination mode, were used to guide the VGRT on the row. "Weed" blobs were added to the row to test the response of the two types of row followers. The weed blobs were the same green color and were approximately 71 cm long by 23 cm wide.

The tests involved different placement of the weed blobs with respect to the row. For each placement of weed blobs a test run of the VGRT was made using contrast mode following and then color discrimination mode following. The first two test runs used each type of row follower with no weed blobs for a clean-row comparison control. For both types of row followers the steering gain was set to 2.0 to provide a greater indication of the different responses of the row followers. For all test runs the VGRT speed was 0.6 km/hr, eight updates per second, and a 1.5m control distance.

The test results were compared using the standard deviation (SD) of the VGRT's lateral deviation as

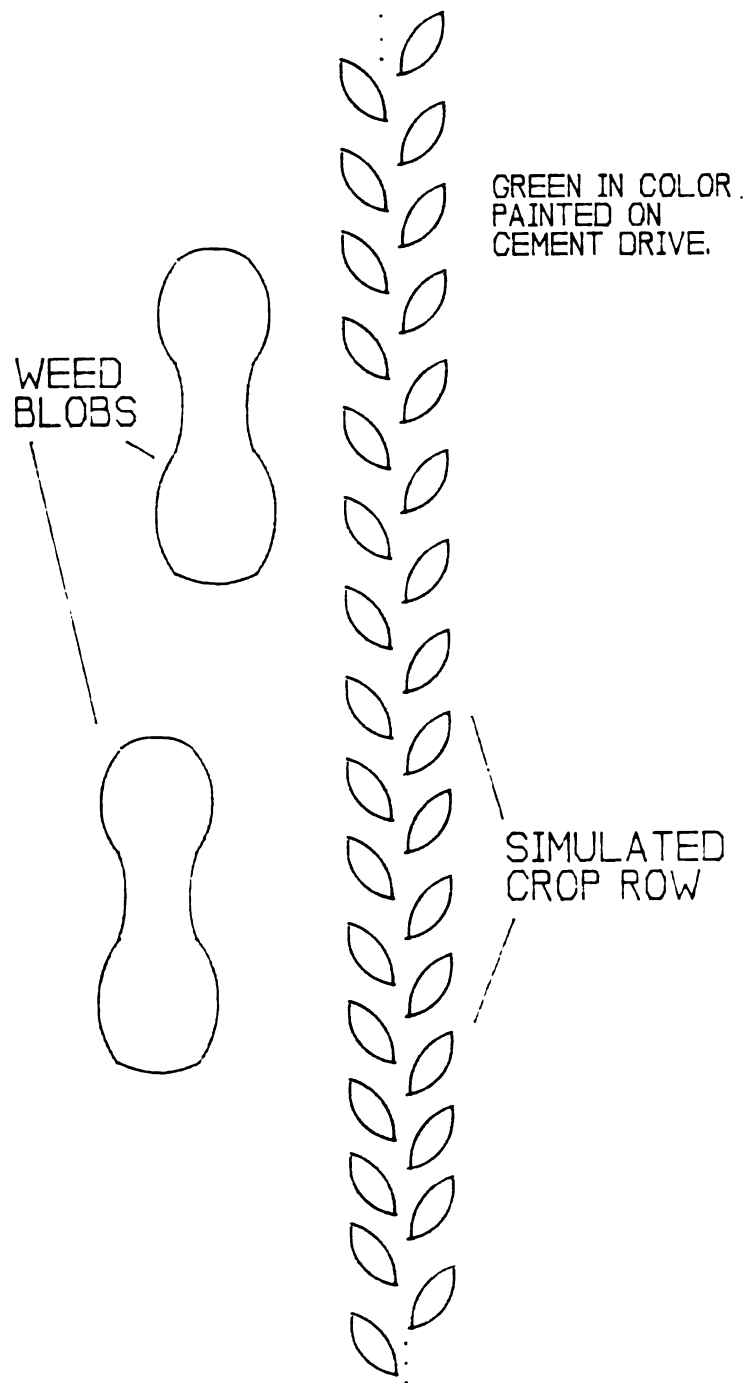


Figure 4-5. Fuzzy row test, simulated crop row and weed blob.

it traveled the row and the maximum deviation (MD) from the row center. The results (Table 4-15) are as follows (all results are in centimeters):

Table 4-15 shows the test results of the VGRT following a simulated field crop row. Results are expressed in variability about the line (standard deviation) SD and maximum deviation from the line MD. N = at least 30 samples per test run. Lateral position accuracy to +/- 0.5 cm.

Table 4-15. Steering Variability - Fuzzy Row.

<u>Test</u>	<u>Edge</u>		<u>Color</u>	
	<u>SD</u>	<u>MD</u>	<u>SD</u>	<u>MD</u>
Clean row	0.6	2	1.1	2
One blob on each side	2.8	8	0.6	2
Two blobs same side - together	4.7	14	2.0	6
Two blobs same side - apart	3.9	9	1.0	2

4.2.3 CROP-ROW-FOLLOWING TEST AND RESULTS - CORN

On June 20th, 1989 the VGRT was taken to a corn field for actual row-following tests. The results of the test would either be go or no-go, that is, the VGRT would either follow a corn row or it wouldn't. The tests took place on a partly sunny day from 1200h to 1430h EDT. The corn rows were oriented east - west on 76 cm centers and the corn plants ranged from 20 to 36 cm tall. The color discrimination mode row follower was used with a control

distance of 1.5m for the VGRT speeds of 0.6 km/hr and 1.8 km/hr, the control distance was 3.0m for the VGRT speed of 4.0 km/hr. An ND4 neutral density filter, an ultraviolet filter, and a linear polarizing filter were placed on the camera.

The VGRT was driven out into the field and manually placed such that it straddled one row and had the right rear tire near the edge of the next row. The VGRT was able to follow a corn row at the three test speeds of 0.6 km/hr, 1.8 km/hr, and 4.0 km/hr. A visual estimate of the lateral deviation of the VGRT about the row at any of the speeds was in a range from zero to five centimeters. The VGRT seemed to exhibit ample steering stability when following rows, very similar to what could be expected from a human operator.

The major problem with the VGRT in an actual row setting involved the response of the video camera to sunlight. Under direct sunlight, the camera's ability to resolve the difference between green corn plants and brown dirt was greatly reduced. The severity of this problem was reduced by placing light filters on the camera. The second problem was the poor response time of the camera in responding to a change of light level. A typical change was from direct sunlight to cloud shielded sunlight. The slow response time of the camera would sometimes cause the VGRT to travel blind for a distance of one to three meters

until the camera had adjusted to the new light level.

4.3 HEADLAND TURNS AND RESULTS OF TESTS

Headland turn tests were performed on both grass (dry and wet) and concrete to see if wheel slip would differ enough to affect the accuracy of a turn. The results of the headland turns are somewhat subjective as the VGRT will repeat a turn no better than what was originally taught. Therefore an effort was made to teach the VGRT accurate turns that followed approximately the same arcs. A three point turn was used as it should have introduced the greatest error. The distance between rows was three meters.

A turn was evaluated by the VGRT's ability to successfully find and follow the target row after making a turn. After making a turn, a visual inspection was made of the VGRTs front right wheel position with respect to the line. The VGRT would then be set in motion to see if it could find and follow the line. Five headland turns were made for each test situation, each set of five turns was based on one learned turn.

In each of the three different test situations, the VGRT could repeat a turn and successfully find and follow the row all five times. Since the main criterion for success of this test was go or no-go, only approximate position offset and heading errors are given. This is to indicate the variability of the VGRTs position at the end

of a turn with respect to the target row. At the end of a turn the position offset was consistently less than 15 cm and the heading error was never more than five degrees.

4.4 POSITION UPDATE RATE TESTS AND RESULTS

As previously mentioned, all software for the VGRT is written in Assembler language to ensure the fastest possible execution times. This is critical since there are some inherent limitations in the vision system. Due to the type of video digitizer board used, the main computer bus speed is limited to 6.0MHZ, not particularly fast by today's standards. The other main inherent limitation in speed is the forced delay of 17 milliseconds to let the new image settle in the video digitizer RAM storage. Each time a new image is acquired this delay is required to insure that the image has been fully loaded into RAM, guaranteeing that the correct video data is present.

As methods were tried to increase the position update rate, it quickly became apparent that bus speed and time delay, primarily the latter, were the most significant in controlling the position update rate. For example, adding more scan lines (than the original two) in the color discrimination mode follower would not decrease the update speed as expected. An increase of one scan line would only decrease the update rate from eight per second to seven, two additional scan lines would only decrease it to six per

second.

For comparison, the 17 millisecond delay (8000H) was decreased to see what effect this had on position update rate. The resultant position update rates as run on the VGRT were as follows in Table 4-16:

Table 4-16 shows the resultant rate of position updates for different image acquisition delay values.

Table 4-16. Position Update Rates vs. Delay Value.

<u>Delay value</u>	<u>Update rate</u>
8000H	10 per second
6000H	12 per second
4000H	18 per second
2000H	31 per second
0010H	198 per second

Writing more efficient Assembler code could increase the position update rate to some extent, but it would be difficult to achieve the rates that shortening the delay can achieve. The position update rate can not be increased by decreasing the acquisition delay without a sacrifice in image integrity.

4.5 PERFORMANCE OF VGRT AS A SYSTEM

One very important aspect of the testing of the VGRT was its performance. Performance could be defined as the

ability of the VGRT to work consistently and robustly. Robust in the sense that the VGRT would be free of minor software and hardware glitches that would necessitate frequently having to rewire hardware and rewrite the software. This performance aspect of the VGRT testing was given careful consideration throughout the development of the system.

It was important to decide, through the development of the electronic systems of the VGRT, when to purchase an electronic sub-system and when to build a custom electronic sub-system. Tradeoffs involved in this decision were costs vs. convenience of existing "off the shelf" electronic systems. Either a readily available component could be easily modified and put into the VGRT system or it would require a degree of modification that might have compromised its reliability. If much modification would be involved, it may have been easier to design and build a custom electronic sub-system. This custom sub-system can be built with specific functions in mind and with a sufficient degree of robustness for the VGRT system.

Of the VGRT electronic's, the slave computer, interfaces to control the tractor, communications link between the master and slave computer, and both computer power supplies were all custom-built electronic sub-systems. To reduce costs and yet provide the greatest degree of robustness, custom sub-systems were deemed to be the best alternative in this engineering prototype. As

regards the master computer, a stock, commercially available, Intel 80286 MS DOS based system seemed to be the best choice. In this instance, based on cost, ruggedness, and flexibility, the commercially available unit had the advantages.

During construction of the VGRT electronics great attention was given to the stability and noise rejection capabilities of the master and slave computer power supplies. The electric tractor created a severely noisy environment that could easily cause computer malfunctions through an improperly designed power supply. Noise radiated through a poorly designed power supply is probably one of the most common ways for hardware malfunctions to occur. These types of malfunctions can be particularly hard to deal with as they may occur only at odd intervals in conjunction with some rare event that is hard to reproduce.

In consideration of the performance aspect of the VGRT, a self-contained power supply should provide the greatest degree of robustness. A self-contained DC to DC converter power supply could work directly from the tractor batteries reducing the number of components the system would require just to get power. Another method would be to use a DC to 110v AC inverter to provide power to the stock master computer power supply. A 110v inverter would have added components to the master computer power supply

which would have increased the chance for a failure. Since the entire VGRT system works from batteries (which by their nature need to be recharged and do not supply an endless source of energy), the inefficiency of the 110v inverter would have reduced the length of operating time reducing the performance of the VGRT system. A custom power supply could provide the greatest noise immunity with the fewest parts which would improve the robustness of the entire VGRT.

Heat can be as significant as electrical noise in causing hardware malfunctions. The VGRT was subject to a wide range of operating temperatures, from zero to 35 degrees Centigrade. This could create problems for the on-board computer systems. During the design of the power supplies for both computer systems, the current (I) loads were measured to determine the size of the heatsinks for the voltage regulators. Two fans were also installed in the box housing the master computer. One fan was set to blow cool air into the master computer case, the other fan to exhaust hot air from the case. Both of these fans were ducted to the outside of the box housing the master computer to ensure the best air circulation.

4.5.1 RESULTS OF PERFORMANCE TESTING

Throughout the entire test of the VGRT (more than eleven months) there was not one single component failure in any of the electronic systems added to the tractor.

Extremes of test conditions included temperatures from zero to 35 degrees Centigrade (master computer internal case temperature as high as 60 degrees Centigrade) and ambient conditions from bright clear sunlight to heavy overcast and even rain. And, at no time during any of this test period could a single malfunction be attributed to a power supply dysfunction. With this type of robustness, any problems in VGRT operation could usually be attributed to the tractor or the video camera. Incorrect software operation or an incorrect design in a hardware component of the system were seldom the cause of problems.

The two major problem areas in the VGRT were the tractor itself and the video camera. Due to its age and lack of previous maintenance, the tractor required a small amount of constant upkeep. The main problem with the tractor was relay contacts. The relay contacts were subject to arcing and pitting which either caused them to stick together or not make contact at all. Filing the contacts usually temporarily remedied the situation. The main problem with the camera was its lack of dynamic range under varying light conditions. As regards the VGRT system, the poor response of the camera was the single greatest contributor to poor performance.

4.5.2 INEXPERIENCED OPERATOR PERFORMANCE TESTS

One difficulty in evaluating total VGRT system performance is that it is a somewhat subjective rating.

With the high degree of familiarity, such as what the person doing the development work of the VGRT would have, it would be easy to overlook lapses in good performance, make a small adjustment, and go on. If other operators are brought in to run the VGRT that are not familiar with it, a lapse in performance will present a major stumbling block to their effective use of the system.

Five people were asked to operate the VGRT in a simulated field situation. These five people all had some previous experience operating farm tractors but they had no experience with the VGRT. They were given a farm scenario in which to test drive the VGRT (see Appendix 1). They were evaluated on how quickly they could learn to operate the VGRT and complete the test farm situation without outside help. All five operators read the instructions and completed a successful operation of the test. The times required to read the instructions and successfully complete the test are listed in Table 4-17.

Table 4-17. Shows the times necessary for the test operators to familiarize themselves with VGRT operation and successfully complete the test scenario.

Table 4-17. User Friendly Test Times.

<u>Test Operator</u>	<u>Time (minutes)</u>
H1	48
H2	64
H3	47
H4	64
H5	52
Average	55

The test operators indicated that they were pleased with the ease with which they could learn to operate the VGRT.

4.6 CAMERA TESTS

Throughout the testing of the VGRT, one of the greatest contributors to poor system performance was the video camera. A poor response at low light levels could be improved by additional lighting, but resolving the high light level problem was more difficult. The high light level problem was most noticeable in actual row crop field conditions. The problem was manifest in the camera having a problem of being unable to resolve the difference in color of green plants and brown soil. To the human eye, the plants had a nice green color and the soil was very

brown. To the camera, the plants were yellow-green and the soil was yellow-brown.

This problem occurred in both direct sunlight and moderate cloud cover. One factor contributing to this problem was that the camera placement permitted incident solar radiation to strike the camera lens (Figure 4-6). Another factor contributing to the problem was that, in the visual spectrum, green plant leaves and brown soil are actually very close together. Since the camera placement was fixed by necessity, another solution had to be found to solve this high light level problem.

Three different types of optical filters were placed on the camera to try to reduce the excessive light problem. Reducing excessive ambient light would hopefully increase the camera's ability to resolve the colors brown and green. Another approach was to alter the hue (H), saturation (S), and intensity (I) constants in the video digitizer board such that a greater apparent difference in color would occur between brown and green. Both methods, separately and in combination were tried to improve camera performance.

A test situation was developed to quantify the effect these two methods had on improving camera performance. A 22 cm by 28 cm piece of brown paper was used as the test "soil" color. On this piece of brown paper 1.3 cm wide stripes of green paper were glued to approximate the crop leaf color. This produced a test image that was 50% brown

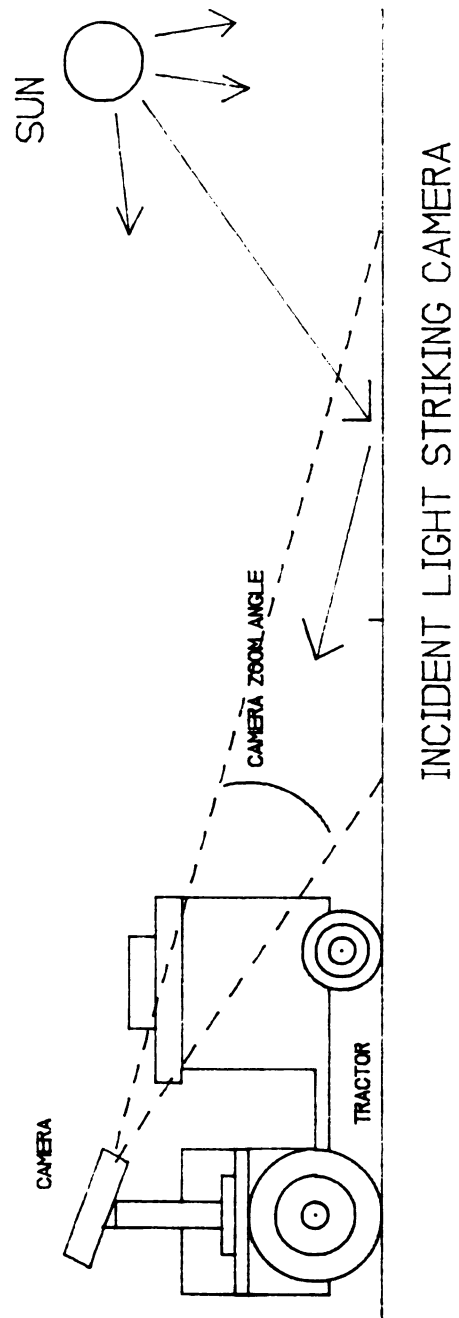


Figure 4-6. View of camera placement on tractor and incident high level light problem.

and 50% green (Figure 4-7). Stripes were used to enhance the noise problem associated with the brown-green interfaces. This test paper was placed so that the camera's view of it was similar to a field situation with up-sun viewing (Figure 4-8).

To evaluate the different test conditions, five histograms were taken of each view. For a given histogram, the red, green, and blue components were analyzed separately. The three separate scores were then added together to provide a composite score for each histogram. The histogram test area consisted of 9900 pixels (220 pixels wide by 45 pixels high) that cut across five of the stripes (the stripes were oriented vertically) in the camera's field of view. Ideally each color band would have a bimodal distribution in its histogram. The better the camera could "see" the two color stripes as separate colors, the greater the distinction between the two peaks in the histogram. As the camera's ability to distinguish the two colors as separate colors decreased, the separation between the two peaks in the histogram would decrease (Figure 4-9).

The scoring method involved quantifying the distinction of the two peaks in the histogram. The separation of the two peaks is viewed as a function of the depth of the valley between the two peaks. This is calculated as what percent the valley is of the low peak

GREEN	BROWN
GREEN	BROWN
GREEN	BROWN
GREEN	BROWN
GREEN	BROWN
GREEN	BROWN
GREEN	BROWN
GREEN	BROWN
GREEN	BROWN
GREEN	BROWN
GREEN	BROWN
GREEN	BROWN
GREEN	BROWN
GREEN	BROWN
GREEN	BROWN

Figure 4-7. Two color camera test paper. Test paper used to simulate brown and green field colors for camera tests.

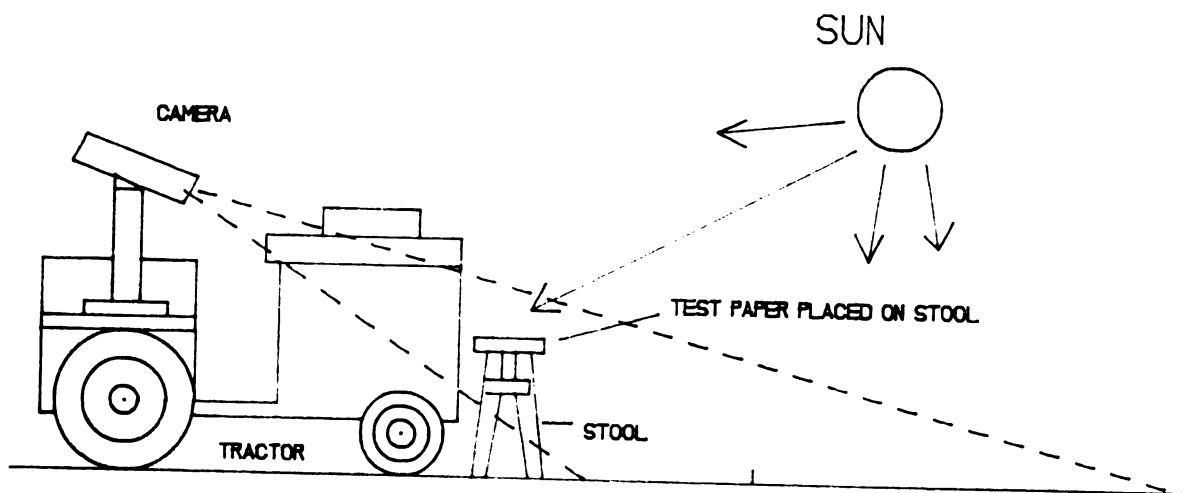


Figure 4-8. Placement of camera test paper to simulate up-sun field lighting conditions.

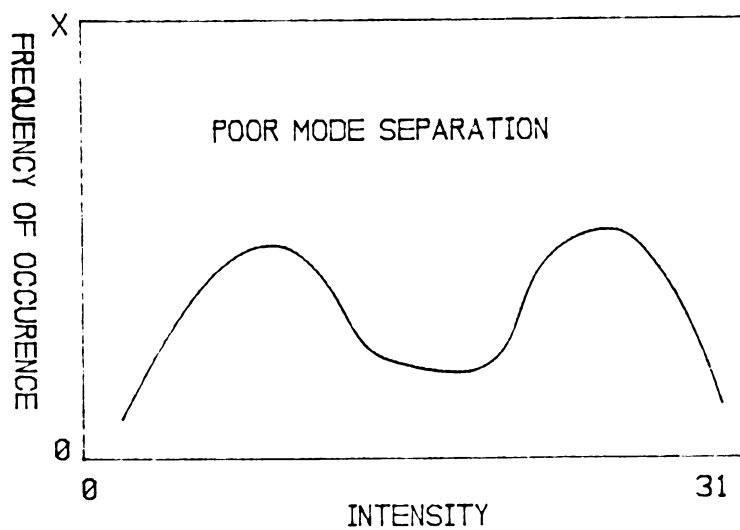
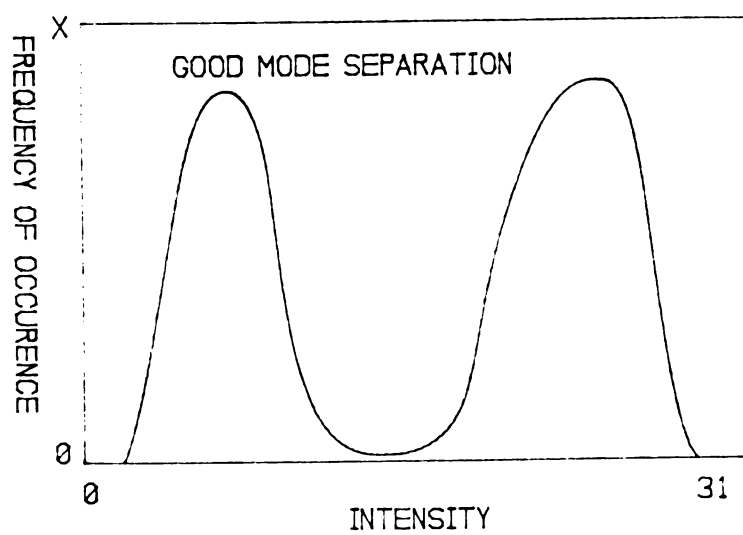


Figure 4-9. Bimodal distribution used in histograms to rate camera resolution improvement methods.

and what percent the valley is of the high peak. These two percentages, six in total for a given test histogram (red, green, and blue) were added together for a total score for a given histogram. A lower score indicated that the camera was better able to resolve brown and green as two separate colors.

4.6.1.1 LENS VARIATIONS

The first attempt to improve camera performance in high light conditions involved obtaining advice from local knowledgeable camera and video equipment retailers and repairers. Their advice was almost unanimous in that lens filters would help reduce the effects of too high a light level. Three different filter types, singly or in combination, were recommended; a neutral density filter, an ultraviolet filter, and a linear polarizing filter. Filters of these types were purchased and tested for their ability to improve the high light level color discrimination of the camera.

4.6.1.2 HUE, SATURATION, AND INTENSITY VARIATIONS

Initially, the video digitizer board had the recommended (default) values of hue (H), saturation (S), and intensity (I), for reproducing acceptable color renditions of digitized video scenes. The second attempt to improve camera response involved altering these values

to try to increase the discrimination between the colors green and brown.

The original values were H62, S100, and I57. After viewing the test image and altering the values a new set of values was determined. These values of H94, S100, and I46 appeared to give a slightly better rendition of the green and brown colors on the test paper.

4.6.2 CAMERA TEST RESULTS

Using the aforementioned test set up (Figure 4-8), the two camera improvements discussed above were tested. The camera response with no filters and with the original HSI values was used as reference. The following combination of methods was evaluated: original HSI values with no filters, each filter added individually (polarizer filter turned horizontally and vertically), and all filters together; the same sequence was applied to the new HSI values. All combinations were tried on days with direct sunlight and days with complete cloud cover. The results are summarized as follows in Table 4-18:

Table 4-18 provides a comparison of the test results for different high light level test conditions of the camera. A lower number indicates that the camera was better able to discriminate between the two test colors. HSI original values (O), new values (N), and sunny (S) or cloudy (C)]. These values are based on five replications.

Table 4-18. Camera High Light Level Tests.

<u>Filter</u>	<u>HSI and light conditions</u>					
	<u>O-S</u>		<u>N-S</u>		<u>O-C</u>	
No filters	585	-	555		295	- 255
U.V. filter	585	-	555		315	- 235
ND4 filter	600	-	600		295	- 280
Pol. vert.	575	-	525		445	- 185
Pol. hor.	600	-	600		380	- 405
All filters	585	-	535		350	- 395

For the "all filters" test the polarizer was set to vertical. (Vertical or horizontal refers to the position of the index mark on the rotatable polarizer ring).

After viewing the ambient conditions, this table can be consulted to determine the best possible combination of camera filters and HSI values to get the best camera color discrimination.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.0 INTRODUCTION

This chapter is a summary of the use of vision guidance as a system used to guide a robot tractor. Could present technology guide the tractor from a row or line, and did the performance compare favorably to a human operator's performance? The robustness of this system was also an important consideration in the system design. Did the Vision Guided Robotic Tractor (VGRT) system perform reliably and consistently through test after test in a variety of ambient situations? These tests had to be sufficient in scope and provide a base of knowledge to indicate the strengths and weaknesses of the VGRT system. Does the resultant performance of the VGRT warrant testing this vision guidance system on a larger tractor or combine in real field situations?

5.1 SUMMARY

As an engineering prototype, the vision guided robotic tractor (VGRT) was developed and tested on an electric lawn tractor. The VGRT used a color camera to sense row or line imagery which was digitized and analyzed by a master computer. The master computer determined a corrective

steering heading which was read by a slave computer. The slave computer provided direct control of the electric tractor, directed the tractor to turn its steering wheels, and also could start or stop the vehicle.

Tests were performed on the VGRT to evaluate its performance. These tests evaluated the basic performance of the VGRT for comparison with the steering performance of human operators. One very important aspect of VGRT testing was the assessment of overall robustness of the VGRT system.

The goal of this research effort was to evaluate current technology and its ability to be used to create the VGRT. This goal was to be realized by building and testing as opposed to mathematical analysis and modeling. Limitations were that the hardware would have to be inexpensive, less than \$5,000, and that the technology should be available in the present retail market.

5.2 CONCLUSIONS

Four objectives were developed as guidelines in realizing the goal of this research effort. The extent to which the objectives were achieved is a measure of the success of the entire project. The results of the project in terms of those objectives are as follows:

- 1) The first objective was to procure a color vision system and install it in conjunction with a controlling computer system on a small tractor. The completion of the

tests in Chapter IV indicate that this vision based guidance system could provide usable steering control of the tractor. The installed system was completely self contained on the tractor with the exception of the video CRT. This system was self contained to the extent that it was also the means of developing the software that was used to operate the system. The length of time that the VGRT system was used and the number of tests successfully performed would indicate a successful completion of the first objective.

2) The second objective was to develop the VGRT to actually follow well defined lines or rows. The ability of the VGRT to do this was evaluated by two methods. One method was to quantify the variability in the lateral deviations of the VGRT when it followed a controlled line or row. The second method dealt with comparing the results of VGRT steering with the results of human operator steering on the same tractor (tractor temporarily converted to manual steering) on the same course. The results of the tests in Chapter IV indicate that the VGRT could successfully follow a controlled line at speeds up to nine km/hr or an actual crop row at speeds up to four km/hr. In comparison to human performance the VGRT's performance fell within the range of human operator performance.

3) The third objective was to develop the VGRT such that it could travel from the end of one line or row,

make a headland turn, and locate and follow a parallel line or row. The VGRT was provided with a learn mode in which the operator would "teach" the VGRT how to make the headland turn. The VGRT would remember the pattern of the headland turn and reproduce the pattern when requested to do so at the end of a line or row. Headland turns brought the VGRT within 15 cm of the target line in all attempts on several surfaces. To accommodate closely spaced rows, the VGRT turn capabilities included up to three arcs of travel. The results of headland turn tests in Chapter IV indicate successful completion of this objective.

4) The final objective was to produce a VGRT that was "user-friendly". People familiar with farm equipment but not necessarily experts in this technology should be able to operate the VGRT with appropriate instruction. A test farm situation was created in which each of five people not involved with the development of the VGRT mastered its operation in less than one hour. The results of this test in Chapter IV indicate successful completion of this objective.

Overall, the results of the tests in Chapter IV indicate a successful development of a prototype VGRT. The success of this project is strong evidence that the technology is ready for adoption to agriculture.

5.3 RECOMMENDATIONS

I recommend that this research effort be continued, to include testing on a full size tractor or combine in actual field situations. This research effort has discovered basic methods of providing a steering control signal from visual images. Future work could improve on this by developing a steering system that would have a variable rate of turning the steering wheels.

To reduce the complexity of the system one computer could be used. This single computer could be used in an interrupt mode to monitor the condition of the tractor and to provide steering correction information directly to the steering control system. If two computers are used in a new VGRT system, a method of communications verification should be used for communications exchanges between the two computers. A faster computer would be useful to increase position update rates. An effective increase in processor speed could also be achieved with the existing PC-AT unit by going to a non-NTSC video system. The faster computer system would allow for more robust following schemes that could extract a control signal from less ideal imagery. One improvement that should be made with an improved system would be to float the color references in the color discrimination row follower. As the plant color undergoes a slight color change in different parts of the field, the VGRT could adapt to this change and not become confused.

Future work could also include testing other camera

types for improved visual response to field light conditions. Other camera types may include cameras that are sensitive in the near or infrared portion of the light spectrum. Another improvement in color vision would be to replace the RGB digitizing video system with a system that utilized the HSI components of the video signal.

With larger sized tractors would come an increased aspect of safety consciousness on the part of the VGRT. Improved safety could be in the form of obstacle avoidance and fail-safe modes of tractor drive and engine controls. Further improvements in tractor performance for the VGRT could come from methods to traverse gaps in the crop row, such as a dual mode of guidance, as well as discrimination between weeds and crop. Along with improved algorithms in determining the crop row could come the ability to vary the forward speed of the VGRT to the speed at which it could tolerate the complexity of the crop row scene.

APPENDICES

APPENDIX 1

OPERATION OF THE VISION GUIDED TRACTOR

CAUTION - Read through all instructions at least once before attempting to operate tractor! Read both pages!

WHENEVER TURNING KEY SWITCH OR GEARSHIFT LEVER ALWAYS STAND TO SIDE OF TRACTOR IN CASE OF ACCIDENTAL MOVEMENT OF TRACTOR
* TRACTOR CAN ALWAYS BE STOPPED BY TURNING KEY SWITCH OFF *

First walk around the tractor and familiarize yourself with the location of the following controls or items:

- 1) Start key - upper right side of dash
- 2) Gearshift lever - in front of seat on floor
- 3) On/off switch for small computer - toggle switch on grey box on tractor hood
- 4) On/off switch for big computer - toggle switch located above left side of fan in front door of green box (door towards center of tractor)
- 5) Lens cover for camera
- 6) Big computer keyboard and floppy drive - inside back door of green box - to rear of tractor
- 7) Locate small blue box with ribbon cable - inside front of green box and place face up on green box
- 8) Computer reset for big computer, just to left of floppy drive

To start the tractor:

- 1) Remove lens cap from camera hood
- 2) Turn key switch off
- 3) Put gearshift in neutral
- 4) Turn on small computer (grey box)
- 5) Turn on big computer (green box)
- 6) Push big computer reset button
- 7) Wait 30sec and a '1234' should appear on display in blue box momentarily followed by a '5678' followed by an '8888' (other numbers will flicker past, ignore them)
- 8) IF ALL DISPLAY NUMBERS WERE CORRECT STAND TO SIDE OF TRACTOR and put tractor in first gear and turn on key switch, tractor should remain stationary

To operate the tractor:

The space bar will stop the tractor - '8888' on display
'Y' will start tractor in drive around mode - '5555'-'3333'
'B' will exit drive around mode - should see '8888'
When in learn mode, or drive around mode first push an up or down arrow to start tractor in proper direction then use left or right arrows to steer tractor, the tractor will not steer until it is moving
'G' will start the tractor under auto guidance
'Q' will start tractor in learn mode, left turn '4440' '4441'
'P' will start tractor in learn mode, right turn '4640' '4641'
'<' to initiate auto left turn - (repeat the saved turn)
'>' to initiate auto right turn - (repeat the saved turn)

* Always look for an '8888' between modes of operation *

TEST DRIVING THE TRACTOR

Due to the size of the tractor and nature of the computer installation, you will 'drive' the tractor from the rear of the tractor using the big computer's keyboard.

The object of the test is to drive the tractor from the lab outside to the test 'field' area. You should complete at least 5 rounds under auto guidance and teach the tractor both a left hand and right hand headland turn. These turns should allow the tractor to go down one row and return on the other row.

First, take the tractor outside and practice 'driving' it around a little bit to get the feel of the steering. The steering is somewhat sluggish so be careful. Push the left or right arrows once. Then let the wheels turn, then push the arrow again if necessary until desired turn is completed.

To enter drive around mode push 'Y' and a '5555' (then '3333') should appear on the display. Use the up arrow to go forward, the down arrow to back up. Use the left or right arrows to steer the tractor. Hit the space bar to stop tractor to change direction. Enter a 'B' to stop driving around.

The display should always show '8888' before starting a new mode of operation.

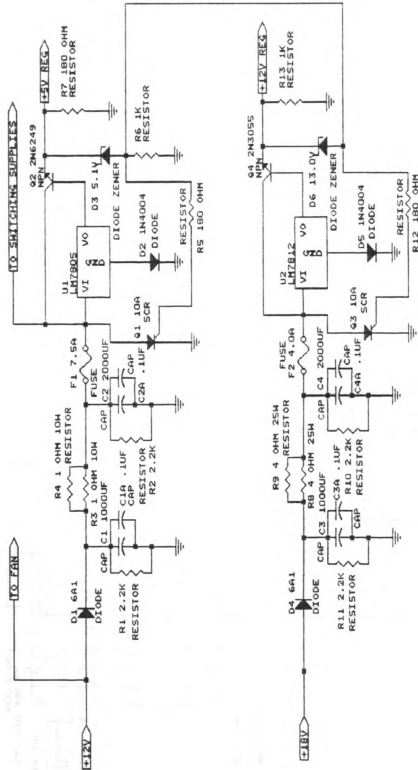
To enter auto-guidance mode, position the tractor so the tractor's front right tire is just to the left of the row (2-3 inches is fine), you should be able to see the row close to the center of the camera viewer. Enter a 'G' to start tractor moving. Push the space bar to stop. When the tractor is near the end of the row (3 to 4 feet), hit the space bar to stop and either teach it a turn or, if it already knows the turn, let it do the turn. When it is in position on the next row, just enter a 'G' to start up again.

You may position the tractor to do turns to the right. Do some rounds, then position it so it will need to do turns to the left.

To teach the tractor headland turns when it is stopped at the end of a row, enter a 'Q' or 'P' and use the arrow keys as before in drive around mode to operate the tractor. Stop the tractor when it is next to the row (row is just to right of front right tire). If you wish to redo a turn, stop the tractor and just put it back into the learn mode, 'Q' or 'P'. The old turn will be erased and the new turn entered (you will of course need to redo the turn).

To have the tractor automatically do the turn, stop the tractor at the end of the row and just enter a '<' or '>', (that's using the less or greater than arrows, use the one that points in the same direction as the corresponding turn).

APPENDIX 2



BERNARD FEHR

AT POWER SUPPLY

Size: Document Number 3

A

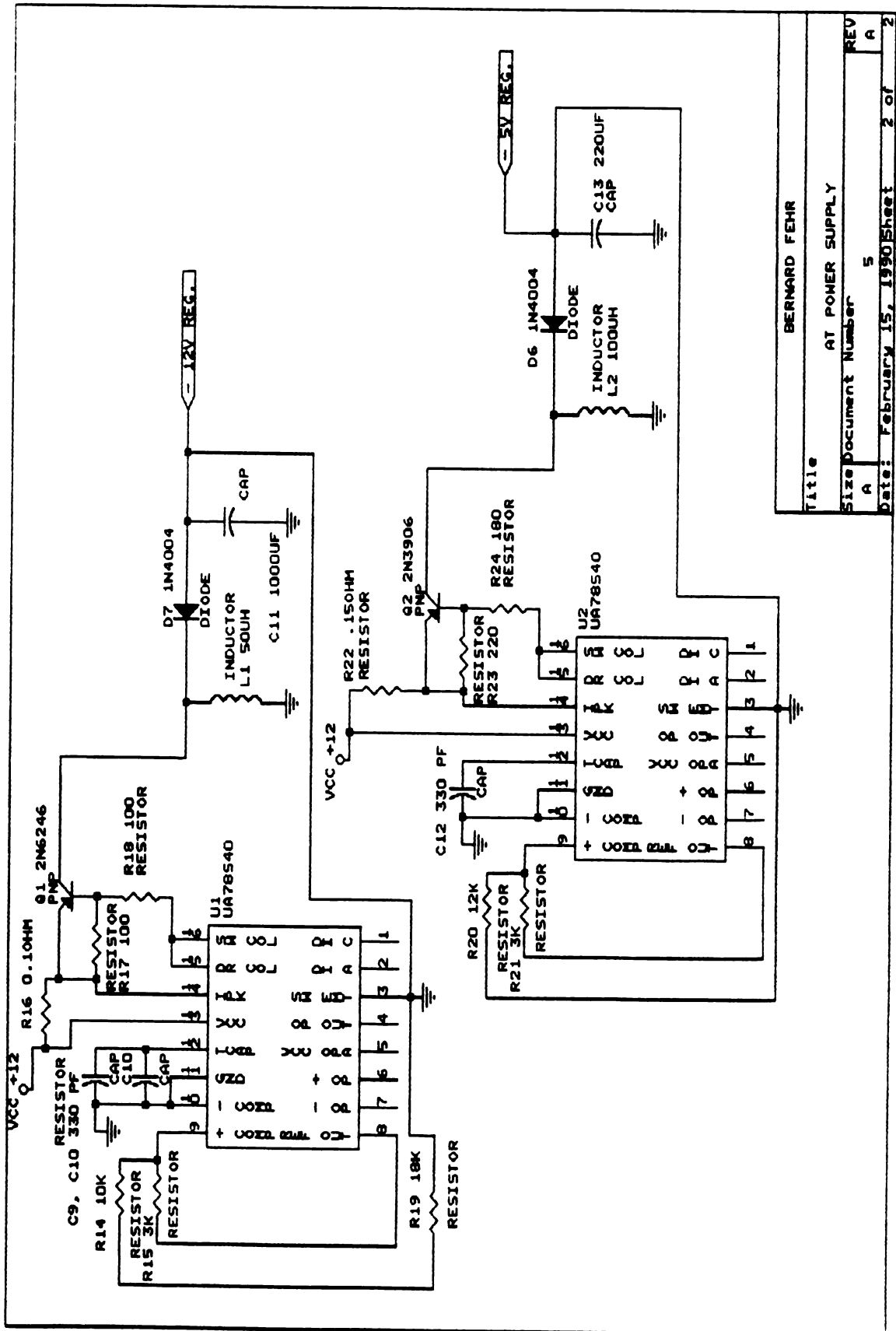
Date: February 27, 1990 Sheet 1 of 2

Title

REV

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REV



BERNARD FEHR

Title

AT POWER SUPPLY

Size

Document Number

5

Date: February 15, 1990

Sheet

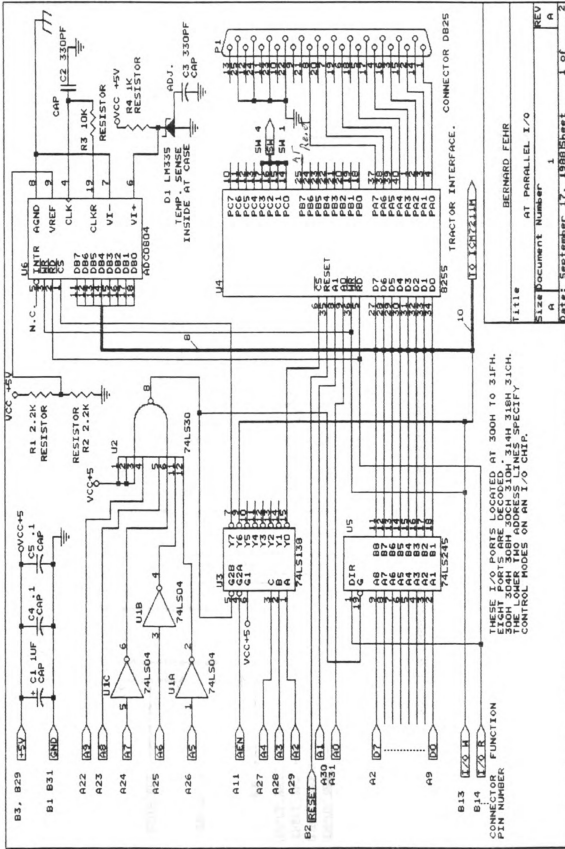
2 of

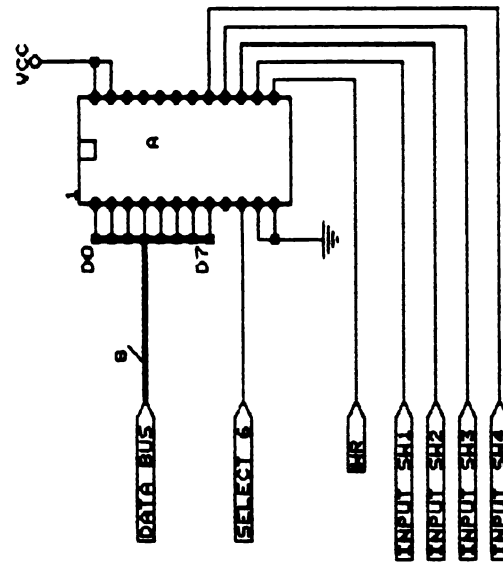
2

REV

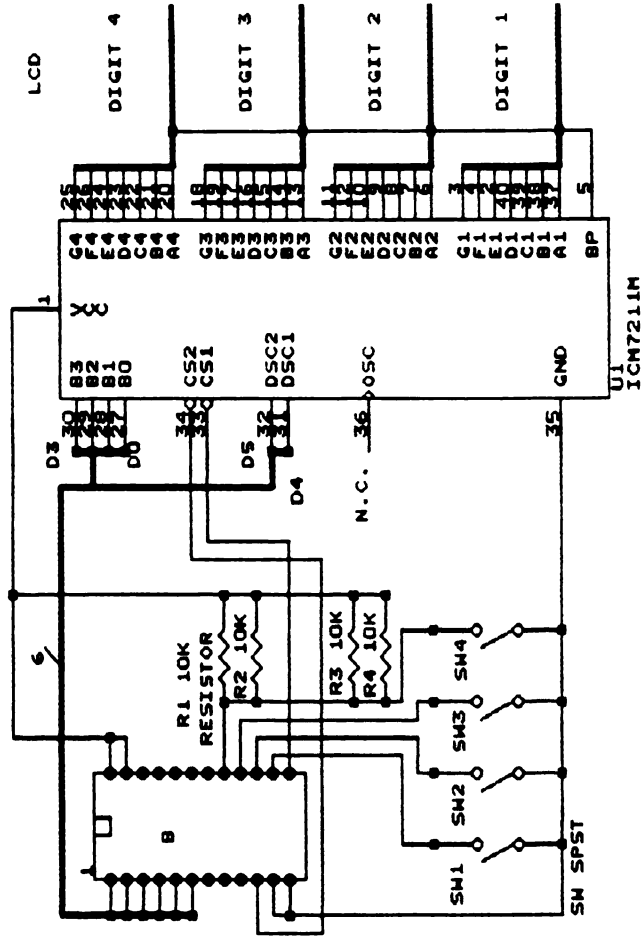
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APPENDIX 3





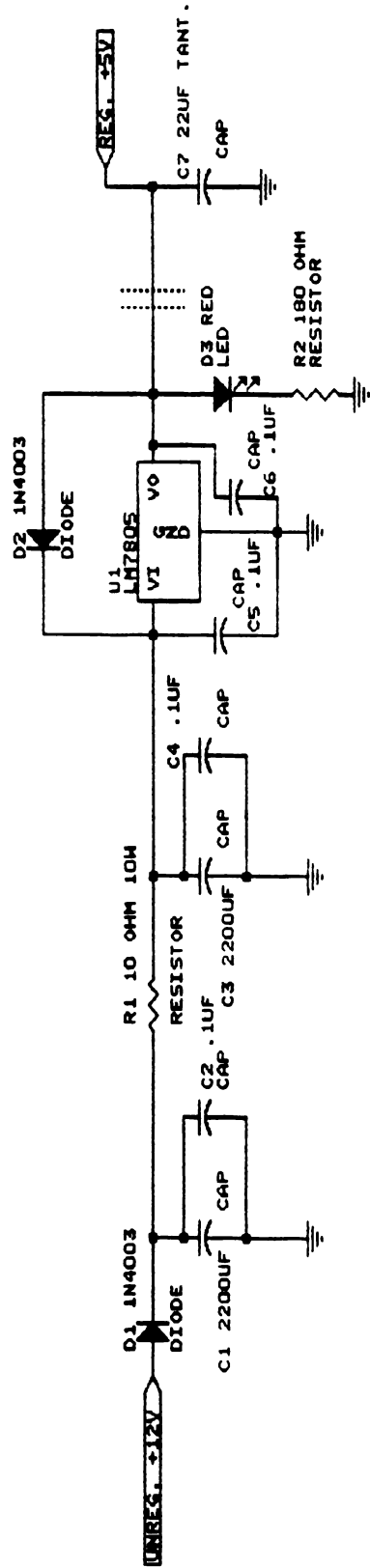
OUTBOARD HAND-HELD BOX



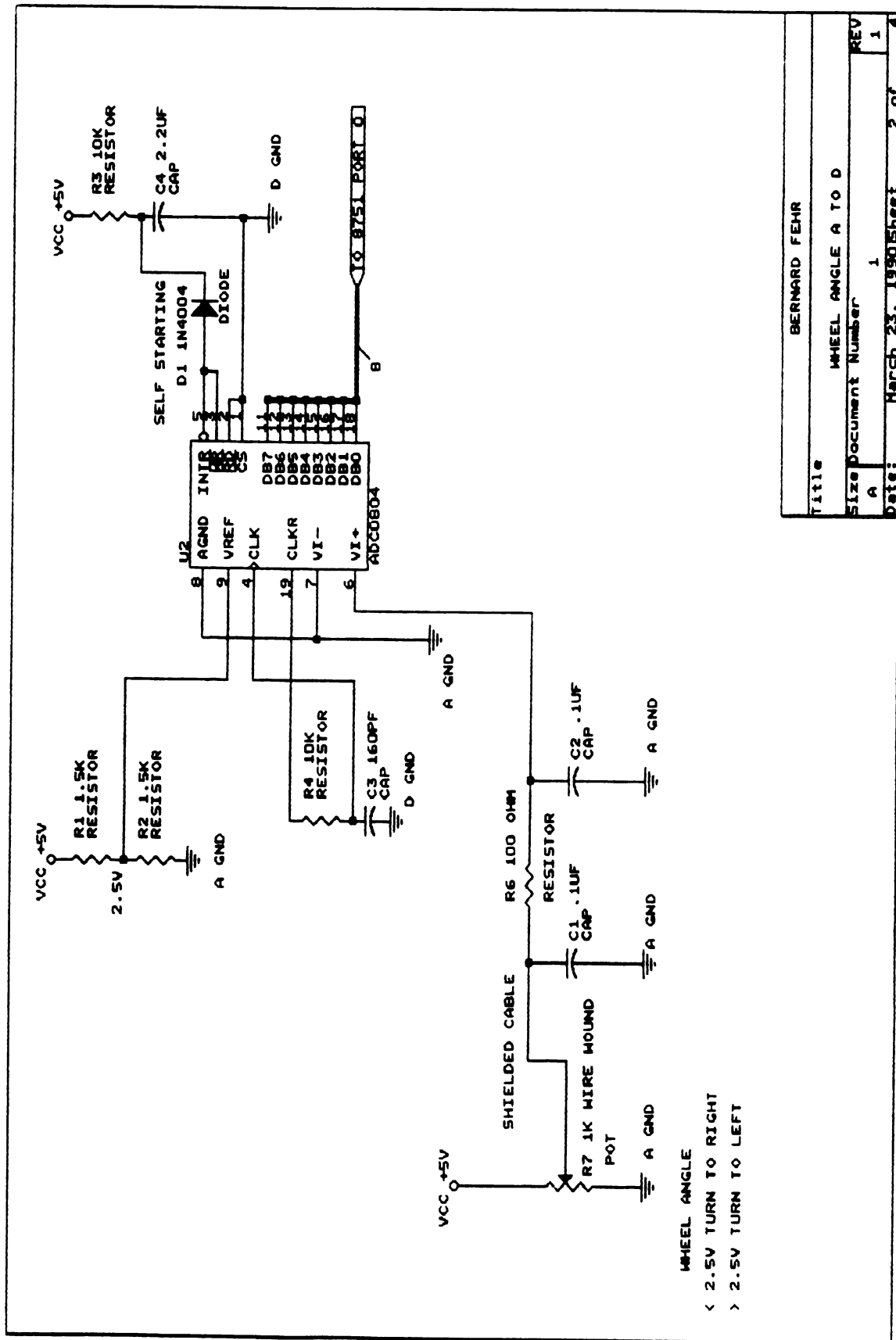
SOCKET A CONNECTED TO SOCKET B BY RIBBON CABLE.

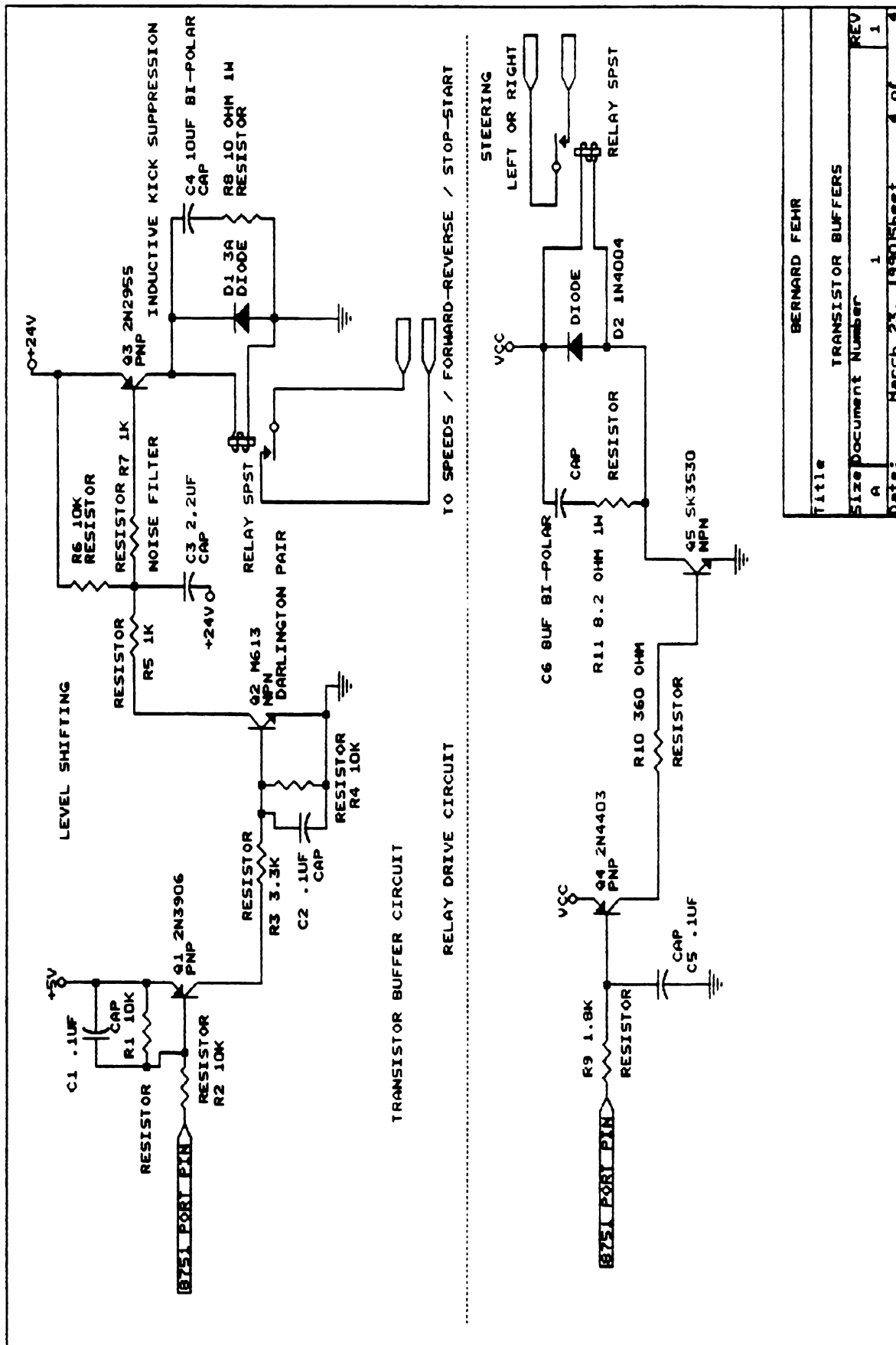
BERNARD FEHR	
Title	
AT I/O LCD	
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Sheet	2 of 2
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APPENDIX 4



Title		BERNARD FEHR
Slave COMPUTER POWER SUPPLY		
Size Document Number		1
REV		1
Date:		March 23, 1990
Sheet		1 of 4





LIST OF REFERENCES

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