DEVELOPMENT OF AN AUTOMATED COMBINE GUIDANCE SYSTEM

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Summary:
A machine vision-based automated corn harvester has been developed at the University of Illinois. The automated combine was field tested during 1999. Key modifications to the vehicle included upgrades to the electrical system and the hydraulic system. The basic guidance methodology utilized fuzzy logic to a) determine when to stop processing b) to evaluate image processing results and c) to calculate an overall vehicle steering command. The results from the steering subsystem identification are presented along with a brief description of the harvest results from the 1999 season.

KEYWORDS:
vehicle guidance, combine, corn harvest, machine vision, system identification, fuzzy logic, fuzzy application

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INTRODUCTION

Harvest is perhaps the most important stage of production agriculture. Within the United States, the corn and grain harvest is highly mechanized. Combines, forage harvesters, tractors and other vehicles play an important role in harvesting and transporting the crop from the field to silos and market.

Harvest brings both expectation and a tinge of nervousness. Harvest is a time when the farm and community come together, working long hours to bring in the crop.

Long hours lead to operator fatigue, posing safety and quality control problems. Operators have to manipulate yield monitors, vehicle speed, header height, reel and rotor speed and a host of other controls as they operate the combine. Vehicle automation has brought automatic header height control and improved ergonomics, but the task is both repetitive and complicated.

Automation is ideally suited to repetitive tasks. Agricultural machinery operation combines both repetitive operations (row following or surface coverage) and unique operations (road travel and a myriad of other farm tasks). The open and changing environment, combined with the safety and robustness requirements, increase the difficulty of agricultural automation. Automation can take different levels from driver assistance to autonomous operation.

Researchers at several institutions have developed guidance methodologies for autonomous agricultural vehicles (Reid and Searcy, 1991, O’Conner, et al., 1995, Hoffman, et al., 1996, Callaghan, et al., 1997). The guidance systems have utilized both mechanical guidance and non-contact sensors. Mechanical systems utilize feelers to detect furrows or rows of plants; the feeler position is converted to a guidance signal. Sensor based systems rely on electronic sensors to determine the location of the vehicle either locally or with respect to an established coordinate frame.

Several manufacturers have developed and marketed mechanical feeler systems. Sato, et al. (1996) demonstrated a feeler based guidance system for Japanese-style rice combines. Within the United States, factory and aftermarket row guidance systems have been used during cotton harvesting.

Sensor based technology has become attractive as sensor capability has increased while prices have decreased. GPS has become widely accepted in precision agriculture, enabling variable rate application, precision soil sampling and yield monitoring applications. Optical and laser based positioning systems have been used to provide accurate local position information. Several researchers have utilized inertial sensors to provide posture information. Machine vision is an attractive technology for vehicle automation, providing accuracy at a moderate cost. Researchers have combined the sensors to provide increased capability versus any one sensor (Young, 1976, Hague and Tillett, 1996, Noguchi, et al., 1998).

Tractor guidance, for example, must take place regardless of the conditions. During early season or preseason operations, the plants have not yet reached sufficient maturity to provide a visual reference for guidance. Non-visual sensors such as GPS and inertial systems can provide the guidance signal. Later in the season, the crops provide can provide a reference for guidance; machine vision can be used to provide the guidance signal. Machine vision can provide information about the current surroundings, allowing obstacle detection and crop condition evaluation.
For harvester guidance, machine vision was the primary option investigated. The nature of harvest should ensure that a grown crop is available in the field. The driver uses the crop as a visual reference for guidance. Machine vision mimics the perceptive process of the operator and can be used to extract a guidance signal from the crop. Most new combines sold today are equipped with yield monitor systems that include a DGPS receiver, however, the typical DGPS receivers sold for yield monitoring do not have sufficient accuracy for vehicle guidance. Early in the development process, the decision was made to pursue the machine vision option for the 1999 harvest.

Machine vision systems are situation specific. While the eventual goal is to develop a system that can be used for most crops and conditions, the problem had to be narrowed to a manageable project. Small grains and corn, for example, differ in terms of reflectance, color, texture and height. Still images were acquired of corn and wheat (Figure 1). The reflectance characteristics of wheat were very similar for both the cut and uncut regions. With corn, in contrast, there were significant height, texture, color and reflectance differences between the cut and uncut regions. Based on the differences, corn was used as the target crop.

The crop determined the possible range of camera locations. Practical considerations restricted the range of feasible camera locations. Ideally, a single camera mounted on the cab would be suitable for the project. A camera mounted on the cab of the combine would be less likely to be damaged a head mounted alternative. With a single camera, the camera would either have to see the entire head width or be manually adjusted to image one edge of the crop at a time. Imaging the entire width of the head would force a compromise between field of view and resolution. Increasing the field of view decreases the resolution and accuracy of the system. Alternatively, a single camera could be
mounted on the cab and fixed to image one cut / uncut edge. Each time the header is changed, however, the camera would have to be realigned and recalibrated. In addition, a single camera would restrict the guidance system to one cutting direction. An option that was used by researchers on the Demeter project was to install two cab mounted cameras. The installation of a second cab mounted camera eliminates restrictions on the cutting direction. The head of a grain combine, however, is changed with regularity.

Perspective shift is a problem as the height of the crop increases. Perspective shift is caused by the camera / crop geometry. The height of the crop is an unknown during harvest. Changes in height cause an apparent change in the apparent ground position of the crop, as shown in Figure 2. A change in crop height can mask an actual change in ground position, making it difficult to accurately control the vehicle.

A head mounted camera can be positioned to directly view the transition between the cut / uncut edge of the crop. Directly viewing the cut / uncut edge avoids the apparent change in ground position due to changes in height. Head mounted cameras, however, are more prone to damage than a cab mounted camera. Fixed head mounted cameras would remain with the head and would avoid recalibration each time the head was changed.

**DEVELOPMENT**

A Case 1 2188 axial flow combine was used as the basis for the research platform. The combine was equipped with an AFS yield monitor, AFS beacon GPS, Powerglide rear axle and FieldTracker header tilt control. An 8-row 1083 corn head was used during the course of the guidance project. The combine is shown in Figure 3.

Combine preparation began during April 1999 and continued through the harvest season. The modifications to the combine fell into three categories: General, Steering, and Sensors.

**General**

The combine was the fifth vehicle prepared for guidance use at the University of Illinois within the last four years. Previous experience showed that the accessory electrical system was inadequate for the typical modifications required for vehicle guidance.

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The electrical modifications consisted of the installation of an external wiring harness and an upgraded power distribution system. The external wiring harness allowed sensor, power and image cables to be run to different parts of the vehicle within a flexible aluminum conduit. Waterproof breakout boxes allowed sensors to be easily attached or removed at different locations on the vehicle. The power distribution system allowed multiple high amperage devices to be reliably connected.

A 450-MHz AMD K6 computer was installed in the cab of the vehicle for control and data acquisition. An ImageNation (Beaverton, OR) PXC-200 color frame grabber and a National Instruments (Austin, TX) PCI-MIO-16E-1 data acquisition card were installed in the computer. A Computer Dynamics (Greenville, SC) external flat screen monitor provided day and night viewing capability.

Steering
The hydraulic steering system on the combine was modified for guidance use. An electrohydraulic (E/H) valve and the associated hardware were added to the system, allowing the vehicle steering to be controlled by computer.

A 300-MHz laptop computer was used as the dedicated steering control computer. Steering commands and calibrated feedback results were transmitted between the main guidance computer and the steering controller via an RS-232 serial link. A National Instruments DAQPad-MIO-16XE-50 data acquisition card handled the input/output for the steering controller. The output voltage from the I/O card was fed to a High Country Tek (Nevada City, CA) pulse width modulated (PWM) driver card. A 5-kΩ Omega (Stamford, CT) linear potentiometer was installed parallel to the left side steering cylinder to provide feedback for the steering controller (Figure 4).

A prototype E/H valve was installed in parallel to the steering handpump. The output from the PWM driver card was used to actuate the E/H valve.

Early experience with the standard hydraulic steering system raised concerns of asymmetrically and insufficient force. As provided, the system has a single 5.1 cm (2") steering actuator installed on the left side of the axle. A modified right side steering knuckle and inside steering support plate were procured from the axle manufacturer. A second factory cylinder was plumbed in parallel to the existing cylinder. A schematic of the modified hydraulic system is shown in Figure 5.
A system analysis procedure was performed on both the standard and modified system. A PID control algorithm was developed in C for the modified system.

**Sensors**
For the 1999 season, machine vision was the primary sensor on the vehicle. During the summer, cameras were installed on both ends of the 1083 corn head (Figure 6) and above the cab of the vehicle. Although several cameras were used during the course of the project, the primary cameras were Cohu (San Diego, CA) 2100 series monochrome cameras.

Filter and lens studies were performed before harvest. The results of the filter study indicated that 800-nm filters provided satisfactory results for guidance. 6-mm lenses provided the best combination of resolution and field of view for the head mounted cameras. A 3-mm lens was installed on the cab mounted camera.

A typical image from one of the head mounted cameras is shown in Figure 7. Several key features have been marked in the image: A) transition between the cut and uncut region, B) shadowed region C) stalk and leaf material and D) horizon. The goal of the algorithm is to accurately locate the transition, marked by line A, between the cut and uncut regions of the crop. The transitions are typically located in only a portion of the image. Shadows (region B) obscure the transition region under certain conditions. The stalk and leaf material (region C) are not used to locate the transition between the cut and uncut crop regions. Region C is relatively noisy and can cause difficulties when segmenting the image. The horizon, line D, roughly separates the image into useable (lower portion) and not useable (upper portion) regions. Since roughly half the image is above the horizon (and not suitable for guidance), clearly the entire image does not need to be processed.

**Software**
Proprietary vehicle control software was developed for the combine. A software flow diagram is shown in Figure 11 in Appendix A. The control is split between the main computer, which contains the machine vision algorithm, and the dedicated control computer, which controls the combine steering. The main guidance computer operates in a continuous loop fashion. The three main functions in the guidance loop are the...
machine vision algorithm, a fuzzy vehicle controller and communication between the main guidance computer and the dedicated controller. The separate controller is able to operate at a higher speed than the main guidance computer.

The machine vision algorithm is detailed in a separate article (Benson, et al., 2000). The algorithm was designed to reduce the amount of processing required and increase the processing rate of the system. The image was processed from the bottom of the image up. Two fuzzy logic modules were used to a) determine when to stop processing the image and b) to evaluate the quality of the regression. The algorithm is adaptive, including the ability to adjust the segmentation level, the fuzzy membership functions and the size and height of the processed region.

Several assumptions were made during the development of the machine vision algorithm. The three most important assumptions were: A) the camera directly viewed the cut edge, B) the wall effect, and C) the objective of guidance was to control the horizontal location of the cut / uncut edge. The first assumption, a direct image of the cut / uncut edge, meant that changes in the crop height would have minimal effect on the apparent ground location of the cut / uncut edge. The second assumption, or the wall effect, meant that the outermost crop row blocked the inner rows from view. The second assumption represents a departure from the typical row crop guidance algorithms. The typical row crop guidance algorithms utilize information from two or more rows. The use of multiple rows provides robustness against weeds, missing plants or crop damage. Directly viewing the cut / uncut edge, exchanged the robustness of multiple rows for minimal perspective shift. The third assumption, horizontal control of the cut and uncut edge, determined the processing needs of the system. From the third assumption, the lateral location of the parameterization of the crop edge was more important than the slope of the same line.

Given the assumptions, a machine vision algorithm was developed. The vision algorithm can be split into row-based and frame-based portions. The row-based operations are contained within a large loop with a fuzzy function determining when to terminate processing. The frame-based operations take place upon termination of the row-by-row processing.

The row-by-row processing includes segmentation, classification, transition detection, sequential linear regression and fuzzy evaluation steps. The machine vision algorithm used two-class K-means thresholding to segment and classify the points as cut and uncut crop. Run length encoding was used to simplify the segmented image. A heuristic algorithm determined the maximum run length for a given scan line. A weighting factor based on the distance between the location of the longest run and the prior frame regression results was used to reduce the impact of outliers. The position and weight of the longest run were added to a sequential linear regression. A three-parameter adaptive fuzzy logic function (Fuzzy Convergence Evaluation) evaluated whether the regression had reached convergence. If the regression had stabilized, adding further points to the regression would not improve the results and the image processing was halted.

At the frame processing level, a second fuzzy logic function was used to evaluate the regression output. A four-input, one-output module (Fuzzy Quality Evaluation) checked to see if the regression output satisfied predefined quality requirements.
An adaptive region of interest (ROI) module trimmed the processing region to reduce the image processing requirements for the next iteration. The adaptive ROI trimmed the horizontal and vertical borders of the ROI based on the regression slope and the image size required for regression. An error handler provided safe ROI values in the event of a problem.

The output from the second fuzzy module was sent to a fuzzy vehicle controller. The fuzzy vehicle controller calculated the required steering command based on the results from the vision system. For 1999, the average regression intercept for the top and the bottom of the image was used to calculate the guidance signal. The vehicle controllers used a single input / single output fuzzy function with five membership functions and five output membership functions. The input membership functions were different for each of the three camera locations while the output functions remained the same for all three camera locations. An example membership function is shown in Figure 8.

The output from the fuzzy vehicle controller was sent via a serial link to the separate controller described above. After transmitting the steering command to the separate steering controller, the computer repeated the process on the next image.

RESULTS

The combine was developed and tested in stages. The initial focus was on developing the hardware for the vehicle. The results can be separated into three sections: steering, machine vision and overall vehicle guidance.

Off-highway hydraulic steering systems frequently contain deadband. On the combine, the deadband was caused by both electronic (PWM driver card settings), hydraulic (valve configuration) and surface conditions. The deadband was identified and a compensation method developed.

Model identification was performed in MATLAB (Mathworks, Natick, MA) using the System Identification toolbox. The original system simplified to a second order system (Equation 1). The root locus diagram is shown in Figure 9 and indicates both poles and zeroes in the right half plane. Poles and zeroes in the
right half plane indicate an unstable system.

\[ G(s) = \frac{2.57(s - 1.0160)}{(s - 0.9992)(s - 0.8267)} \]  

After the system was modified with an additional steering cylinder, the system identification procedure was repeated. The modified system reduced to a simplified first order system that was conditionally stable (Equation 2). The root locus for the modified system is shown in Figure 10.

\[ G(s) = \frac{0.1606}{(s - 1.004)} \]

In addition to more favorable model characteristics, the additional cylinder improved the high-speed driveability of the combine. The steering system modifications alleviated the symmetry and force concerns.

A PID steering controller was developed for the combine. A compensation module was added to correct for the deadband. The steering controller was tested with sine and step input signals. The results from a representative test are shown in Figure 11. The steering controller developed was able to satisfactorily control the steering of the combine.

The image processing software was developed using video footage from the 1999 harvest. A representative processed image is shown as Figure 13 in Appendix B. Additional machine vision performance information is available in Benson, et al., 2000.

The vehicle guidance system was tested late in the harvest season. The only available crop was from another project and had been intentionally nitrogen stressed. The crop was in poor condition from the combination of nitrogen stress and weather. The overall vehicle guidance system met with mixed success. The system was able to successfully autonomously harvest corn at speeds of up to 9.6 km/h.
As field and crop conditions worsened, the system was unable to successfully guide the vehicle. Under poor crop conditions, the machine vision system was unable to successfully segment cut and uncut portions of the image. An image of the late season corn is shown as Figure 14 in Appendix B. The late season corn violated one of the initial assumptions for the machine vision system: the outermost rows of corn would block the inside rows from view. As shown in the image, late in the season, it was possible to see the inside rows from the outermost row. The poor crop condition was believed to have a negative effect on the performance of the system.

FUTURE WORK
The current combine guidance prototype was developed in under 9 months. The machine vision system encountered difficulty segmenting the cut and uncut portions of the image. Different camera configurations and algorithms and their effect on overall guidance accuracy will be investigated for the 2000 season.

CONCLUSIONS
An autonomously guided combine harvester was developed. A machine vision algorithm was developed to determine the parameterization of a row of corn. The algorithm used sequential linear regression linked to a pair of fuzzy logic modules to determine the processing requirements and to improve the quality. A fuzzy vehicle controller calculated the required steering angle based on the output from the machine vision system. The system was tested under actual field conditions and was able to guide the combine through the field under limited situations.

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**APPENDIX A: SOFTWARE FLOW DIAGRAM**

![Software flow diagram for the main guidance computer and the dedicated steering controller](image)

**Figure 12.** Software flow diagram for the main guidance computer and the dedicated steering controller

**APPENDIX B: REPRESENTATIVE CROP IMAGES**

![Representative processed image. Note: from the outer row, it is not possible to see the inner rows of com.](image)

**Figure 13:**

![Late season com. Note: from the outer row, multiple rows of com are visible.](image)

**Figure 14:**