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Development of a Flexible Platform for Agricultural Automatic Guidance Research

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Summary:

This paper describes an agricultural vehicle modified to serve as a research platform for agricultural engineering. A tractor was equipped with a global positioning receiver, inertial/GPS system, geomagnetic direction sensor, and a monochrome camera for local and global sensing. For steering control, the tractor was equipped with an electro-hydraulic proportional steering valve, PWM coil valve driver, and potentiometer wheel angle sensor. The high flexibility of this platform has enabled research in the areas of row crop guidance, sensor fusion and evaluation, automation, vehicle dynamics modeling, and steering control. We discuss the benefits and drawbacks to this platform and the research made available through its development.

Keywords:
Vehicle Guidance, Global Positioning System, Sensor Fusion, Machine Vision, Geomagnetic Direction Sensor

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Introduction

Many challenges face today's world of off-road equipment engineers. Off-road equipment continues to become more complex to meet the needs of advancing technology. As better sensors and control devices are introduced, researchers seek the best possible ways to incorporate them into useful products for agriculture. The need for flexibility in development and synthesis of various technologies compel researchers to adopt a wide range of approaches for development.

The use of a diversity of sensors and control techniques is well documented throughout history. Mechanical sensors have long been in use (Richey, 1959, Rushing, 1971) and continue to be used today. Field-based location systems (Gordon and Holmes, 1988) have gradually given way to satellite-based systems such as the Global Positioning System (GPS) (Langley, 1997). Inertial sensors have been used to give velocity and position (Grovum and Zoerb, 1970) and are still in use today (Noguchi et al., 1997). Heading information can be obtained by sensing the earth's magnetic field by use of a compass or more complicated geomagnetic direction sensors (GDS). Control of vehicles have seen much change and improvement as well over the years, as can be seen by the progression from the tethered-based controls of the 1940's (Andrew, 1941) to more modern methods of computer-based electro-hydraulic control (Stombaugh, 1998).

In our endeavor to incorporate and evaluate a wide range of technologies for the advancement of agricultural guidance techniques, we have developed a flexible platform for agricultural research, focusing on sensor fusion for automatic guidance. The platform consists of a two-wheel drive tractor outfitted with a portable computer, GPS, inertial sensors, GDS, vision sensors, and steering control. Goals for our system include the development of an automatic row crop guidance system, development of vehicle dynamics analysis, path planning, and the advancement of sensor fusion techniques. Aditionally, the wide range of systems and controls on our platform allow us to evaluate new sensors quickly, investigating their performance and applicability for our goals.

Research Platform

Our choice for the agricultural vehicle on which to mount the sensor platform was a 115 kW Case (Racine, WI) 7220 Magnum[1] two-wheel drive tractor. The tractor had a mass of 8120 kg and had an estimated yaw moment of inertia of 23,000 kg-m^2 according to data provided by Case Corporation. Tests were conducted with three standard wheel weights on each rear wheel and no extra weights on the front weight bracket, yielding front and rear axle masses of 2155 kg and 5965 kg, respectively.

To serve as the main control center for the sensors, a Dolch (Freemont, CA) PAC 586 portable computer was installed in the tractor. This computer consisted of a 150 MHz Pentium and motherboard, integrated 80 nit 800 x 600 TFT display, a 1.2 Gb hard drive,

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[1] Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the University of Illinois, The Ohio State University, or Hokkaido University and does not imply the approval of the named product to the exclusion of other products that may be suitable.

and 64 Mb of RAM. To this base system was added an Iomega Jaz Drive for removable storage, a serial I/O card for two extra communications ports, and a SCSI interface card. The computer had a dual power supply, allowing it to be powered by 10-40 VDC or 110 VAC. Additional cards were added to this system, as described later with the various complementary sensors. Microsoft Visual Studio 4.0 software was installed on the computer to facilitate changes to custom programs while in the field. A wide range of proprietary software was also installed for each individual sensor, although the majority of system control was performed through custom programs in the C programming language. The computer was mounted above and to the right of the dashboard of the tractor.

Figure 1. Tractor Research Platform

GPS Sensor

Global position information was obtained mainly through a GPS receiver. Our system was based on the NovAtel (Calgary, Alberta) RT-20 real-time kinematic (RTK) GPS receiver. This system consisted of two L1-C/A code, 12 channel parallel receivers. Overall system accuracy was 20 cm, with a maximum position update rate of 5 Hz. One receiver was mounted in the cab of the tractor and was interfaced to the Dolch computer via a serial communications port. Novatel provided proprietary software (GPSolution) to interface with the device, but the system was also capable of outputting NMEA strings for use with custom written programs.

To run the RT-20 system in RTK mode, the second reciever must be located at a base station at a known position. This receiver's GPS antenna was installed at the top of a farm building in the vicinity of our research. To determine the exact position of the base station antenna, a local surveying firm surveyed the position of the antenna. This was achieved by simultaneously logging the satellite ephemeris data at 1/10 Hz at the base station (from the Novatel antenna) and at three known benchmark points. With this data, the surveying firm was able to calculate the position of the phase center of the Novatel GPS antenna with a precision of < 1 cm.

For real-time solutions, a radio link was required between the base station and the roving GPS receiver. A pair of 9600 baud Pacific Crest (Santa Clara, CA) radio modems were used to broadcast the differential corrections from the base station to the rover. The antenna for the base station was mounted on top of a two-story building at a height of approximately seven meters. The operating range on the modem was approximately 10 km, allowing us ample space for the rover (tractor platform) to operate. The radio operated in the 150 and 470 MHz bands with an output power of 35 Watts. A special FCC license was required to operate at this power.

The Novatel RT-20 system proved to be a quite effective system. The receiver was easily configurable and it could output a number of different customizable strings. Additionally, the software included with the system provided a number of useful utilities such as data logging, status reports, and graphical mapping.

GDS Sensor

A Watson (Eau Claire, WI) FGM – 301 geomagnetic direction sensor was installed on the vehicle. The device consists of a three-axis analog fluxgate magnetometer. 12 VDC power from the tractor was used to drive the self-regulating sensor. An analog to digital converter was used to read the three output channels.

The sensor was tested in several different mounting configurations. The sensor mount was required to be sturdy, non-magnetic and away from any potential sources of electromagnetic interference. The optimal sensor location was found to be behind the cab of the vehicle. To avoid vibration problems, a cross-braced aluminum box girder was fabricated to hold the sensor. Several aluminum supports further reduced the vibration. This final mounting solution is shown in Figure 2.

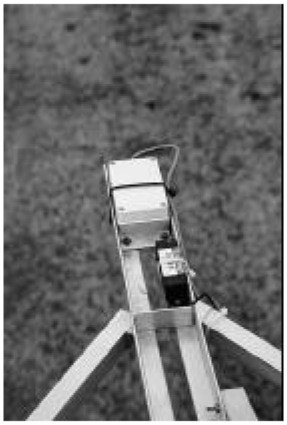

Figure 2. GDS Sensor and Mounting

Two methods were used to calibrate the sensor. The first method, reported by Noguchi et al., (1997) involved driving the vehicle on a circle and recording the output from the magnetometers. Since the vehicle was driven in a circle, the magnetometer output should have also produced a circle centered at the origin. Any shift in the center location, or offset, was due to localized magnetic field distortion and could be compensated for by the calibration.

The second calibration method (Peters, 1986) consisted of driving the vehicle in several known directions and recording the output from the magnetometers as well as the GPS. A second order curve fit was used to minimize the difference between the geomagnetic and GPS indicated heading.

AgNav Unit

The AgNav Navigational System is a product developed by Lockheed-Martin and distributed by Ag-Chem (Jackson, MN). The sensor measures current position and outputs a NMEA GPGGA string giving latitude, longitude, and altitude. The product is a black-box configuration consisting internally of three GPS receivers and a two-axis inertial unit, as well as an input for vehicle velocity, read from the vehicle's radar gun. The sensor outputs are integrated using a Kalman filter developed by the manufacturer. There is an option to externally deliver differential GPS correction to the unit in order to increase accuracy.

The specified accuracy on this device was 3-5 m horizontally. During a comprehensive series of tests of this unit, it was found to be well out of that specification. The error in position ranged from 1-100 m. It was found that the unit had fair precision, as the errors on most test runs clustered within approximately a 5 meter range. It was found that this sensor was not useful as a position sensor alone for our research, and that a cheaper solution with an order of magnitude greater accuracy could be found using an RTK GPS receiver, at about half the cost. Adding the differential GPS correction input to the device did not significantly improve the quality of the solution. Figures 4 and 5 show typical AgNav performance with no differential input.

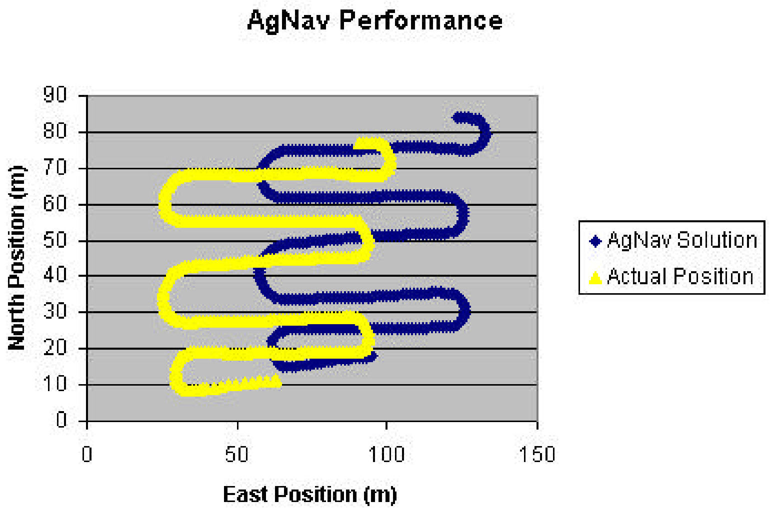

Figure 3. Typical AgNav Solution Accuracy

The AgNav unit did bring one useful capability to the overall platform. By using a special query with the most recent version of firmware (Rev. F.2) on the test port of the unit, we had access to some of the internal sensor information. The special status string includes information about the vehicle's heading, roll, pitch, yaw, and speed and can be quite useful in many applications of research. One of our main goals has been to incorporate this sensor (which itself is a fusion of sensors) into our overall sensor array. An important benefit of this system is that the position solution is not totally dependent on satellite information. If satellite communication is temporarily obstructed, the inertial unit can continue to navigate during the interim. This characteristic makes this unit quite attractive for a sensor fusion application.

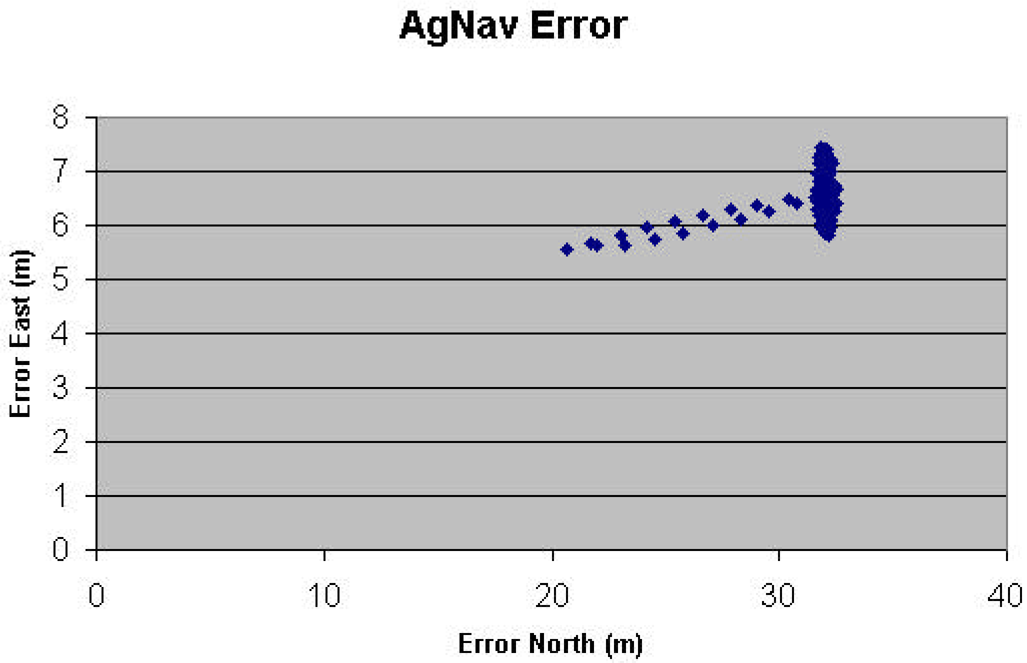

Figure 4. Typical Error Clustering for AgNav System

Steering Controller

The configuration of the automatic steering controller (Figure 5) included a 5 kΩ linear potentiometer wheel angle sensor with an 0.3 m stroke, which was mounted rigidly to the steering cylinder of the tractor. The sensor was excited with a 5 V DC signal. The actuating rod of the sensor was connected to the tractor frame with a tongue-in-slot mechanism to protect the sensor from misalignment and cylinder flexure. The steering angle sensor was calibrated by conducting circular path tests on a relatively level asphalt surface. A series of fixed steering wheel angle commands were issued to the steering controller. For each wheel angle, the tractor was driven slowly in a constant radius circle. The NovAtel GPS sensor was used to record positions of the vehicle center of gravity along the circle. The steering angle was then calculated from the radius of the circle traversed and vehicle geometry. The results of these tests showed that sensor performance was very linear (Stombaugh, 1998).

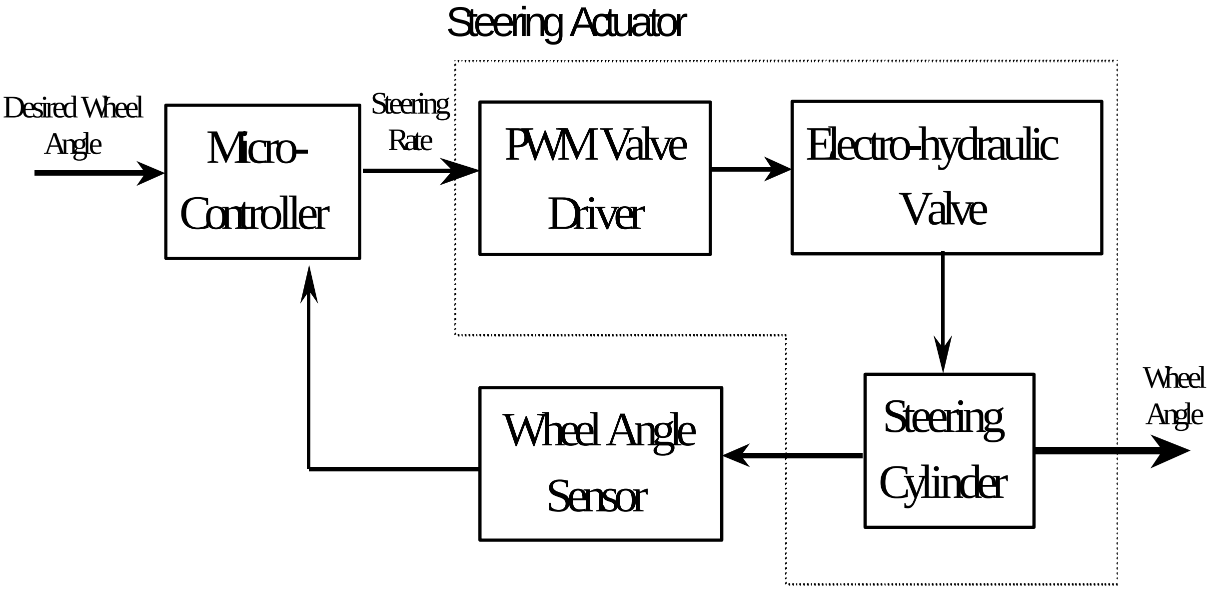

Figure 5 Steering Controller Configuration

The experimental electro-hydraulic proportional steering valve was provided by Case Corporation. The valve was plumbed in parallel with the existing steering hand pump.

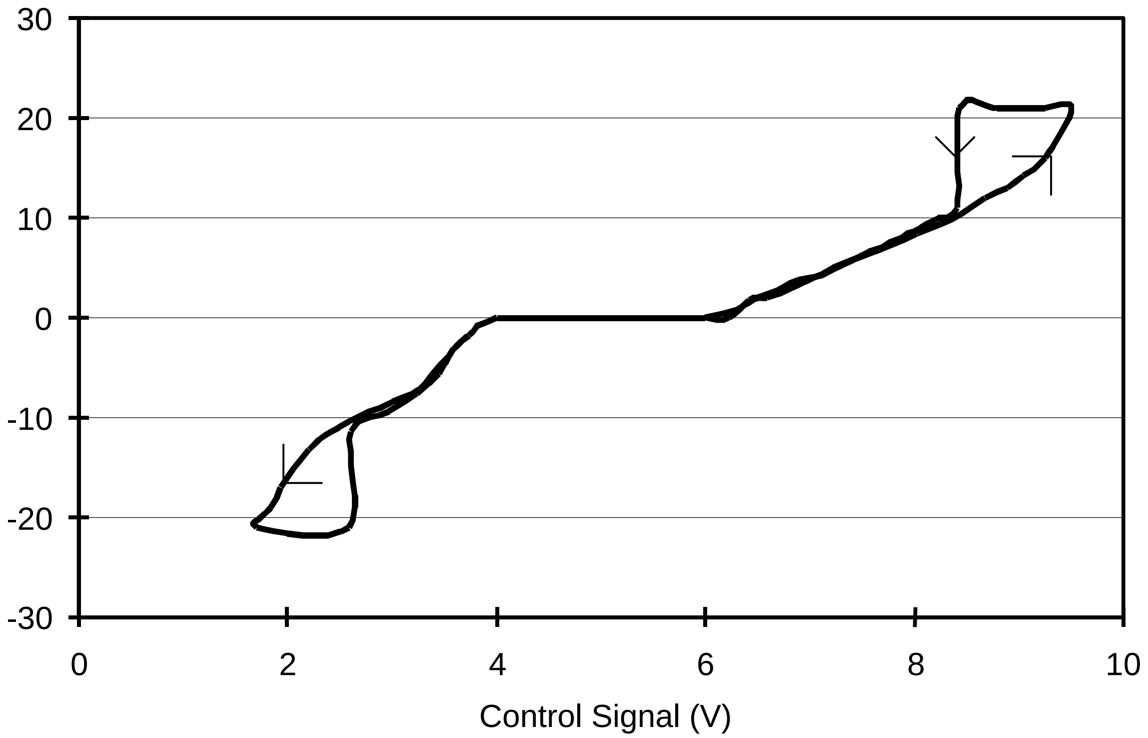

Figure 6. Steering Valve Flow Characteristics

The pressure sense lines of the two valves were prioritized with a shuttle valve. When activated, the electro-hydraulic valve would override manual steering inputs. When the automated valve was neutral, manual hand pump performance was not affected. The electro-hydraulic valve required a pulse-width-modulated (PWM) signal for proportional control. A High Country Tek (Nevada City, CA) model HADKSF100 dual-coil valve driver was used to provide the PWM signal for valve control. This driver converted an analog DC voltage to an appropriate PWM signal.

The flow characteristics of the valve controlled by the PWM driver were evaluated on a hydraulic test bench before installation on the tractor. The flow rate through the valve as a function of input voltage to the PWM driver (Figure 6) shows several things. 1) There was a 2 V dead band at spool center, 2) There was a significant amount of hysteresis in valve performance, and 3) Positive and negative flow were not symmetrical; negative flow exhibited a higher gain. The major challenge, then, in designing the steering controller was specifying a feedback-based control signal that would provide acceptable steering performance.

Feedback control for the automated steering system was provided by a Z-World Engineering (Davis, CA) Model BL1100 Little Giant microcontroller. This 9 MHz controller featured a 12-bit A/D converter, a 12-bit D/A converter, and several serial communication ports. Because the voltage range of the D/A output was 0-2.5 V and the PWM controller required 0-10 V, a signal conditioning circuit (Figure 7) was constructed and installed between the microcontroller and PWM controller. The actual steering wheel angle was read from the wheel angle sensor through an A/D converter channel. This value was compared to the desired value obtained either through another analog input or one of the serial ports. The desired steering action was then sent from the D/A converter through the signal conditioning circuit to the PWM driver.

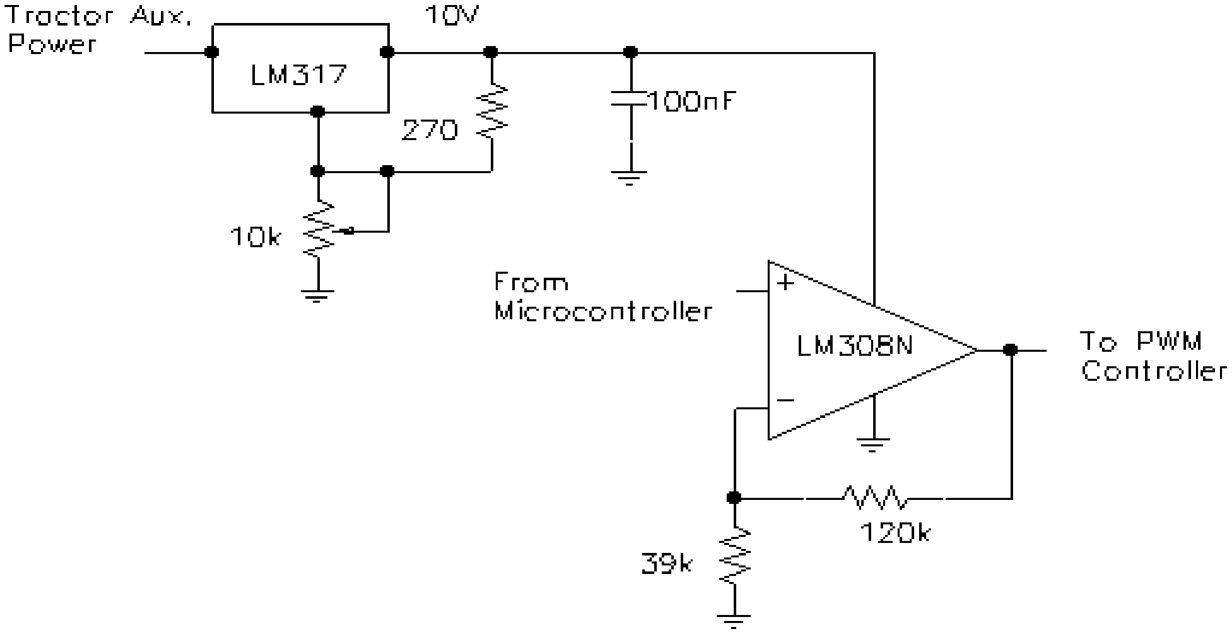

Figure 7. Signal Conditioning Circutry For Microcontroler to PWM card interface

All hardware components were installed on the tractor and feedback control software was developed. Initial feedback control design was based on perceived performance. A steering input was generated from a rotary potentiometer, and feedback parameters were adjusted to maximize speed of response while minimizing overshoot and oscillation. Because of the asymmetrical performance of the valve, it was necessary to specify two sets of feedback parameters corresponding to the direction the wheels were being turned. It was found that a proportional-integral-derivative (PID) control scheme would provide relatively fast, near critically damped response.

After substantial vehicle dynamics quantification studies, Stombaugh (1998) found that the steering system dynamics were very close to desired overall vehicle dynamics. He also found that the analog output of the microcontroller was very susceptible to electromagnetic interference. Because of these noise and dynamics problems, the microcontroller was removed from the control system. In later tests, guidance controller design compensated for the open-loop steering actuator components as a component of the whole system. The open-loop actuator dynamics were quantified by Stombaugh (1998) as

$$G(s) = \frac{13.8}{s(s + 11.4)}\,. \tag{1}$$

GPS Antenna Location

The GPS antenna was originally mounted on top of the tractor cab directly above the vehicle center of gravity. Studies conducted by Stombaugh (1998) revealed that the phase lag introduced by locating the sensor behind the control point (front wheels) made guidance controller design very difficult. To facilitate guidance controller design, the GPS antenna was placed on a mast bolted to the front weight bracket of the tractor. The antenna was 3 m off the ground (to prevent satellite obstruction by the cab structure) and 0.45 m ahead of the front wheel axles. With the sensor at this location, satisfactory guidance performance was achieved using relatively simple feedback control strategies.

For longer-term guidance solutions, it is desirable to have the GPS antenna mounted in a position where it is invulnerable to physical damage. Qualitative studies were conducted to evaluate the controllability of the vehicle with the GPS antenna mounted on top of the tractor cab. These studies showed that with the antenna mounted over the center of gravity, system stability could be achieved by digitally integrating the GPS position data to introduce phase lead. However, overall guidance system performance was not satisfactory. Future studies are needed to identify numerical and/or sensor augmentation techniques that will add adequate phase lead to the system.

Machine Vision

An ELMO (Plainview, NY) model TSE-271 monochrome camera was used for image acquisition. The camera provided an RS-170 video output which was connected to an image capture card. An EE lens option was used for adjusting for ambient illumination. The video signal was tapped and used to control the aperture of the lens. Lens control was set to a low video level gain and control based on the peak level of the video signal. The camera was modified to make it sensitive to near-infrared illumination by removing an IR blocking filter and replacing it with a narrow-band interference filter. Ranges of filters were used but in general had a central pass-band wavelength of 800 nm with bandwidths of 10 to 100 nm. An ImageNation (Beaverton, OR) CX-100 frame-grabber was used for image acquisition. Images were acquired in a low-resolution field mode providing 256 x 240 pixels of resolution. Quick detach heads were used to allow detachment and storage for the image sensors.

Figure 8. Mounting of the Elmo vision sensor

Some applications of the vision system required a calibrated vision sensor. Camera calibration was based on a direct linear transformation matrix method for relating the image plane to the plane of the field within the tractor field of view. Calibration required the determination of known world coordinate locations and relating them to observed pixel locations on the image sensor. A test area was established where the tractor was carefully positioned along a grid of known world coordinates. White styrofoam cups were placed on a grid of points in the field of view of the tractor. The positions of the reference points and of the vehicle were marked with spray paint for subsequent calibrations. An image was captured in the appropriate mode of application of the vision sensor and pixel coordinates of the known locations were determined. The direct linear calibration method provided a 3x3 matrix relating world coordinates to field coordinates. The inverse of this matrix was generally used to relate image coordinates to world plane coordinates.

Conclusions and Future Work

This research platform is of a dynamic nature. New sensors are added and integration techniques are improved. Near future plans include the addition of a fiber optic gyroscope, as well as a higher-precision GPS unit. Studies involving various camera positions and calibration techniques will be developed. Better control algorithms and input-output communication are being facilitated. An improved networking system is planned for late summer of 1998 to allow high-bandwidth communication to base station computers.

This tractor platform has served well to support a number of concurrent, diverse research projects. These projects have included steering automation (Noguchi et al., 1998), sensor fusion (Benson et al., 1998, Noguchi et al. 1998), vehicle dynamic studies (Stombaugh 1998, Wu and Reid, 1998), and sensor evaluation (Benson et al., 1998) Additionally, the variety of available sensors led to novel implementations for many solutions. This flexible research platform continues to serve as a vehicle of progress for agricultural development.

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