Development of Autonomous Robots for Agricultural Applications

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Abstract.

Two autonomous robots were developed as platforms for crop/soil scouting and future robotic field operations. The robots have differing technological philosophies. AgBo is a flexible industrial style robot with a sophisticated steering, sensing and communication arrangement. It has independent four-wheel steering, four steering modes (including crabbing and spinning) and inclination control. A SICK laser range finder, combined with an electronic compass, was used for crop guidance. The main communication among sensors, actuators and controllers was implemented using a Controller Area Network (CAN).

AgTracker, in contrast, was built with ruggedness, simplicity and low cost in mind. It features simple skid steering and an arrangement of eight low-cost infrared sensors, two ultrasonic sensors and an electronic compass were used for crop guidance. All of these functions, including Remote Control were implemented using a single microcontroller and no communication network was applied. AgTracker's simplicity and ruggedness make it a strong candidate for a generic platform for scientists to develop autonomous crop scouts and field operation machines. This could refocus the research emphasis from the robots themselves to the

truly important development of small, reliable, no-calibration, real-time sensors for the detection of stresses, diseases, weeds, pests and soil parameters.

The human urge to automate our world seems unstoppable. Kasler (2001) claims that the

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Introduction

transfer of human intelligence into computer-controlled machines such as robots is an analogy to the fundamental scientific aim to devise theories in a form that makes them reproducible. In essence, we transfer factual data and procedural theories into a computer such that the machine can carry out humanlike tasks. Agricultural operations will inevitably be automated to the extent of economical feasibility. Driving factors are the need for more precise application of materials to prevent environmental damage and increase profitability. Autonomous full-scale vehicle guidance research in agriculture is well represented in the literature. Excellent references to automated vehicle guidance research in Canada, Japan, Europe and the USA can be found in Wilson, (2000), Torii, (2000), Keicher and Seufert, (2000) and Reid, et al., (2000). Much agricultural robotics research has been performed in controlled environments such as robotic picking of cherry tomatoes (Kondo, et al., 1996a), cucumbers (Van Henten, et al., 2002), mushrooms (Reed, et al., 2001) and other fruits (Kondo, et al., 1996b). In horticulture, robots have been applied to citrus (Hannan, 2004) and apples (Bulanon, et al., 2001). Also, milking robots have had much attention particularly in the Netherlands (Rossing, 1997). Few journal articles are available regarding the development of Autonomous Robots for

Field Applications. A weed control robot was developed by Baerveldt and Astrand (1998), and

Bak and Jakobsen (2004) proposed a small field robot capable of traveling between crop rows to register the locations of crops and weeds using a camera and GPS receiver. If the robot is to be used solely for scouting, it can be as small as planet rovers (Biesiadecki et al., 2000, Kuroda, 2003). Gomide et al. (2003) used a radio-controlled robotic helicopter to cover a smaller area to improve the resolution, but it required a professionally skilled operator. To obtain detailed local crop state information, Field Robots are needed that can travel between crop rows and collect data in an autonomous fashion. There is much interest in the development of Field Robots in Europe as evidenced by Wageningen University in the Netherlands which organized a Field Robot competition in 2003 and 2004 where students, faculty and research institutions were represented (Van Straten, 2004). AgBo, as described in this paper, competed in the 2004 competition.

The emphasis in the development of autonomous Field Robots is currently on speed, energy efficiency, sensors for guidance, guidance accuracy and enabling technologies such as wireless communication and GPS. Although these activities are of scientific interest, the public acceptance of Robotic Farming will be greatly accelerated by focusing on 'bare bones' field robots that autonomously negotiate crop rows for under \$500 in material costs as described in this paper. The bare-bones robot could also serve as a standard research platform to develop robotic scouts and the focus could be directed to the development of small, precise and reliable sensors that give information about the status of the crop and the soil.

Secondly, there is a need to develop small-scale equivalents for current field operations such as robotic tillage, planting, cultivation, chemical application and potentially harvesting of row crops.

1) Robotic Crop and Soil scouting

Remote sensing has been used widely to collect overall information about the crop status as well as soil conditions (Dicker, 2002). While aerial photography can efficiently gather information from a large area, crop guided scouts, working in close proximity to the crop, can collect detail information about the crop and soil conditions. To date, research has been performed to measure crop stresses in corn, such as nitrogen stress using a tractor mounted imaging system (Noh, et al., 2003), water stress (Gomide, et al., 2003), weed detection (Cho, 2002) and disease detection (West, et al., 2003). All of these sensors approaches are too large to be directly applied to robotic application. An important problem in the Mid-West is insect activity detection such as the Western Corn Rootworm (WCR). Currently there are no alternatives to digging up roots and human damage assessment and hence, the development of a real-time WCR larvae detector would be of great importance.

Soil scouting is a similar operation where sensors can measure physical and chemical properties to optimize the crop growth and prevent adversary effects to the environment. To measure physical properties, such as density, texture, structure and compaction methods have been devised such as Mechanical (Adamchuk, 2001a, 2001b), Acoustic (Tekeste, 2001, Oelze, 2003) and Pneumatic (Clement, 2000). Oelze (2003) used acoustic backscatter as a method to determine the surface roughness, which may be an important parameter for runoff/erosion prediction. Chemical properties such as pH, moisture and nitrate content can be measured using near-infrared spectroscopy (Ehsani et al., 1999) as well as electrical resistivity (Banton, 1997).

2) Robotic Field Operations

A strong argument for replacing a large machine by a small fleet of robots is the reduced compaction potential. Currently primary tillage is practiced using highly powered tractors to

alleviate the compaction caused by the large machines themselves. By replacing the larger machines by a fleet of communicating autonomous robots, a major decrease in compaction and the need to alleviate it could be attained.

Apart from being able to work around the clock, robotic field operations can be more efficient than current operations. A striking example of this is the Micro-Spraying approach where minute amounts of chemical are used to directly target weed plants, in contrast to the current practice of treating the whole field with a 1% active ingredient water solution. In addition, in-row mechanical weed control using robots is being researched mainly in Europe. Robotic tillage operations may be implemented using acoustics as well (Abu-Hamdeh, 2004).

Assuming the total field area remains constant, a number of autonomous robots would have to deliver the same field capacity as a large machine. For instance, the amount of material being transported to and from the field in the form of seeds, fertilizers and harvested crop is not likely to change and quite a number of robots would be needed to transport it. Robotic equivalents for planters and chemical applicators can be developed but the sheer volume of material during harvesting might justify the conversion of current combine harvesters to be integrated into the robotic framework.

3) The Automated Farm

The lights-off factory, which was envisioned during the industrial automation era, never made it to fruition. Similarly, full-scale farm automation is doubtful to become a reality in the near future. It is more likely that a high degree of automation will be combined with manual tasks for operations that are uneconomical to automate. Although the holy grail of farm automation may never become reality, it is an ideal that can give direction to research.

The challenge in producing a highly automated farm operation is in the development of machinery, fitted with sensors and data communication capability. Furthermore, the machinery must be rugged enough to withstand outdoor influences, energy efficient to minimize battery charging time, reliable, low maintenance and safe. As evidenced by the robots described in this paper, most of these properties can be approached by producing robots from off-the-shelf components, combined with relatively simply guidance algorithms. GPS guided robots will benefit from the European Galileo project which is presumed to become functional in 2009 and deliver high positional accuracy for public use.

One of the most challenging problems lies in developing algorithms that optimize the functioning of a fleet of robots. Not only does this require intelligence in terms of object avoidance, cooperation and conflict resolving are important components as well. It might be feasible to treat the fleet of robots as a mechanical ecosystem where beneficial behaviors emerge automatically when the proper optimization functions are set and cooperative behavior is promoted.

AgBo

AgBo was developed as an industrial style robot for crop row applications (Figure 1).

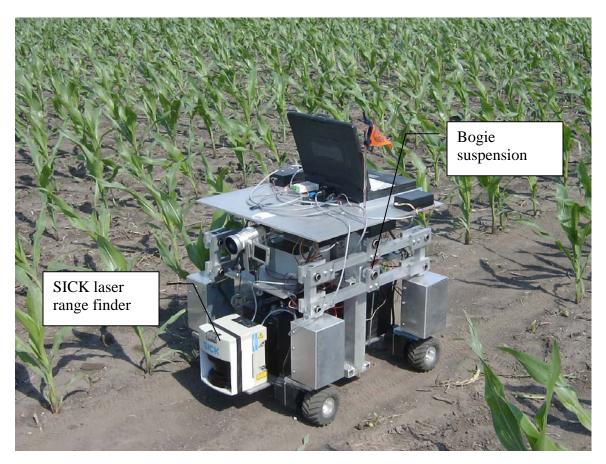


Figure 1. AgBo, a flexible, industrial style robot for row crop applications

Mechanical layout

The width of the robot was set to fit within a standard cornrow spacing of 75 cm and for simplicity of turning and cosmetic reasons, the length was chosen equal to the width. The total height was approx 80 cm. Although the majority of components was made out of aluminum, the total weight, including batteries, was approx. 100 kg.

AgBo was fitted with Bogie suspension (parallel linkage suspension on either side), which guarantees that all wheels are in contact with the ground at all times. In addition,

inclination control was implemented which allows the robot to tilt forward and backward (used to control the angle of attack of the laser guidance unit).

AgBo has four steering modes 1) Front Wheel steering (used in crop guidance), 2) All Wheel Steering (enables short radius turns), 3) Crabbing (moves robot laterally) and 4) Zero Radius Turn (spinning in place). The steering also correctly incorporates the Ackermann principle. Each wheel was fitted with 50W DC brushless gear motor for propulsion and a 20W DC gear motor for steering.

Electronic Layout

The electronic layout of AgBo is shown in Figure 2.

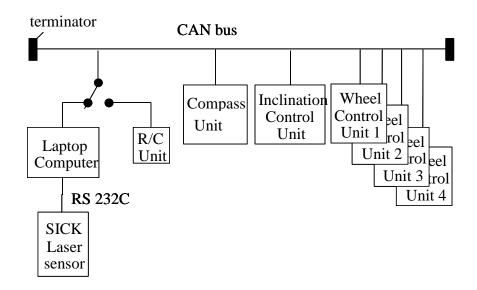


Figure 2. Diagram of AgBo's electronic control systems

Each wheel was controlled by a Wheel Control Unit, which contained a BasicAtom
microcontroller (ATOM PRO24-M, Basic Micro, Farmington Hills, MI) under control of a
dedicated MBasic program. A major advantage of the BasicAtom microcontroller is the
hardware PWM generators, which allow for reliable motor control. The function of the Wheel
Control Unit was to generate the appropriate PWM signal for the motors when a steering/driving

input is received from the main controller unit. In crop guidance mode, this steering input was transmitted by a laptop computer that interfaces with a SICK (LM291, SICK® AG, Duesseldorf, Germany) laser range finder. In Remote Control mode, these signals were generated by another BasicAtom microcontroller unit that interfaced with the Remote Control Receiver. An electronic compass (126703CL, Jameco Electronics, Belmont CA, www.jameco.com) was used for end-of-row turning. The laptop computer was used to interface with the SICK laser range finder as well as the Electronic Compass and to compute the appropriate steering and speed control message for the Wheel Control Units. The communication between the laptop computer and the SICK Laser Range finder was implemented using RS232C, and the communication with the electronic compass was implemented using a Serial Peripheral Interface (SPI) bus. All other communications were implemented using a Controller Area Network (CAN) bus (Etschberger, 2001). The programming language used for the guidance tasks was 'C'.

Guidance

The crop guidance functionality of the robot was based on a SICK laser range finder unit. This unit projects a 180-degree horizontal laser sheet and calculates the distance to any object in the field of view with an angular resolution of 0.5 degrees. Table 1 shows the specifications of this sensor.

Table 1. Specification of SICK laser scanner

			Range	Data	Transfer rate	_	
Туре	Scanning	Resolution/Accuracy	(10%	Interface		Power	Weight
Type	angle		`	1110011000		consumption	
			reflectivity)				
				RS232	9.6/19.2/38.4/500		
LMS291	180 °	10mm/±35mm	30m	20122		20W	4.5kg
				RS422	kb		

A simplified model of corn stalks was to regard them as perfectly cylindrical shapes, placed in rows at constant distances as shown in Figure 3. The laser scanner measures the shortest distance in 0.5-degree increments. To control the robot, information is needed regarding the left and right side nearest row. Data filtering was performed using the following steps:

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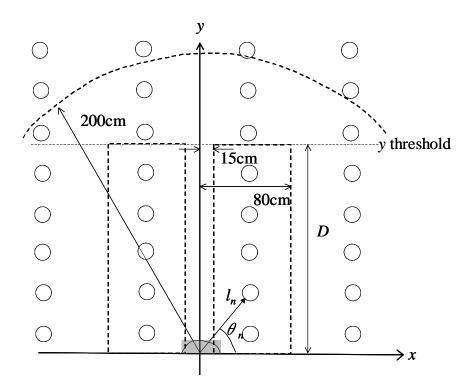
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- 1. Collect distances and associated angles from SICK laser scanner.
- 2. Convert cylindrical coordinates to Cartesian coordinates within 2 m radius.
- 183 3. Discard lateral coordinates outside 15 < |x| < 80 (this window was chosen arbitrarily)
- 4. Discard longitudinal coordinates larger than threshold D. This value is adaptive; D is 150cm
 during between-row guidance and 80cm during headland turns.



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Figure 3. Simplified model of corn stalks in the field

Between-the-row guidance

The between-row guidance control was based on the difference between the current heading and an aiming point, which was calculated using the filtered data from the SICK laser scanner. The aiming point was simply the mean value of the Cartesian coordinates of the corn stalks. A low pass filtering action was applied over time to compensate for the movement of corn stalks under high wind conditions.

End-of-row turning control

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The turning at the end of the row was performed using a series of steps as follows:

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- 198 1. Detect the end of row by observing loss of data from SICK range finder.
- 2. Continue moving forward using current heading for 10 seconds (chosen based on maximumtravel speed).
- 201 3. Perform zero radius turn through 180° using electronic compass.
- 4. Fine tune robot orientation with latest row using SICK range finder. Proper alignment was assumed when the average of the corn stalk coordinates (aiming point) is in the center of the detected coordinates.
 - 5. Move transversely (using crab steering) and stop when the robot is in line with the adjacent row using SICK laser sensor. As in step 4, proper alignment was assumed when the average of the corn stalk coordinates (aim point) is in the center of the detected coordinates.
- 208 6. Enter adjacent row.

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Figure 4 shows the end-of-row turning method of AgBo.

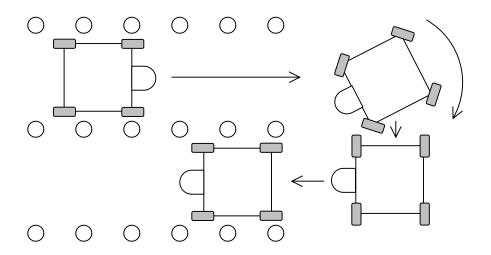


Figure 4. End-of-row turning sequence

AgTracker

AgTracker is a rugged, general-purpose robotic platform that was built with reliability, cost and simplicity in mind. The basic crop guidance functionality was implemented using a single BasicAtom microcontroller. This involved controlling the speed of the 2 motors (which subsumes skid steering), receive and process information from infrared sensors and the electronic compass, outputting data to a serial LCD unit as well as interfacing with a Remote Control Receiver in RC mode.



Figure 5. AgTracker, a simple, rugged, low-cost agricultural robotic platform

224 Mechanical layout

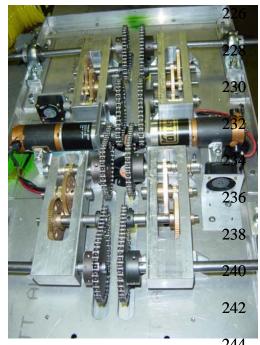


Figure 6. Mechanical layout of

AgTracker 246

AgTracker's drive motors are DC brushless High Torque types (Astroflight 940P Geared Motor). The motors have a continuous power output of 750 Watts and can be run on 12V or 24V. During operation, the motors heated up significantly and thus heat sinks and fans were added to limit this.

The output of the motors was geared down significantly using chains and gearboxes which limits the speed to approx 2 m/s. The complete drive train is shown in Figure 6.

Electronic layout

AgTracker's electronics layout is much simpler than AgBo's. The electronics were built around a single 40-pin BasicAtom module and no network was required. The advantage of the BasicAtom unit is its built-in hardware Pulse Width Modulation unit, which is very well suited to drive DC motors. To interface the microcontroller with the motors, motor controller boards were used (OSMC Power Unit, www.robot-power.com) To interface with the 8 infrared sensors and 2 ultrasonic sensors, a dedicated board was developed which multiplexed the sensors to the microcontroller unit. The ultrasonic sensors (134105CL, Jameco Electronics, Belmont CA, www.jameco.com) used analog output voltages, and were connected to Analog/Digital converter ports on the BasicAtom. The electronic compass (126703CL, Jameco Electronics, Belmont CA,

www.jameco.com) had a Serial Peripheral Interface (SPI) and output pulses that were counted using a pulse counting command in MBasic. A 20*4 serial LCD unit (LK204-25, Jameco Electronics, Belmont CA, www.jameco.com) was added to display the output of the sensors in real time. Figure 7 shows a diagram of AgTrackers electronic units.

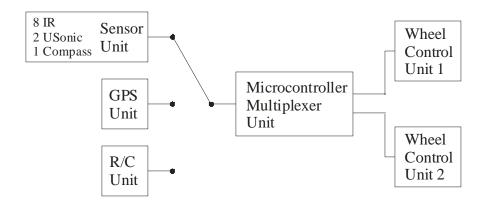


Figure 7. Diagram of AgTracker's electronic units with 1) Remote Control, 2) GPS and 3) Crop guidance modes

For the programming BasicAtom's MBasic language was used. This language is a modern Basic variety that supports compilation and allows for simple uploading of the compiled code into the microcontroller using a fast serial connection.

Crop guidance

For crop guidance, AgTracker uses an array of sensors for in row guidance and end-of-row turning (Figure 8). The crop guidance of the robot was performed by simply attempting to keep an equal distance from the corn stalks on the left and right. As a distance indicator, the average value of the infrared and ultrasonic sensors was used and outliers were removed using a median filter approach.

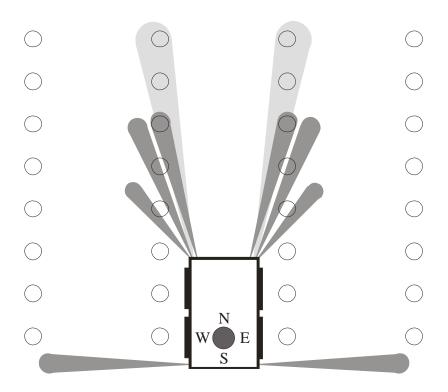


Figure 8. AgTracker's sensor arrangement with 2 ultrasonic sensors and 8 infrared sensors (6 long distance, 2 short distance)

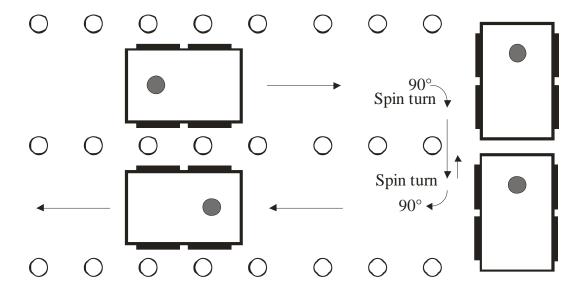
Between-the-row guidance

When the average left sensor output was higher (closer to stalks) than the average right sensor outputs, the right motors were decelerated which steers the robot to the right and vice versa. The amount of deceleration was proportional to the difference between the average left and right sensor outputs, a classical proportional/integrating action control approach. Constants for the proportional and integrating action were obtained by experimentation and observing the amount of sway in the crop rows.

End-of-row turning control

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- The end-of-row turning was accomplished using the following steps (Figure 9):
- 291 1. Detect the end of row by observing loss of data from infrared sensors.
- 292 2. Continue moving forward using current heading for 5 seconds (chosen based on maximum
- travel speed).
- 294 3. Perform zero radius turn through 90 degrees using electronic compass.
- 4. Move perpendicular to the crop rows until the rear sensors 'see' the previous crop row.
- 5. Reverse the robot through 10 cm (time based, about 1 sec in 75 cm rows)
- 297 6. Turn again in the same direction through 90 degrees using electronic compass.
- 298 7. Move forward into the new row.

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Figure 9. End-of-row turning sequence AgTracker

Conclusions

To investigate what type of robot is most suitable for field applications, two robots were built with differing philosophies. AgBo showed to be somewhat excessive in terms of capabilities and cost, estimated at \$7,000 material costs. The flexibility of the robot was not truly employed, since simple front wheel steering proved sufficient for between-row guidance. The SICK laser unit provided more information than was used, and significant low pass filtering was applied over time to compensate for wind induced lateral movement of corn stalks and to eliminate the influence of moving leaves. Turning at the end of the row was performed using the Spin Turn and Crab motion. The end-of-row turning method used a compass for two 90-degree turns and the SICK laser was used to precisely align the robot to enter the adjacent row. The four- wheel layout of AgBo necessitated the use of bogie suspension, which added significant weight. Also, the SICK laser application required tilt control, which added an additional tilt sensor and linear actuator. AgBo's wheels (10 cm diameter) proved too small for muddy conditions and even to overcome ruts in dry conditions. In the future, instead of wheels, small tracks may resolve this problem.

AgTracker (\$500 material costs) proved to be a very robust and effective field robot. Its larger wheels provided sufficient traction under any condition, and the skid steering principle (coupled wheels left and right) did eliminate the need for suspension. The sensor layout was cost effective and the combination of ultrasonic and optical sensors provided sufficient information for between-row guidance. The end of row turning method using the electronic compass was reliable and reproducible. The BasicAtom microcontroller showed capable of real time communication with sensors, output to LCD display and motor control.

In conclusion, AgTracker was found to be the most promising agricultural robot. It's performance to price ratio was superior, its fewer parts proved more reliable and like AgBo it negotiated corn crop rows autonomously without damaging any plants. In addition, its physical layout made it more rugged and easier to mount sensors and actuators for future development. **References:** Abu-Hamdeh, N.H. 2004. The disturbance of topsoil using ultrasonic waves. Soil & Tillage Research 75:87–92. Adamchuk, V.I., M. T. Morgan, and H. Sumali. 2001a. Application of a strain gauge array to estimate soil mechanical impedance on-the-go. Trans. ASAE 44(6): 1377-1383. Adamchuk, V.I., M.T. Morgan, and H. Sumali. 2001b. Mapping of spatial and vertical variation of soil mechanical resistance using a linear pressure model. ASAE Paper No. 01-1019. St. Joseph, Mich.: ASAE. Baerveldt, A., J., B., Astrand. 1998. Vision-guided mechanical weed-control. Halmstad University. Available at: http://www.hh.se/staff/bjorn/mech-weed/. Accessed 21 Oct 2004. Bak, T., H., Jakobsen. 2004. Agricultural robotic platform with four wheel steering for weed detection. Biosystems Engineering 87(2): 125-136.

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