replacement at this time. Mechanization practices are very dependent on a portable fuel supply for tractors and other power units.

References


3.2. Precision Farming

_H. Auernhammer and J. K. Schueller_

3.2.1. Introduction

Crops and soils are not uniform but vary according to spatial location. Large-scale nonuniformities have long been countered with different cropping practices in different
regions. But precision farming responds to spatial variability within individual fields or orchards. This leads to a more cost-effective and environmentally friendly agriculture by

- Increasing food production
- Optimizing the use of restricted resources of water and land
- Reducing environmental pollution
- Engaging the efficiency capabilities of intelligent farm machinery
- Improving the performance of farm management

Precision farming concepts include:

- More accurate farm work by better adjustments of settings and by improved monitoring and control mechanisms
- Localized fertilizing on demand in accordance with the variability of soils, nutrients, available water, and plant growth
- Weed and pest control by localized crop production needs
- Automated information acquisition and information management with well-structured databases, geographic information systems (GIS), highly sophisticated decision-support models, and expert-knowledge systems in integrated systems connected by standardized communications links (Fig. 3.1).

Precision farming is not a fixed system, but rather a set of general concepts that may have different physical realizations with

![Figure 3.1. An integrated precision farming system.](image)
Table 3.7. Positioning accuracy requirements

<table>
<thead>
<tr>
<th>Required Accuracy</th>
<th>Task</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>±10 m</td>
<td>Navigation</td>
<td>Targeting of fields (machinery ring, contractor)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Targeting of storage area (forestry)</td>
</tr>
<tr>
<td>±1 m</td>
<td>Job execution</td>
<td>Local field operations such as yield monitoring, fertilizing, plant protection, soil sampling, action in protected areas</td>
</tr>
<tr>
<td></td>
<td>Information</td>
<td>Automated data acquisition</td>
</tr>
<tr>
<td></td>
<td>Documentation</td>
<td></td>
</tr>
<tr>
<td>±10 cm</td>
<td>Vehicle guidance</td>
<td>Gap and overlap control (fertilizing, spraying)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Harvesting without skips</td>
</tr>
<tr>
<td>±1 cm</td>
<td>Implement (tool) guidance</td>
<td>Mechanical weed control</td>
</tr>
</tbody>
</table>

- Different soil types under different climate conditions
- Different farm management systems and production levels
- Different mechanization solutions

3.2.2. Positioning in Precision Farming

Positioning is the key element in many precision farming systems. In most cases x–y (longitude and latitude) coordinates are sufficient. For some cases and for more sophisticated requirements, z (elevation) may be of interest. A categorization of accuracy requirements into four different classes can be seen in Table 3.7.

Satellite Navigation Systems

With the installation of satellite navigation systems during the late 1980s, military and civilian industries acquired access to worldwide cost-free location data available continuously independent of daylight and weather conditions. These systems often are generically termed GPS after the most popular system.

Components and Method of Operation

The two currently available systems, GPS (United States) and GLONASS (Russia) have similar characteristics (Table 3.8).

Table 3.8. Configurations of GPS and GLONASS

<table>
<thead>
<tr>
<th></th>
<th>GPS-NAVSTAR</th>
<th>GLONASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Global Positioning System—NAVigation System by Time and Range</td>
<td>Global NAVigation Satellite System</td>
</tr>
<tr>
<td>Ownership</td>
<td>USA: Department of Defense</td>
<td>Russia: Department of Defense</td>
</tr>
<tr>
<td>Satellites</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Orbits</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Altitude (km)</td>
<td>20,183</td>
<td>19,100</td>
</tr>
<tr>
<td>Coordinate system</td>
<td>WGS84</td>
<td>SGS85</td>
</tr>
<tr>
<td>Approximate accuracy</td>
<td>100(^*) for civilians (2 drms) (m)</td>
<td>35</td>
</tr>
</tbody>
</table>

\(^*\) With Selective Availability intentional degradation.
GPS and GLONASS each consist of three segments (Fig. 3.2):

- The monitoring and control segment, which maintains the overall control of the system and is operated secretly by the system owner.
- The space segment consisting of positioning satellites (currently 24) with a lifetime of up to 7 years in "blocks" of equal configuration and performance.
- The user segment on land, at sea, and in the air with an unrestricted number of receivers.

Location is determined in each individual GPS or GLONASS receiver based upon at least three satellite signals (satellite position and time of signal generation). The location of the receiver is determined by the known satellite locations and the measurements of the ranges between the satellites and the receiver.

GPS and GLONASS have inaccuracies that depend upon atmospheric effects and the instantaneous geometric configurations of the satellites. In addition, the owner of GPS purposely degrades the civilian accuracy to 100 m, which is insufficient for agriculture. This inaccuracy must be corrected for GPS to be useful.

**Differential Corrections**

The accuracy of GPS location sensing can be improved by using an addition receiver at a fixed known position (e.g., the DGPS base station in Fig. 3.2). The additional receiver compares the GPS indication of its position to its known location to determine the instantaneous magnitude and direction of the GPS error. Assuming the same error...
Table 3.9. Correction methods and agricultural operations suitability

<table>
<thead>
<tr>
<th>Method</th>
<th>Mapping Operations</th>
<th>Control Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Own base station</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Commercial correction</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Post-processing</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

is present for the receiver at the unknown location of the moving farm equipment, the GPS indication of that receiver can be corrected easily for the error. Different methods can be used for correction (Table 3.9).

Real-time correction signals are necessary for operations in which agricultural equipment is controlled based upon position, such as fertilizer or pesticide application. The GPS error correction is transmitted from the stationary receiver to the mobile (rover) receiver on the agricultural equipment. The correction can be supplied by the rover user's own base station, although it should be close to the rover due to governmental restrictions on the power of private radio links. Alternatively, a commercial or governmental correction service may be used. Less financial investment and user maintenance is required with a correction service, although there may be a usage charge from the correction provider.

Postprocessing corrects the position data after the data has been collected and transferred to an office computer. No radio link is needed, and higher accuracy might be achievable. However, because accurate position information is not available until after the operation, control operations cannot use this technology. In addition, corrections must be obtained and used to process the uncorrected location data.

Other Location Systems

Other nonsatellite location-sensing systems may be of regional or farm-specific interest (Table 3.10).

Due to the large investment in sender installations, maintenance requirements, and the fulfillment of legal constraints, these positioning systems are concentrated in small areas or fulfill specific purposes in which they are competitive with satellite systems.

3.2.3. Concepts of Precision Farming Systems and Required System Elements

Precision farming is based on mapping systems, on real-time sensor–actuator systems, or on combinations of the two.

Table 3.10. Examples of nonsatellite location systems

<table>
<thead>
<tr>
<th></th>
<th>Infrared</th>
<th>Beacon</th>
<th>Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rover equipment</td>
<td>Sender/receiver</td>
<td>Receiver</td>
<td>Receiver</td>
</tr>
<tr>
<td>Fixed equipment</td>
<td>Reflectors</td>
<td>Senders</td>
<td>Commercial sender network</td>
</tr>
<tr>
<td>Range (km)</td>
<td>&lt;5</td>
<td>&lt;600</td>
<td>&lt;400</td>
</tr>
<tr>
<td>Accuracy</td>
<td>10–20 cm</td>
<td>1–3 m</td>
<td>20–30 cm</td>
</tr>
<tr>
<td>Approximate 1997 price per mobile unit (US$)</td>
<td>5000</td>
<td>1500</td>
<td>4000</td>
</tr>
</tbody>
</table>
Map-Based Systems

Map-based systems use GPS or other locator systems to establish a geographic basis for precision farming (Fig. 3.3). Components of map-based systems include:
- Locators to establish equipment position
- Sensors for yield and soil measurements
- Mapping software with color display and printing capabilities
- Controllers for map-based applications
- Actuators to perform the control

Map-based systems allow information to be gathered from various automatic and manual sources. Then a desired control map can be generated to guide such field operations as variable irrigation, fertilization, or pesticide application.

Real-Time Systems

These systems do not require locators or mapping software and hardware. The relevant quantity is sensed and then an appropriate action is immediately taken. Examples include herbicide application based upon sensed organic matter and anhydrous ammonia application in growing maize (corn) based upon sensed soil nitrate level.

The primary limitation of real-time systems is that only the current sensor data can be used. For example, soil-type information is not available in the previous herbicide or anhydrous ammonia examples. Prior crop-yield data also are not available.
Real-Time Systems with Maps

The most sophisticated systems combine the capabilities of map-based and real-time systems. Maps of yields, soil types, and nutrients can be used with real-time sensors of plant growth, soil moisture, and weed infestation to control field operations. Because such systems require all the components listed previously, they are complex and expensive. But they allow the optimization of the field operations. Intelligent decision software that decides the proper action based upon map and sensor data in real time is crucial.

3.2.4. Yield Mapping

The main target of agriculture is the production of crop yield. The farmer is therefore very interested in knowing yields. Yield measurement documents the result of the previous farm activities and can be used to plan for the coming crop. Components for most yield-mapping systems (e.g., Fig. 3.4) include:

- Yield sensor (and moisture sensor)
- Location-sensing system (usually GPS)
- Working-width sensor (or DGPS with decimeter accuracy)
- Monitoring and data-storage unit
- Data transfer to office computer
- Mapping software on the office computer

Grain Combine Harvester Systems

For grain measurement, on-the-go sensors are available to detect either the volume flow or the mass flow. The sensors usually are installed near the top of the clean grain
elevator and are approximated as having a 12- to 15-second time lag between when the
grain is cut and the flow sensed. Several sensors are available (Fig. 3.5).

Depending on the measurement principle, the accuracy of yield sensors is influenced
by factors such as moisture, density, throughput, elevator speed, and inclination. Each
sensor therefore has its own accuracy under particular conditions (Table 3.11).

Calibration of the sensor is crucial and should be done frequently. Feedback cali-
bration using field-transport wagons with weighing capabilities or scale measure-
ments will improve the accuracy.

Other Continuous Crops

Yield sensors are in various stages of development and commercialization for many
crops.

- Sugar-beet and potato harvesters may use belt weighing sensors (Fig. 3.6). Accu-
  racy is influenced by heavy vibrations during transport and by dirt in these root
crops.
- Sugar-cane harvesters similarly measure the mass flowing across a conveyor portion.
- Forage harvesters, mainly choppers, balers, and self-loading trailers, have a through-
  put of high-moisture material. High accuracy therefore also requires real-time mois-
ture sensing. Available systems use various sensor systems (Fig. 3.7).
- Cotton yield may be measured by passing the picked bolls through a light beam,
  against an instrumented plate, or by accurately measuring the change in weight of
  the harvester’s storage basket.
Table 3.11. Accuracy of grain yield sensors

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Measurement Deviations in 1 s (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flat Surface</td>
</tr>
<tr>
<td>Yield-O-Meter</td>
<td></td>
</tr>
<tr>
<td>(Class, D)</td>
<td>Volume flow</td>
</tr>
<tr>
<td>CERES 2 (RDS, UK)</td>
<td>Volume flow</td>
</tr>
<tr>
<td>Flowcontrol (MF, DK)</td>
<td>Mass flow</td>
</tr>
<tr>
<td>Yield Monitor (Ag-Leader, USA)</td>
<td>Mass flow force</td>
</tr>
</tbody>
</table>

Note: Results of tests conducted at the Technical University of Munich.

- Other crops may be measured in similar manners, using existing sensors from the more popular crops or by developing new sensors. Volume can be measured by having the moving crop interrupt light beams or by a positive-displacement metering device. Mass can be measured by the force from a momentum change, by radiation absorbance, or by weight in a transport or storage component.

Figure 3.6. Fig. Sugar beet yield monitoring equipment setup and connection diagram (based on Walter, et al.).
Non-Continuous Yield

Some harvesting methods (for example, hay bales or fruit bins) will result in discrete units of yield at particular points rather than continuous crop output. If the bales or bins can be assumed to have an equal amount of crop, their positions are simply recorded. The density of position marks on a map indicates yield. If the assumption is invalid or better accuracy is required, the weight of each bale or bin is recorded through the use of load cells, strain gages, or hydraulic pressure on the loader or transport equipment.

Data Storage and Mapping

Signals from all sensors (continuous-yield, moisture, location, working-width) are processed to give yield per area in short-period cycles (usually once per second) and stored in an on-board controller. Signalling to the driver is necessary to monitor continued error-free functioning of the sensors and to show the actual situation of the work.

Data transfer to the on-farm office computer can use chip cards, PCMCIA cards, or radio links. Besides yield and positioning data, other information about the harvested plots may be added later for farm management.

Mapping programs in the office computer then can produce tracking maps and yield maps: Tracking maps show the work sequence and the accuracy of location sensing and can be further analyzed for task times (Fig. 3.8). Yield maps can be established using either grid or contour mapping. Both types present similar information, and the choice may depend upon the user.
Yield maps show the large-scale variations in a field (Fig. 3.9). To understand the reality of a certain plot, several (perhaps at least three) consecutive yield mappings are necessary (Fig. 3.10). Strong correlations (perhaps 0.7–0.9) between different crop years confirm highly stable yield patterns.

3.2.5. Soil and Weed Mapping

Soil mapping for variable fertilizer application and weed mapping for pesticide application can be part of a complete precision-farming system.

Soil Sampling

Soil sampling may be done using different strategies, such as random, aligned, zoned, and repetitive.

- Random soil sampling involves choosing sampling points at random within a field or a portion of a field. Often, a field is divided into a grid and a random sample is taken within each grid square. Random sampling minimizes some of the systematic errors possible in sampling.

- Aligned sampling takes samples on a systematic grid in the field. Aligned sampling minimizes the maximum distance to sample locations within a field and has simplifying advantages during some interpolations and other analyses. But it is susceptible to systematic errors, such as being confounded with natural or cultural patterns.

- Zoned sampling can be done after stable yield and soil patterns are established. Within the zones of uniform yields and soils, sampling is done randomly at a lower
density. This reduces the number of needed samples and the total costs of soil sampling by assuming that the soil properties follow the zone boundaries.

- Repetitive soil sampling tries to monitor the changes of soil nutrients over time. The sample location is accurately determined with DGPS and revisited during subsequent samplings in other years. The original locations of sampling may have been determined by one of the other methods.

**Weed Mapping**

Weed mapping is in an earlier state of development than crop yield or soil mapping. The following types of systems (Fig. 3.11) can be used:

- Manual mapping uses the detection of weed infestations by people combined with precise DGPS location to generate maps. Such mapping only locates areas of heavy infestation for later pesticide application using spot sprayers.
- Plant-coverage systems detect the overall plant coverage of the soil and distinguish between plant coverage without weeds and plant coverage with additional weeds or between fallow fields without weeds and fallow fields with weeds. Because the sensor measures only the amount of green plant, increased crop may be falsely sensed as increased weeds.
- Image processing analyzes images on the basis of size, shape, color, or location and transmits the location and type of weed or crop. Components of a sample
system include a CCD camera, high-speed image analyzer, database with image information, controller, and sprayer actuator. Such a system is more complex and costly but will distinguish between crop and weeds if performing properly.

**Remote Sensing**

Remote sensing uses overhead images of a field or farm to indicate weed infestations or crop health. The images usually are acquired from satellites, airplanes, or remotely piloted vehicles. The presence of weeds between crop plants or rows of plants may be detected, or changes in the crop health, such as size, shape, maturity stage, or color, may be determined to indicate variations in insects, fungal infections, salinity, drainage, or other problems. Remote sensing can use single or multiple visible, infrared, or radar frequencies. Analyses often take the relative reflectance of solar wavelengths for differentiation (Fig. 3.12). Spot sprayers that turn on and off, or vary application rate, then may be programmed to spray according to the remote-sensing maps.

**3.2.6. Control of Field Operations**

Yield-, crop-, soil-, or pest-mapping indicates nonuniformities. The farmer may use those maps to develop understanding or make decisions. Often those decisions will be to perform field operations in a manner varied to correspond to those nonuniformities. Controlling fertilization, pesticide application, tillage, planting, or irrigation is a common part of precision farming. Fertilizer and pesticide application have seen the most
common implementations of precision control, because suitable equipment is available and nutrients and chemicals should only be applied as needed for both economic and environmental reasons.

**Requirements and System Components**

Field operation control requires an accurate real-time locator to indicate the equipment's position in the field, a map of the designed operation setpoints in a control computer, and an actuator on the equipment that can implement the controller’s commands. The location must be accurate and the dynamics of the equipment must be compensated for so that the exact action occurs where it is desired.

**Fertilization**

The application rate of granular fertilizers (and similar materials such as lime) usually is varied by a microprocessor controlling hydraulics that actuate a variable-speed metering wheel, a variable-position gate, or a variable-speed chain conveyor. If the mixture of the nutrients is to be varied as well as the rate, multiple product bins and delivery systems are needed (Fig. 3.13) on the applicator, and the material-handling system must be able to efficiently refill the multiple bins.

Liquid fertilizer may be applied in a similarly variable manner. Variable rates can be achieved by varying either pump speeds, recirculation valve flow, or flow at individual nozzles through a variable pressure drop before the nozzle or turning the nozzle flow on and off with pulse-width modulation.
Both granular and liquid applicators must be designed for adequate dynamic response and to make sure the spread pattern is satisfactory at varying application rates. Variable mixture applicators can be designed to mix near nutrient storage, although then there will be significant time delays for changed mixtures to be transmitted to the soil, or mix near the nozzles or other distribution device, although then care must be taken to get complete mixture and additional hoses or conveyors are required.

**Pesticide Application**

Liquid pesticides may be applied either by varying the amount of premixed pesticide-carrier liquid or by injecting a variable amount of pesticide into a relatively constant flow of carrier (Fig. 3.14). Many of the same design concerns for fertilizer applicators apply to pesticide applicators, whether liquid or granular.

**Other Controller Operations**

Planting or seeding also may be controlled variably to achieve precision farming goals by varying variety, often in response to soil type or topographic position; population, in response to varying productivity potential; or depth, to find sufficient moisture.

Depth would be determined by real-time sensing while variety and population sensing would be more likely to be map-based.

Irrigation may be variably controlled by either maintaining full flow but changing the length of time of application, or maintaining length of time of application while reducing water flowrate.
Tillage and landforming operations also may be controlled in either real-time or map-based manners.

3.2.7. Information Management

Sophisticated precision farming integrates a variety of computerized tools. Safe and reliable information transfer among all these tools needs standardized communication lines, standardized interfaces, and powerful software tools.

BUS Systems on Mobile Equipment

The advancements in agricultural electronics have led to a wide variety of controllers and electronic components. For example, fast and reliable communications are required between a tractor and the various implements attached to it (Fig. 3.15).

Compatibility is insured by communications standards. Two such standards, both using Controller Area Network (CAN), are as follows:

- The German LBS (Landwirtschaftliches BUS-System [Agricultural BUS-System]), codified as DIN 9684/2-5, is based on the 11-bit identifier of CAN V2.0A. It connects a maximum of 16 controllers, including the user terminal.
- The ISO 11783 standard works with the extended identifier of CAN V2.0B and is able to connect a maximum of 32 controllers. Its detailed structure using the ISO/OSI layer model and an additional six parts of special definitions tries to cover all requests of agricultural tractor-implement combinations.
Compatibility between both standards is achieved in the overall function and in the physical layer.

**Data Transfer to and from Farm Management**

Complete precision systems are centered in the office computer. All information goes to and from this main unit. Yield and soil maps are displayed on it and desired control maps are generated on it. Data transfer can be done using human media transfer with chipcards or PCMCIA cards, or by bringing a portable computer to the office computer. Alternatively, radio links can be used. GPS differential corrections, remote sensing data, soil test laboratory results, and so forth can be obtained from e-mail or the Internet.

**Data Management and Geographic Information Systems**

The capabilities of computerized data gathering generate large volumes of data, which must be handled efficiently. Because precision farming data has position attributes, it usually is manipulated by geographic information systems. Such a system's representation of a field may contain layers of

- Soil type and topography
- pH and cation exchange capacity (CEC)
- Crop yields
- Weed maps
- Fertilizer and pesticide application maps
Compatibility between both standards is achieved in the overall function and in the physical layer.

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- Soil type and topography
- pH and cation exchange capacity (CEC)
- Crop yields
- Weed maps
- Fertilizer and pesticide application maps
These various layers can be analyzed or combined manually or automatically to generate a control map for field operations (Fig. 3.16).

**Decision-support Systems**

The control maps for map-based field operations must be generated according some sort of decision system. Even if the decisions are made manually, the volumes of data and the complexities of crop production favor a decision-support system. For example, the phosphorous application rates in Fig. 3.16 were calculated by a computer program for each area to remedy deficiencies and to provide sufficient nutrients for a crop of wheat. The input data included soil type, soil-test data, and yield potential based upon past yields.

The decision-making computer program can be deterministic, based upon rules or formulas. The computer determines the correct control action for each small part of the field or orchard based upon the geographic information system’s data layers and the guidelines written into the decisionmaking program. It also can be stochastic, based upon computer simulations. Validated crop-growth models are run with different field-operation control strategies for representative weather scenarios in each field portion. The strategy with the maximum economic return and acceptable risk is used to establish the field operation control map.

Real-time systems must have control algorithms that immediately vary the actuator to the appropriate output based upon the sensor data.
Figure 3.16. Layers for the generation of application maps.

References