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Map-Based Control for Autonomous Tractors

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Abstract: An autonomous tractor requires not only automatic steering (automatic guidance) but also automated control of tractor functions and implement operations. Examples of tractor functions include engine throttle, transmission speed, and 3-point hitch position. Implement operations include tillage, planting, and cultivating. This article provides an overview of a map-based methodology used for the implementation of autonomous field operations of agricultural tractors. The procedure for developing autonomous field operation maps were presented, and several important issues in the implementation of map-based autonomous operations were discussed. These issues included combining field operation maps, position offset, and real-time sensing and update of field operation maps.

Keywords: Tractor, Autonomous Vehicle, Automatic Guidance, Map-Based Control

Introduction

The potential benefits of automated agricultural tractors include increased productivity, increased application accuracy, and enhanced operation safety (Reid, et al., 2000). As such, automation of agricultural tractors has been a dream for many years. Two stages of development in tractor automation are anticipated. The first stage is the automatic guidance, or automatic steering of tractors. Automatic guidance of the tractor can free the operator from the steering task but he/she still needs to perform other tractor operations. The second stage of development will be the automatic control of tractor functions and implement operations. Examples of tractor functions are engine throttle, transmission speed, and 3-point high position. Implement operations include tillage, planting, and cultivating. When these two levels of automation are integrated, the fully autonomous tractors can become a reality.

Automatic guidance of agricultural tractors has been studied over the past several decades. Various guidance technologies, including mechanical guidance, machine-vision guidance, radio navigation, and ultrasonic guidance, have been investigated (Reid, et al., 2000; Tillett, 1991). In recent years, high-accuracy Global Positioning System (GPS) receivers are widely used as guidance sensors (Bell, 2000; Larsen, et al., 1994; Yukumoto, et al., 2000). Using an absolute positioning system, GPS-based guidance technology has the potential to achieve completely autonomous navigation. On the other hand, machine-vision-based guidance has the advantage of using local features to fine-tune the tractor navigation course. Both GPS-based and machine-vision-based guidance technologies possess the technological features and characteristics most closely resembling those possessed by human operator, and thus have great potential for implementation of a tractor guidance system (Wilson, 2000). A more robust tractor guidance system can be achieved by integrating GPS, Fiber Optical Gyroscope (FOG), machine-vision, and potentially other sensors using sensor-fusion technology (Zhang, 1999).

The next level of tractor automation, i.e., the automatic control of tractor functions and implement operations, is beginning to emerge as the concept of precision farming becomes widely accepted. The goal of precision farming is to apply chemicals, water seeds, or other inputs to fields in quantities sufficient to meet the demands of the crop growing on each square meter of the field in a timely manner, with no excess (Rawlins, 1996). As such, many field operations such as tillage, planting, fertilizer and chemical applications, need to be site-specific based on the spatial variability of crop production factors (e.g., soil, water, crop variety). It becomes essential to automate

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site-specific field operations because otherwise to manually perform these operations is extremely difficult, if not impossible. Although commercially available variable-rate systems can automatically adjust the rates on-the-go, they are not able to control the associated tractor functions (e.g., tractor travel speed in a variable-rate seeding system), and therefore, the operations may not be optimum.

A fully autonomous tractor should have both the automatic steering and the automatic control of tractor functions and implement operations to perform autonomous field operations. A limited number of researchers have dealt with the issues related to autonomous vehicle systems (Reid, et al., 2000). However, the University of Illinois researchers have developed and demonstrated a prototyped autonomous tractor that can perform autonomous planting and field cultivation. A real-time kinematic (RTK) GPS and a FOG were used to provide tractor position, speed, and heading. In addition to the steering control, engine throttle, transmission speed, and 3-point hitch position were automatically controlled via a Controlled Area Network (CAN) bus based on field locations. Both the desired tractor path and the tractor function (e.g., travel speed, hitch position) were developed off-line and then loaded into the navigation computer before the field operation started.

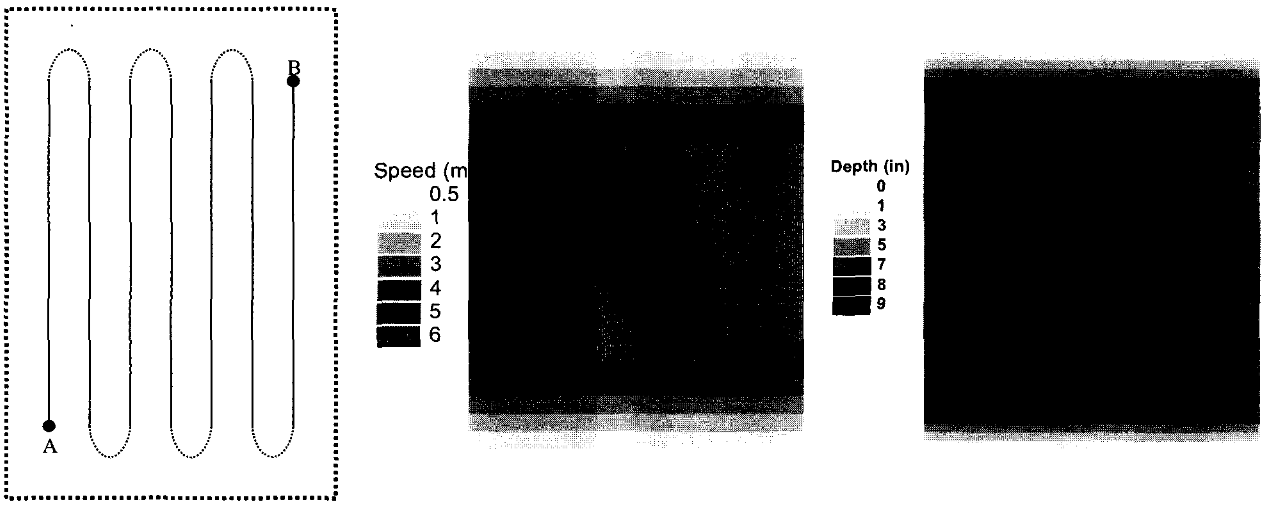
This article gives an overview of this map-based methodology used for the implementation of autonomous field operations of agricultural tractors.

Map-Based Operations

1. Field Operation Maps

An autonomous field operation of a tractor can be accomplished by providing the tractor with a sequence of instructions that both guide the tractor movement in the field and control the concurrent tractor functions and implement operations. Each instruction contains a location in the field (x_i, y_i), and k desirable control values (z_{1i}, z_{2i}, ..., z_{ki}), at that location. Examples of control variables include steering wheel angle, tractor travel speed, and implement depth controlled by the 3-point hitch position. Since each control variable is associated with a field location at any time, the time sequence of a control variable can be viewed as a 2-D map called a field operation map. A collection of field operation maps defines an autonomous field operation. An example of autonomous tillage operation is shown in Fig. 1.

Fig. 1-a defines the desired tractor path in the field. The desired path is made of parallel straight lines within the field and turning curves at the end of the field. This type of path is typical for many other field operations as well, assuming the field is a rectangle with no obstacles (e.g., waterways, trees) inside the field. The parallel straight lines are pre-defined before



(a) (b) (c)

Fig. 1 An example autonomous tillage operation is represented by a collection of field operation maps, which include (a). a map of the desired path; (b). a map of the desired tractor speed; and (c). a map of the desired tillage depth.

the operation starts, but the turning curves can be dynamically created based on the actual tractor positions just before the turnings. Fig. 1-b defines the desired tractor speed zones. In the center of the field, the tractor should travel at a constant high speed (2.7 m/s, or 6 mph, in the example). When the tractor approaches the end of the field, it should gradually slow down to a near-zero speed. Fig. 1-c defines the desired tillage depth with 3 normal tillage zones in the center of the field (depths=0.178, 0.203, 0.229m, or 7,8,9 inches, respectively), 2 transition zones close to the edge of the field (depths=0.025, 0.076, 0.127m, or 1,3,5 inches, respectively), and 2 end zones without tillage (depth=0m). The different tillage depth requirements can be considered to match the different soil types inside the field.

2. Representation of Field Operation Maps

A geographic information system (GIS) is a computerized system designed to store, process, and analyze spatial data. Since a field operation map is essentially a GIS map, the concept and functionality of the GIS can be applied to handle the field operation map.

Geographic features such as point, line, and area can be represented in a GIS by either a vector data model or a raster data model. A vector data model uses a single (x, y) coordinate to represent each location. Thus, a point is stored as a single coordinate; a line is stored as a series of ordered coordinates; and an area is stored as a series of line segments that enclose the area. In the raster data model, each location is represented as a cell. Each cell is assigned a value that represents the geographic feature contained within the cell. The vector data model can accurately represent the geographic features, but the accuracy of feature representation in the raster data model is dependent on the cell size. For example, a field boundary can be represented either by a vector data model with lines (Fig. 2-a), or by a raster data model with cells (Fig. 2-b). In general, the raster data model is computationally easy but requires large storage space. On the other hand, the vector data model requires small storage space but is computationally intensive (Evans et al., 1995).

A field operation map can be represented by either the vector data model or the raster data model. If the spatial accuracy of the feature is concerned, the vector data model should be used. For example, the desired operation path (Fig. 1-a) should be represented as points or lines using the vector data model, because the positions of these points (lines) are critical to the required guidance accuracy. On the other hand, many existing data sources provide raster-based data because they are compatible with many digital image processing systems. Unless spatial accuracy is a problem, the raster data model is preferred because of its simplicity.

3. Creation of Field Operation Maps

Field operation maps for an autonomous tractor are often created off-line using a GIS, and then loaded into the navigation computer before the operation starts. However, these maps may need to be updated during the operation based on the real-time sensing data.

The process to generate field operation maps has been discussed in Earl et al. (2000). This process typically involves an asset survey, mapping and interpretation of individual transient data sets, combinations of different transient data sets, and creation of field operation maps. The asset survey is to obtain the permanent spatial attributes of the field that are pertinent to field operations. Typical examples of these data include field boundaries and topography. Transient data represent those attributes of a field that changes during the growing season. Typical examples of these data include crop and soil nutrient status. Transient data are often sampled at the selected locations in a field and interpolated onto a regular grid. Maps of multiple transient data sets, together with the permanent spatial attributes of the field, can be used to develop the field operation maps such as a variable-depth tillage map, or a variable-rate seeding map. Both GIS and decision support systems are important tools for developing these operation maps.

In some cases, the pre-loaded operation maps may need to be adjusted during the field operation according to locally sensed conditions. In a real-time sensing and control system, the operation maps may not be necessary at all. For example, a machine-vision guidance system could obtain the guidance information from the real-time processing of images, and thus may not require a pre-loaded global navigation map. However, the development of appropriate sensors for real-time sensing and control is still lacking, and the complete autonomous operation based on the real-time sensing will not happen soon. As such, map-based autonomous operations will be the primary format for autonomous tractors.

Implementation of Map-Based Operations

This section discusses several important issues related to the implementation of map-based autonomous operations.

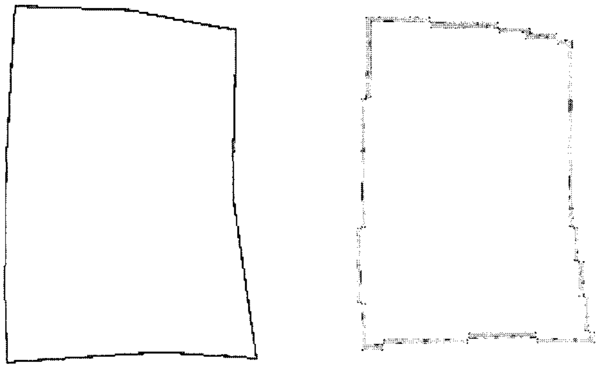
1. Combining Field Operation Maps

At any given field location, the navigation computer needs to acquire a set of instructions that both guide the tractor movement and control the concurrent tractor functions and implement operations. If all the field operation maps (including a map of the desired path for steering control) are pre-loaded into the navigation computer before the field operation starts, the navigation computer can simply retrieve each individual instruction from the corresponding field operation map and execute these instructions in a serial or parallel mode.

However, if two or more field operation maps are stored in raster data format, they may be combined into a single control map and loaded into the navigation computer. This approach will not only reduce the map size but also increase the processing (retrieval of instructions) speed. In many cases, processing speed is critical for an autonomous field operation.

When two or more raster-based field operation maps have the same cell size, the cell value of the combined control map is the combination of cell values of each individual operation maps at the corresponding cell locations according to a pre-defined encoding format. However, when field operation maps have different cell sizes, they have to be first converted into maps with the same cell size, typically the smallest among all the sizes, and then to be combined. Theoretically, the optimum cell size depends on the maximum accuracy requirement of all the field operations involved. Practical considerations in selecting a minimum cell size include the availability and quality of the (sample) data used for generating the operation maps, applicator response speed, machine width, and the accuracy of the positioning system (Han et. al., 1994).

Fig. 3 shows an example of combined control map from Fig. 2-b and Fig. 2-c. The combined control map has 19 distinct control zones, as compared with distinct control zones in each of the individual operation map.



(a) (b)

Fig. 2 A field boundary is represented by (a). the vector data model; and (b). the raster data model.

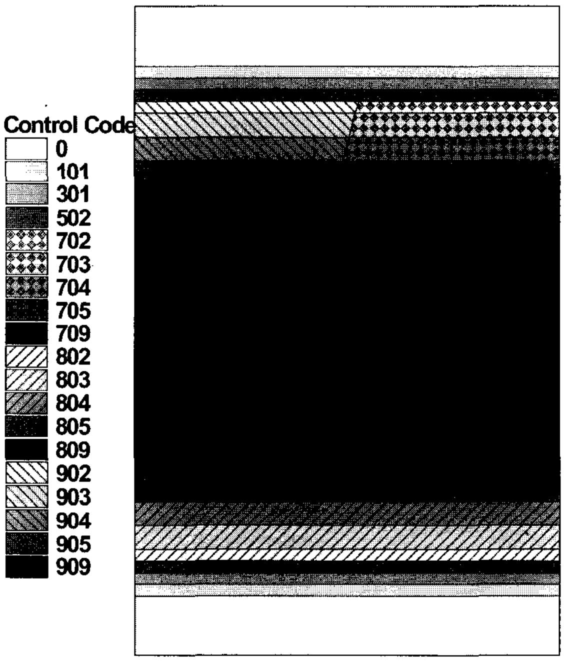


Fig 3. An example control map by combining the map of the desired tractor speed (Fig. 1b) and the map of the desired tillage depth (Fig. 1c).

2. Position Offset

Each control instruction in a control map contains a position in the field. It is important to know that this position is associated with a pre-defined location, called a control point, on the tractor or implement. The control point can also be associated with an imaginary point on the tractor/implement system. As examples, the desired tractor path (Fig. 1-a) is often associated with the center of gravity (COG) of the tractor, so is the desired tractor speed (Fig. 1-b). The desired tillage depth (Fig. 1-c) should be associated with the COG of the tillage implement.

However, the positioning system of an autonomous tractor does not directly give the position of the control point, but the position of the measurement point. The measurement point is usually at a different location than the control point. For example, the GPS position of the tractor is the antenna position of the receiver while the control point for the desired tractor path can be the vehicle's COG. The position of the control point has to be calculated by the position of the measurement point, and the relative geometry between the control point and the measurement point. Fig. 4 gives an example of this relationship.

In Fig. 4, assume that an autonomous tillage operation is performed and the control point is located on the COG of the tillage equipment (Pc). The measurement point is located on Pm (the GPS antenna position). At any time t, the global position at Pm and vehicle heading are given by (x_{pm}, y_{pm}) and θ, respectively. The global position of the control point is calculated by:

$$\begin{bmatrix} x_{pc} \\ y_{pc} \end{bmatrix} = \begin{bmatrix} x_{pm} \\ y_{pm} \end{bmatrix} + \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} x'_{pc} \\ y'_{pc} \end{bmatrix} =$$

$$\begin{bmatrix} x_{pm} \\ y_{pm} \end{bmatrix} + \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} 0 \\ -Ec \end{bmatrix} \tag{1}$$

where (x_{pc}, y_{pc}) are the global coordinates of the control point (x'_{pc}, y'_{pc}) are the local coordinates of the control point, referenced to the measurement point, and Ec is the offset distance from the control point to the measurement point. The control value at the control point is the cell value directly underneath the control point, and can be easily retrieved when the global coordinates (x_{pc}, y_{pc}) are known.

It is noted that the position of the control point is not only dependent on the position of the measurement point, but also the vehicle heading, θ in Eq. (1). The heading error results in the inaccuracy of the position of the control point and thus the inaccuracy of the control of the control output variables. If a GPS is used as a heading sensor, the heading error may be significant in low speed conditions.

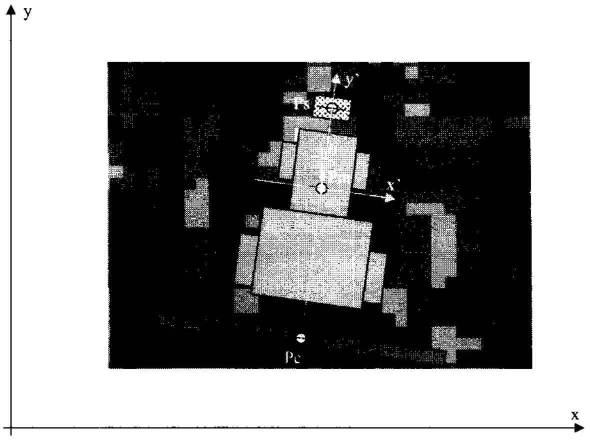


Fig. 4 The relationship among the measurement point (Pm), the control point (Pc), and the sensing point (Ps).

3. Real-time Sensing and Update of Field Operation Maps

In a real-time sensing and control system, an operation map may not exist before the field operation starts, or a pre-loaded operation map needs to be adjusted / updated during the field operation based on locally sensed data. This situation is illustrated in Fig. 4 where a sensor in the front of the tractor is obtaining new data from a rectangle area centered at Ps. Assume that the control point is still on the back of the tractor (Ps), the control value obtained at time t_1 has to be executed at a later time t_2, where $t_2 > t_1$.

The delay time, $\Delta T = t_2 - t_1$, is not fixed unless the tractor travel speed and heading direction are constant from t_1 to t_2. In reality, this condition is seldom satisfied. A map-based approach can easily solve this problem.

At any time t, the global position at Pm and vehicle heading are given by (x_{pm}, y_{pm}) and θ, respectively. The global position of the sensing point (Ps) is calculated by:

$$\begin{bmatrix} x_{ps} \\ y_{ps} \end{bmatrix} = \begin{bmatrix} x_{pm} \\ y_{pm} \end{bmatrix} + \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} x'_{pc} \\ y'_{pc} \end{bmatrix} =$$

$$\begin{bmatrix} x_{pm} \\ y_{pm} \end{bmatrix} + \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} 0 \\ Es \end{bmatrix} \tag{2}$$

where (x_{ps}, y_{ps}) are the global coordinates of the sensing point, and Es is the offset distance from the sensing point to the measurement point. The cell value(s) underneath the rectangle area centered at Ps can be easily updated when the global coordinates (x_{ps}, y_{ps}) are known.

The retrieval of the control value from the updated operation map is the same as in the previous step using Eq. (1). This process assumes that the control value underneath the control point has been updated when it is needed. Therefore, the sensing point must be placed ahead of the control point, and the tractor must be driven a near straight-line course.

Conclusions

An autonomous tractor requires not only automatic steering (automatic guidance) but also automated control of tractor functions and implement operations. This article gives an overview of a map-based methodology used for the implementation of autonomous field operations of agricultural tractors. The procedure for developing autonomous field operation maps was described.

The raster GIS data model was a preferred model to represent autonomous field operation maps. Several important issues in the implementation of map-based autonomous operations were discussed. These issues included combining field operation maps, position offset, and real-time sensing and update of field operation maps. Finally, solutions to these issues were also provided in the article.

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