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On-Farm Analysis of Corn Silage Harvesting Systems Observation and Data Processing Techniques

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Abstract. *Harvesting corn silage is a major cost for large dairy producers. Information about machinery utilization in forage harvesting systems can help farm managers make better decisions on selection of machinery and management practices. A method is presented to gather information on harvesting machinery using low-cost GPS technology. Data from GPS data loggers mounted on self-propelled forage harvesters and accompanying transport vehicles is processed using geometric algorithms to determine machine utilization. A convex hull algorithm is presented for identifying field boundaries, and a well developed cartographic technique is applied to the boundaries to reduce the complexity. Machine activity and utilization are then calculated based on the position and speed of all the machines in the system.*

Keywords. GPS, Forage Harvesting, Machinery Selection, Logistics, Data Processing, Cartography, Field Mapping

Introduction

Corn silage is a major feed source on most dairies in the United States. Harvesting costs can be one of the largest contributors to the overall cost of production for forage crops. As dairy farms have grown larger, the forage harvesting systems have become more complex, and require more careful management. An efficient harvest operation must include enough appropriately sized transport vehicles to keep the harvester working. The number and size of vehicles required varies with the vehicle capacity and transport distance, as well as the forage harvester capacity and utilization (Buckmaster and Hilton, 2005).

As harvesting technology changes, periodic study of the use of the machinery can assist farm managers in sizing systems of machines appropriate for a given operation. Harrigan (2003) performed a time-study of nine silage harvesting operations to provide information about the utilization of equipment in the system. As machines have grown larger in recent years, updated information is needed. As new data collection technology has become available it has also become more feasible monitor farming operations for longer periods of time. This paper presents some of the techniques used to gather this information using low-cost GPS technology.

McDonald (2005) used Global Positioning System (GPS) data from a data recorder in a log skidder to perform a time study analysis of logging operations. Another study was conducted by Amiama (2008) using GPS data coupled with a yield monitor system to gather data on forage harvester throughput and utilization, harvesting corn silage in northern Spain. The present study monitored systems of machines (harvester and transport vehicles) throughout Wisconsin to better understand the interactions which affect the utilization of each individual machine. In the operations monitored, the harvester and all of the transport vehicles were equipped with a GPS data logger.

Data Collection

Producers were selected to participate in this study that were using truck scales to weigh harvested forage, and were taking samples on regular intervals to measure crop moisture. Most producers used Koster (Koster Moisture Tester, Inc., Brunswick, OH) moisture measurement equipment, although one producer used a microwave, and one used a real-time HarvestLab NIR sensor (Deere and Company, Moline, IL) mounted on the harvester. Producers were also selected based on their interest in the research being conducted. One of the major challenges in on-farm research is making sure that general activities on the farm don't interfere with the data collection equipment. It was determined that producers who were interested in how the information from the study could be used as a tool on their own operations were much more likely to help the researchers ensure that the data collected was as valuable as possible. Selecting these producers through an informal interview process helped minimize such problems as data loggers being unplugged, or machinery being exchanged without the notifying the researchers.

Data Logging Hardware

When selecting hardware for on-farm research one major consideration is minimizing the impact for the operators. This includes making sure the running hardware does not interfere with regular operations on the farm, and that installing the hardware causes only a minimal disturbance. It is of course also important that the quality of the data meets the needs of the study.

Geospatial data was collected on all transport vehicles and harvesters using Columbus V900 GPS data loggers (Fuzhou Victory Technology Co., Fujian, China). This low-cost consumer-grade logger plugs into the cigarette lighter socket in a vehicle, and stops logging when the power is switched off. The loggers record position and time at a rate of one hertz. Loggers for this study were installed using a dual socket adapter to so the operator did not sacrifice use of the power socket. For improved reliability loggers were installed in the harvesters using an auxiliary power source instead of the cigarette lighter whenever possible. A logger can be installed in the cab of the machine in less than one minute, causing minimal interruption for the operator.

The technology used in these data loggers is capable of positional accuracy of about plus or minus three meters. When installed inside the cab the positional accuracy was observed to be closer to plus or minus eight meters. This is due to the cab enclosure creating an obstruction between the internal antenna and the GPS satellites.

Data Processing

When processing a large dataset, organizing the data and recognizing patterns is critical. During the corn silage harvest of 2009, 37 million data points were recorded. Procedures were developed out of necessity to efficiently store, access, and process this data.

A relational database was used to store the data. Data was stored on a dedicated server using the open source software package MySQL (Oracle Corporation, Redwood Shores, CA). This storage system allowed for multiple users and applications to access the data at the same time. FileMaker Pro (FileMaker Inc., Santa Clara, CA) was used for all manual data entry operations, and Mathematica (Wolfram Research, Champaign, IL) was used for automated procedures and complex calculations. Both Mathematica and FileMaker were able to communicate directly with the MySQL database.

Care was taken to develop a user interface with data validation and error checking for manual data entry operations. A FileMaker Pro application was installed on a laptop which would then synchronize with the MySQL database. This application was used for recording information about where loggers were installed, along with details about the machinery. Data entry forms were also developed for entering information about harvested weights and moistures.

Map Projection of GPS Data

Geospatial data in the form of longitude and latitude coordinates must be projected into a planer coordinate system (known as map projection) before it can be used to calculate ground distances and areas. The most commonly used map projection is Universal Transverse Mercator (UTM). The UTM projection is defined by the US Department of Defense, and divides the surface of the earth into 60 zones, each with its own projection datum. Distances measured within a single zone using the UTM projection are accurate to within 1 part in 2,500, or forty centimeters per kilometer (Defense Mapping Agency, 1989). Since Wisconsin in split between two UTM zones, a projection known as Wisconsin Transverse Mercator (WTM) was used for this research. WTM was developed by the Wisconsin Department of Natural Resources, and differs from UTM only in that the datum has been shifted 3 degrees longitude to capture the entire state in a single zone (Wisconsin State Cartographer's Office, 2009).

Mathematica was used to compute the WTM easting and northing coordinates as the data was saved to the MySQL database.

Locating Fields and Defining Field Events

A visual system was developed using Mathematica to allow researchers to quickly locate fields from the GPS data. This application overlays the path data from the selected machine on aerial imagery collected by the National Agricultural Imagery Program (NAIP) (US Department of Agriculture, 2010). The user can then zoom to different sections of the data, or limit the displayed data by the time it was collected. The user is presented with an adjustable quadrilateral with which to enclose the field. The software will then determine at what times the machine was within the quadrilateral, thus defining what we have called *field events* (Figure 1).

Figure 1. Application used for locating fields

The field events defined using the locator application were then refined using a similar field event application. This application allows the user to view individual events, and assign a type to each event (Figure 2). Field events were assigned the type *open, split, chop,* or *other.* Open events consisted of harvesting the headland or edge rows, and generally involved loops which followed outside contour of the field. Split events were assigned when the forage harvester had unharvested crop on both sides, meaning the transport vehicle was traveling directly behind the harvester. Chop events were defined when the harvester was traveling along the edge of a land, allowing the transport vehicle to travel next to the harvester. If the event did not fit clearly into one of these groups, it was assigned the type “other.” This application also allows the user to divide an event into multiple pieces if it includes two or more harvesting types.

Figure 2. Field event application

Field Boundary Definition

To define when a machine was in a field, it was necessary to define a boundary for each field. Boundaries were also defined for the inside of the headland of each field, to determine when machines were performing a headland turn. An application was developed which uses a *convex hull* algorithm to locate these boundaries. Another algorithm refined this information by discarding points which were not required to maintain the basic form of the boundary. The set of points used to find the field boundaries consisted of all of the points defined in the events procedure to be part of an *open* event.

A convex hull can be defined for any set of points, and is the smallest convex polygon for which all of the points in the set are either on the edge or in the interior (Cormen, Leiserson, Rivest, & Stein, 2001). This can be visualized as the shape which a rubber band would form when placed around a set of pegs (Figure 3). Since most agricultural fields are not strictly convex, the algorithm developed calculates many smaller convex hulls and combines them to form the outside boundary of the field.

To begin the algorithm a threshold was defined for the largest concave feature which would be ignored. For this study the threshold was chosen by visual inspection to be nine meters. If the threshold is set too large not only will there be a risk of ignoring small features, but the algorithm will take more time to compute. This occurs because a large threshold includes more points in each set used for a convex hull. If the threshold is small there is greater possibility the algorithm will fail because there are no points within the threshold distance. When the algorithm starts a point known to be on the field boundary is defined as a seed. In this case the point with the lowest easting value was chosen. The convex hull is then calculated for the set of points which are contained inside a square with side-length of twice the threshold value centered at the seed. A square was used to generate this set because it is computationally more efficient than using a circular region. The convex hull is returned as an ordered set of points. It is possible that the seed will not be contained in the convex hull set, in which case it is inserted between the two closest points which are contained in the set. For the first iteration within a field, one of the two line segments which has the seed as an end point is arbitrarily chosen and added to the boundary. The next seed is then defined as the point at the opposite end of that line segment, and the process is repeated. In subsequent steps both the seed and the previous seed are added to the convex hull set if they are not already present. Of the two line segments ending at current seed, the one which is not shared with the previous seed is added to the boundary, and the process repeats. Figure 4 shows a partially completed boundary. The process completes when the original seed is again found in the set of nearby points. The boundary is then saved as an ordered set of points forming a polygon which is the outside contour of the field.

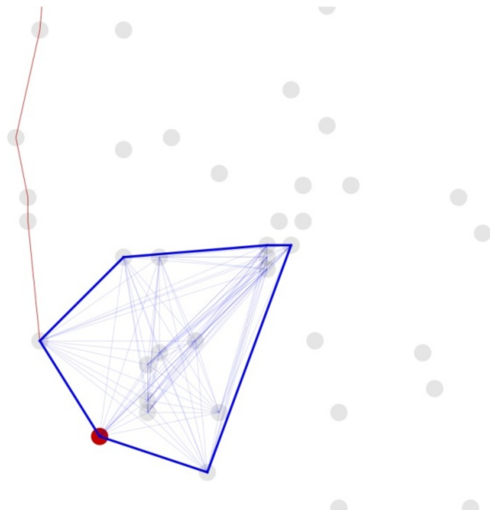

Figure 3. Convex hull used for boundary definition

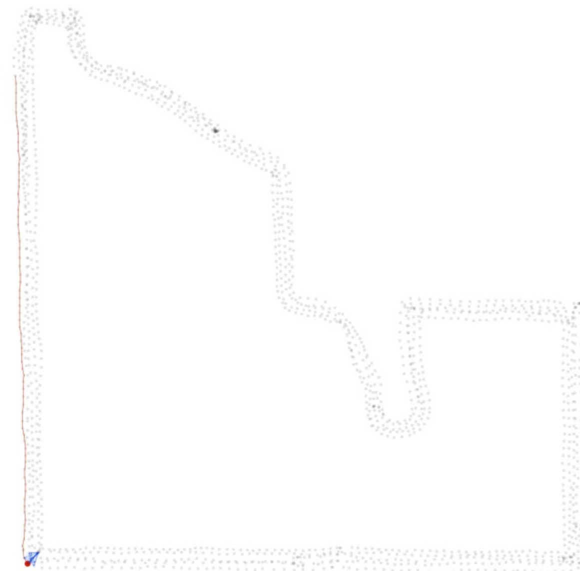

Figure 4. Partially defined field boundary

When field boundaries are defined using the above algorithm, there are invariably more points identified than are needed to define the shape of the field. A cartographic technique known as the Douglas-Peucker method was then applied to the boundary set to save only the points which are needed to describe the shape of the field (Douglas and Peucker, 1973). The Douglas-Peucker algorithm takes a set of points defining a path and identifies which points define the caricature of the path, based on a user-defined threshold. An appropriate threshold for this application was found by trial and error to be eight meters. To determine which points are retained, a line segment is constructed between the first and last point in the path, from which the orthogonal distance is calculated to each other point in the initial set. If the maximum orthogonal distance is greater than the threshold value, the corresponding point is deemed necessary to describe the path. The working set then contains the first point, the last point, and one additional point, ordered as they were in the initial set. The orthogonal distance procedure is repeated for the ordered segments formed by this working set. Each time the maximum point-segment orthogonal distance is found to be greater than the threshold value the corresponding point is added to the working set. The process stops when there is an iteration which does not add any new points to the working set.

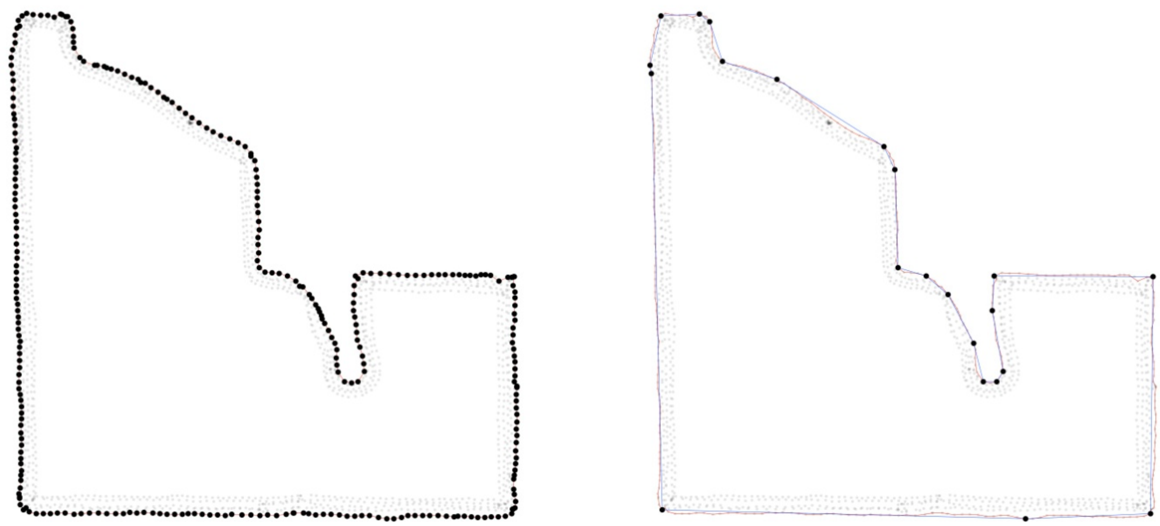

Figure 5. Field boundary before and after application of Douglas-Peucker algorithm. Number of points reduced from 305 to 22.

The final step in generating the field boundaries was to offset the boundary by half the harvesting width, since the GPS receiver was positioned roughly in the center of the machine. The boundary is offset using a straight skeleton technique, which generates a new polygon with the same number of sides, each parallel to the corresponding side of the original polygon.

Identifying Machine Activity

Machine activity was identified from the GPS data for each of the machines. The activities and criteria are shown in Tables 1 and 2. Machine activity was then graphically displayed as shown in Figure 6. This type of graphical display allows researchers and farm managers to see where machinery was unproductive. As managers gain more specific information about where machinery is under-utilized, management practices can be changed to increase productivity.

Table 1. Harvester Activities

• Working	Harvester is moving and is inside the boundary defined by the headland
• Headland Turn	Harvester is moving and is outside the boundary defined by the headland
• Changing Trucks	Harvester is stopped and has two trucks close by, at least one of which is moving
• Waiting for Truck	Harvester is stopped and there are no trucks stopped in the field
• Idle	Harvester is stopped and at least one truck is stopped in the field

Table 2. Transport Vehicle Activities

• Loading	Vehicle is traveling near harvester, and harvester action is working
• Field Travel	Vehicle is moving within the field, but not loading
• Road Travel	Vehicle is moving and not within the field
• Weighing	Vehicle is stopped inside the boundary defined around the scale
• Unloading	Vehicle is stopped or moving slowly inside the boundary defined at the storage site
• Wait For Chopper	Vehicle is stopped in the field, and the harvester action is working
• Idle	Vehicle is stopped within the field and the harvester action is down

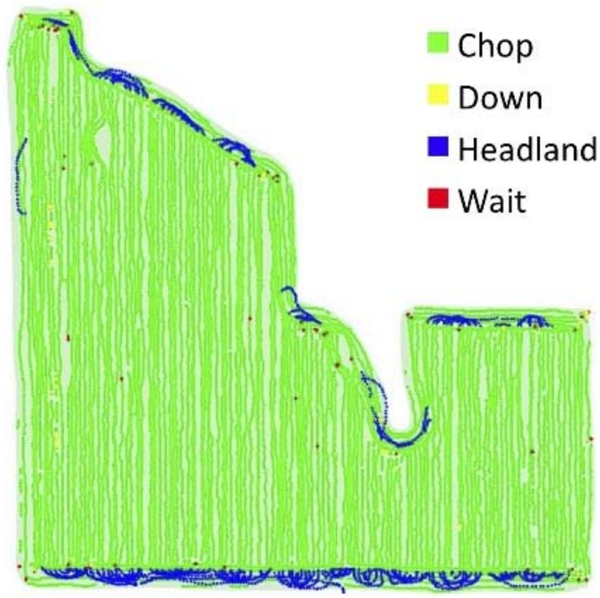

Figure 6. Machine activity displayed by position

Conclusion

A method was developed to gather information about productivity of forage harvesting machinery. Using GPS logging technology and advanced computer processing, information can be gathered much more efficiently than with a comparable "stopwatch" method. Fields are identified graphically by the end user. Geometric algorithms are then applied to the data to determine the field boundaries, and identify the activities of each machine. An original technique was developed to indentify the field boundaries, and an established cartographic algorithm was then applied to simplify the identified boundaries. Activities were then defined for each machine during each second of the harvest operation based on the location and speed of all of the machines in the system. This information can be used by researchers and farm managers to appropriately size machinery, and change management practices to minimize forage harvesting costs. A large set of harvest data has been collected and is being analyzed for future publication.

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