Assessing a Mechanical Furrow-Following System to Obtain Multiple Pass Precision Guidance for Vegetable Production

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Abstract. The economies of scale enable large farming operations to adopt GPS guidance technologies with sub-inch accuracy capabilities for multiple pass operations. For small to intermediate-size vegetable growers, precision guidance technologies are usually considered too expensive and are rarely utilized. A low-cost mechanical guidance system could be particularly beneficial for smaller-scale vegetable farms with limited labor pools because it can free up the driver for other operations requiring manual input such as transplanting, thinning, harvesting, etc. The purpose of this study was to develop a mechanical furrow-following system suitable for smaller-scale vegetable production and to assess its accuracy over multiple passes to determine whether it could achieve accuracy and precision similar to that of much more expensive GPS guidance systems. To assess the accuracy of the system, a GPS receiver was mounted on the frame of an existing wide-stance three-wheeled machine to precisely record machine position as it was used to carry out work on fixed beds. Guidance furrows were created by the narrow front wheels of the machine when it was initially manually driven in freshly-tilled soil. GPS data from the initial pass on each row was recorded and used as a baseline that all subsequent passes were compared to. Results show that it is possible to achieve high levels of accuracy (1.3 in. [3.3 cm]) with multiple passes on a fixed bed over the course of the growing season utilizing the proposed mechanical furrow-following guidance system.

Keywords. Automatic Guidance, Automatic Steering, Low Cost, Vegetable Production, Fixed Beds, Crop Production, GPS, Guidance Furrow, Furrow Following
Introduction

There has been strong interest in developing automated guidance technologies since tractors were first used in agriculture in the late 19th century (Snyder, 1885). Researchers remain challenged by the complexity of the problem – even with today’s high-tech sensors and automation. Old technology such as dead reckoning, leader cable, or marker follower systems have largely been replaced or integrated into the present day technologies of machine vision and GPS guidance systems, but the question of whether the benefits outweigh the costs still remains.

Vegetable crop production is an area that needs low cost mechanization. Market growers, those farmers who sell the bulk of their produce at local farmers markets, restaurants, or directly to consumers through community supported agriculture (CSA), are faced with a difficult challenge when it comes to expensive automation or mechanization: either expand their operation enough to cover the costs through the economics of scale or, because of labor constraints, remain so small that it is difficult to make a living. Low cost mechanization efforts can reduce the financial and labor constraints that market growers face.

For manually-intensive vegetable production for local markets, a guidance system has the potential to provide such a reduction in labor requirements because the driver does not have to steer and is thereby freed up for doing other things such as transplanting, weeding, thinning, scouting, etc. This consolidation of work could reduce time/labor requirements for managing crops throughout the growing season, potentially allowing smaller growers to expand their operations.

According to Grovum (1970), regarding the requirements of a guidance system: “To be acceptable to the present day farmer, an automatic control system as applied to the guidance of farm tractors must be reliable, flexible, versatile, easy to maintain, and be reasonably priced.” This statement still bears truth – over 40 years later. Unfortunately, current guidance systems do not meet these criteria for market growers. Most of the advancements made relative to agricultural guidance systems have increased in complexity, decreased in flexibility, and have most certainly increased in price.

Objectives

The purpose of this study was to develop a mechanical furrow-following system for use with vegetable production and to assess its performance over multiple passes to determine the possibility of achieving accuracy and precision similar to that of a much more expensive Global Positional Systems (GPS) guidance system.

The specific objectives for this study were to:

1) Develop a reliable furrow-following system.
2) Determine the capability of a furrow-following guidance system to achieve multiple pass precision guidance.
3) Assess the utility of a furrow-following wide stance machine for small scale vegetable production through field tests on a growing crop.
4) Evaluate GPS data to determine the accuracy of the furrow-following guidance system over a growing season.

Review of Literature

An automated guidance system for agricultural vehicles has been a pursuit of farmers and agricultural engineers since the late 19th century. Since that time, research has produced several types of guidance systems, some of which are fully automatic while others are semi-automatic (still
require an operator). Contact and non-contact are two sub-categories of guidance systems. In contact guidance system, the machine is guided by a physical contact between soil, a crop or some other physical object. Non-contact guidance systems operate in relation to its surroundings or predetermined path, they often require computational power and are often highly automated. This research project combines several different types of guidance technologies.

**Contact Guidance**

*Marker Follower*

The effort to develop a guidance system for farming operations began as early as 1885 (Snyder, 1885) with a system called “furrow pilot”. This system automatically steered a traction engine based on a previously formed furrow. The system was primarily used for tillage applications. Several other furrow following systems were developed in the 1900’s, but all were used for tillage applications and did not provide guidance capabilities that could be utilized after a single pass (Rohan, 1909) (Phillips, 1949).

Kirk (1974) detailed a marker follower system that utilized a furrow following device that translated physical deviation from a guide furrow to a steering system mounted to the tractors steering wheel. The tractor drawn implement would form a furrow in an adjacent row that would be used to guide the machine across the field. The system used a combination of sensors and mechanical components and performed well, with maximum front wheel tracking error of 1-2” [2.54 – 5.08 cm], providing stable guidance at speeds up to 6 mph [1.6 kph], and a turning radius of 15 ft [4.57m] at 2.5 mph [4.02 kph]. The first pass in a field was manually driven, but all subsequent passes could utilize the guidance furrow created from the trailing implement until the turns became too sharp for the guidance system to negotiate. Kirk (1974) estimated that 75% of the field could be worked in a fully automatic fashion, and could be used for tillage and seeding operations.

Swetnam et al. (1981) developed a machine used as a tobacco harvesting aid that was self-steering, guided through physical contact with the standing tobacco plant stalks. On each side of the stalk there was a feeler arm, which was used to detect needed steering corrections, and the corrections were transmitted through mechanical linkages to the front steered wheels. The self-steering capability of the machine allowed the operator to do the work of spearing tobacco plants on the stick from a seated position on the machine, reducing the effort required to harvest the tobacco plants. The machine platform used for the harvesting aid was also outfitted with cultivator tines and evaluated for cultivating tobacco (Casada et al., 1984). It performed well, attributed to factors such as excellent crop visibility, good maneuverability, quick steering response, and a less aggressive cultivation (resulting in less weed seed germination). In the 1980’s several hundred of these machines were manufactured and sold by the company Four Star, Inc. (Swetnam, 2014).

**Non-Contact Guidance**

*Controlled Traffic and Automatic Guidance*

Controlled traffic systems can be used to service fixed plant beds, which are important for vegetable production systems. Hood et al. (1990) did research on controlled traffic systems. Their machine navigated through the field by a driver, not by an automatic guidance system. They stated that agricultural equipment had too many limitations when it came to vegetable production, but that a fixed bed system, where there were designated crop growing areas, a controlled traffic guidance system could be beneficial to the industry. A controlled traffic system offers some distinct benefits such as minimal compaction in the crop growing zones and improved traction in the areas that compaction did occur. The paths that are created and subsequently followed throughout a growing
season create strips of compacted soil, leaving the growing zone free of compaction related issues. Compacted strips of soil offer unique flood irrigation benefits, flotation, and traction related benefits, since there is a reduced amount of drive-wheel slippage and/or sinking in soft/wet soil conditions (Li et al., 2004).

Buried leader cable guidance systems, where current carrying cables are shallowly buried in the soil and used in combination with sensors to guide a machine along a desired path, have also been studied (Brooke, 1968; Brooke, 1972). Leader cable guidance systems, although effective, could not overcome the challenges created by the material and labor costs required for the installation or removal of the cables for tillage, as well as the problems that varying implement widths created (Parish and Goering, 1970; Aghkhani and Abbaspour-Fard, 2007).

A wide stance agricultural field power unit, also referred to as a gantry, has been developed and manufactured in Georgia, Israel (Gan-Mor and Clark, 2001). Studies done at the USDA-ARS National Soil Dynamics Laboratory in Auburn, AL with this gantry unit combined controlled traffic with a leader cable buried 40 cm underground. The guidance system showed good results but the lack of implements was a major obstacle.

**GPS Guidance**

The Global Positioning System (GPS) utilizes a network of satellites (a minimum of four) to accurately determine an object's location (latitude and longitude) on earth (Heraud and Lange, 2009). GPS was first developed and used by the United States Department of Defense as a military system, but GPS technologies became available for civilian use in the 1980’s, and since that time, it has been heavily adopted in agriculture (Buick, 2006).

There are several different types of GPS guidance systems, classified by different levels of accuracy. As GPS receivers communicate with satellite systems orbiting the earth, there are many opportunities for errors to occur (multipath, dilution of precision, number of satellites, atmospheric conditions, and quality of GPS receiver), which degrade the accuracy of a GPS system. Differential GPS (DGPS) can be used to combat some of these errors, and one type of DGPS is Real Time Kinematic (RTK). A RTK base station consists of a surveyed location where an antenna is set up, which sends a correction signal to the receiver that is on the tractor, correcting errors, and thus increasing the accuracy levels to 2 cm or less. For today’s agriculture guidance systems, a dedicated RTK base station is the most common as it allows numerous benefits (i.e. reduced fatigue, less skips/overlaps, allowed for new farming practices like drip irrigation or strip tillage). There are three main types of GPS guidance systems: Integrated steering systems (automatic), bolt on steering (manually engaged), or light bar guidance (manually steered, using the light bar as a reference) (Heraud and Lange, 2009). While GPS guidance systems provide reliable and repeatable passes over the same path, they are quite expensive. At today’s cost a RTK base station system and an integrated automatic steering system can cost $30,000 to $50,000 (Stempfhuber and Buchholz, 2011).

**Materials and Methods**

**Machine System for Furrow Guidance**

A mechanical furrow forming and following guidance system was proposed to as a low cost mechanized system to benefit small to medium scale vegetable growers. Furrow formed by narrow tires the first time the machine is driven through freshly tilled soil is followed for all subsequent
passes, thereby making the machine self-steering and reducing labor requirements by freeing up the
driver to perform various manual crop production tasks (transplanting, weeding, thinning, scouting,
etc.) while riding the machine. To achieve the intended benefits, the proposed guidance system
needed to show reliable furrow following capabilities over the course of a growing season.

The machine used for this project, a modified Four Star tobacco harvesting aid developed by
Swetnam et al. (1981), has a three wheeled configuration, with two widely-spaced front steered
wheels and a single powered traction wheel in the back. Casada et al. (1984) considered the three-
wheeled machine geometry and wide stance to contribute to better machine performance for
operations such as cultivating for weed control. It is powered by a 12 hp engine, which drives the
rear wheel through a V-belt drive and 4 speed transaxle. The spacing of the front wheels is
adjustable. For this project, that front wheels were spaced 85 in. [2.16 m] center-to-center, to
straddle two 42.5 in. [1.08 m] spaced beds or rows. The machine was outfitted with a category 0
three point hitch system mounted on a toolbar on the passenger side of the machine. The hitch
system utilized an electric lift and facilitated the use of common implements (planter, drip tape layer,
cultivators, etc.), increasing the functionality of the system. Although the three-wheeled machine
straddles two rows, operations utilizing the hitch system are carried out on a single row per pass (see
Figure 1).

![Figure 1. Planter units on toolbar mounted on hitch system.](image)

Preliminary field trials conducted with this machine to test the furrow guidance concept utilized a
three-point hitch-mounted shank with a shovel attachment to create the furrow in a separate pass.
Subsequently, the larger traction tires used for the front steered-wheels were replaced with narrow
single-ribbed tires (4.00-15SL) so that the guidance furrows would be created by the steered-wheels
themselves when the machine was first driven in freshly tilled soil (Figure 2). Creating the furrows in
this way has the main advantage that no additional passes or tools are required for creating the
furrows. Having two furrows has the further advantages of increasing the potential reliability of
furrow following and providing a furrow to follow for adjacent passes with the machine. The narrower
furrow also has the potential to increase the precision of the guidance.
Figure 2. The original wheel (left) was wider for better flotation, while the new narrower (4.6 in. [12 cm]) wheel (right) was selected to create a deeper and firmer furrow in recently tilled soil.

The steering system was fitted with a pair of guidance arms attached to the steered-wheel frames, one mounted directly ahead of each wheel. The arms, which pivot on a horizontal axis located 18 in. [46 cm] in front and 6.25 in. [16 cm] above the steered-wheel axle, can be raised up for manual steering or lowered into position for furrow guidance (see Figure 3). The arms were made from telescoping square steel tubing so that the length was adjustable. Two different furrow-following devices were tried at the ends of the arms, one a steel sled or shoe, and the other a small wheel with pneumatic rubber tire (4.10/3.50-4). The steel sled/shoe worked well in firm soil conditions, but it was more likely than the rubber wheel to cut into the side of the furrow in soft soil conditions and therefore go out of the furrow. It was also considerably heavier than the rubber wheel, making it more difficult to raise and lower the guidance arms. Accordingly, the rubber wheels were chosen for use with the furrow guidance system.

Figure 3. A single guidance arm is deployed in a common furrow as the first pass on an adjacent row is made.

Shown in Figure 4 is a diagram of the three-wheeled machine and the furrow guidance system. The machine is initially manually steered through freshly tilled soil to create a pair of guidance furrows.
Crop production operations such as laying drip tape can be carried out on one row (right side, where the three-point hitch is located) during this initial pass. Upon completion of the initial pass, the machine turns around at the end of the row and returns over the same path in the opposite direction so as to do work on the 2nd bed that was straddled during the initial pass. On this return pass, the operator lowers the guidance arm into the furrows created by the steered wheels during the initial pass so that the machine is self-steering on the row. Adjacent passes use a shared furrow formed during the previous pass (with one of the two guidance arms down) so that consistent row path and spacing is maintained across the field. All subsequent passes for crop production operations throughout the growing season can be mechanically guided by furrow-following provided the furrow quality is sufficient for guidance reliability.

Figure 4: A labeled diagram of the three-wheeled machine.

An initial field trial was conducted with the three-wheeled machine and furrow guidance system to determine what configuration of the guidance arms would give the required reliability of guidance. For the system to be reliable enough for self-steering on established crop rows, it needs to never “fail,” with failure considered to be a case of the guidance arms coming up out of the furrow. Tests were conducted in a freshly-tilled, flat field approximately 100 ft long [30.5 m], at a speed of approximately 1.36 ft/s [40 cm/s] using two different arm lengths (45 in. [114 cm.] and 53 in. [135 cm.] long) with a single or with both guidance arms down (in the furrow), using the rubber wheel furrow-following devices. The reliability of the furrow guidance was checked following initial manual-driven passes. There were no failures in any of the passes, indicating excellent reliability regardless of the configuration and speed. Based on the results of this preliminary field test, the shorter arm length was chosen for all subsequent work with the furrow-guidance system. These tests also confirmed that reliable guidance could be obtained with a single guidance arm, allowing the machine to be self-steering using furrow guidance for adjacent passes, when only one guidance furrow exists. Both guidance arms were typically used for subsequent passes over the same paths, where both furrows are present.

Experimental Methods

Tests were conducted to assess the accuracy of the furrow-guidance system over the course of a season growing vegetable crops. The primary interest of these tests was to evaluate how the accuracy of the guidance changed with additional passes over the same guidance furrows during the course of the growing season. Also of interest was how well the accuracy was held across the field using furrow-guidance for adjacent passes and how it was affected by the speed of the machine.
During the course of other preliminary work with the furrow-guidance system, and these experimental tests, it was noted that intense rainfall events caused sediment to move into the guidance furrow, thereby reducing the depth of the furrow and adversely affecting both the reliability and accuracy of furrow-following. Accordingly, a furrow-reforming operation was carried out during the course of the growing season using a shovel attachment to one of the guidance arms (see Figure 5). The depth of the shovel was adjusted by changing its position on the guidance arm. All of the furrows were reformed once during these tests, and the effect of the reformed furrows was evaluated in the analysis of the data.

The experiments were conducted at the University of Kentucky Horticultural Research Farm in a 50 ft [15.3 m] wide x 150 ft [45.7 m] long plot. According to the Kentucky Geography Network (Kentucky Soils Data Viewer, 2014), the test site has a soil type of Bluegrass-Maury Silt Loam with a 2-6% slope, but the particular test plot seemed to be nearly flat, with a 0-2% slope. Before the initial pass in the field, the soil was worked so that the freshly tilled soil was slightly damp and easily compressed. The first machine row in the field (actually a pair of beds or plant rows) was planted with beans and used for practice both for machine operation and data collection (row 1). Adjacent to this first practice row were planted four more machine rows, two with direct-seeded green beans (rows 2 and 3) and two with transplanted broccoli (rows 4 and 5). These four rows (rows 2-5), which were the ones used for the data analysis for the experiments, all used common furrows for making adjacent passes across the field (see Figure 6). They did not use a furrow common to first practice row. Note that the first pass in row 2 was manually steered, and all other passes (the return pass on row 2 and all adjacent passes in rows 3-5) were furrow-guided. Several different farming operations were carried on the rows out over the course of the 2013 growing season. These operations included the laying of drip tape, seeding (beans), transplanting (broccoli), thinning, and cultivating (see Table 1). The initial pass, used for laying drip tape, was used as the baseline that all subsequent passes were compared to for assessing furrow-following guidance system.
Figure 6: The mechanical furrow guidance system using a common furrow between a machine row of broccoli transplants and a machine row of green beans.

Table 1: Summary of field operations, dates, and rainfall amounts for field operations.

<table>
<thead>
<tr>
<th>Date</th>
<th>Operation</th>
<th>Rainfall Since Previous Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/20/2013</td>
<td>Laid drip tape and planted two rows of green beans</td>
<td>0”</td>
</tr>
<tr>
<td>8/22/2013</td>
<td>Demonstration/Data collection</td>
<td>0.04”</td>
</tr>
<tr>
<td>8/28/2013</td>
<td>Laid drip tape and planted two rows of broccoli</td>
<td>0.05”</td>
</tr>
<tr>
<td>9/10/2013</td>
<td>First pass on each row was just a data collection run, the second pass on each row was a furrow reforming pass</td>
<td>2.8”</td>
</tr>
<tr>
<td>9/11/2013</td>
<td>Cultivation</td>
<td>0”</td>
</tr>
<tr>
<td>10/9/2013</td>
<td>Data collection pass/cultivation</td>
<td>3.56”</td>
</tr>
<tr>
<td>10/14/2013</td>
<td>Visual confirmation of following characteristics</td>
<td>0”</td>
</tr>
</tbody>
</table>

Machine position data was collected during each pass in a machine row by a MS990 GPS receiver that was mounted on the front axle, centered between the steered wheels, of the three-wheeled machine (see Figure 7). The data string was in the form of a National Marine Electronics Association (NMEA) GGA data string, sampled at a rate of 1 Hz. The data string contained a time stamp, latitude, longitude, heading, altitude, horizontal dilution of precision, and correction type; the data was logged on a cellular phone through a Bluetooth radio. To get RTK level correction, the Kentucky Transportation Cabinet Continuously Operating Reference Station (KYCORS) was utilized. The specific KYCORS station had a station identification tag of KYTG.
Results and Analysis

Data Analysis

The collected GPGGA data string was incompatible with Arcmap and needed to be converted from degrees decimal minutes (DDM) to decimal degrees (DD). After projecting the latitude and longitude coordinates using Kentucky State Plan Coordinate System, ARCMAP’s near function, which calculates the distance between any input feature and near feature, was used to determine the accuracy of guidance system. The input feature was set as the individual data points collected during a pass and the near feature was the path that was recorded during the initial pass in a field. The deviation (near distance) from the desired path is the measurement used to evaluate the guidance system’s accuracy.
Preliminary data analysis revealed that there was an offset distance depending on the direction of the pass was made. It was determined that this error was the result of the GPS receiver not being mounted directly in the center of the front axle. To overcome this issue, passes were grouped by the direction of travel. For example, if the direction of pass 1 was north to south and pass 2 travelled south to north, two separate baselines would be used to compare pass 3 (north to south) and pass 4 (south to north). Position data that was collected during the end of row turns was eliminated, and the remaining data was trimmed to the length of the initial pass.

Since normal farming operations were carried out for these tests, there were times that the machine was stopped, such as when transplanting or thinning. Speed was not in the output string of the GPGGA string, so a formula was used calculate the instantaneous velocity for each point based on the distance between each point (from the latitude and longitude) divided by the number of seconds between samples. The results from this formula were used to determine points at which the machine was stationary. If speed was less than 0.1 mph, the machine was assumed to be stationary. These points were eliminated to prevent skewing in the statistical analysis.

Results and Discussion

A total of 7441 data points were used in the statistical analysis. The data showed that the mean deviation from the desired path was 0.108 ft (1.30 in. [3.30 cm]) with a standard deviation of 0.089 ft (1.07 in. [2.72 cm]). Data from all four rows was used to evaluate the accuracy of the furrow guidance system. Rows 2 and 3 were double rows of seeded green beans, and rows 4 and 5 were broccoli transplants. The guidance system did not fail, but, as previously stated, a furrow-reforming operation was conducted in order to maintain furrow-guidance capabilities during the latter part of the growing season. Figure 9 shows the frequency of deviation levels across all rows. Ninety percent of the data fell within the range of 0 - 0.24 ft (0 – 2.8 in. [0-7.2 cm]).

![Histogram of Deviations](image)

Figure 9: A histogram of the frequency of deviations (near distances) from the desired paths.

Shown in Figure 10 is a plot of the deviation (near distance) as multiple passes were made on the same row. There is a general upward trend until pass 9, which is when the furrows were reformed.
As the number of passes increase on a row, the guidance system became less accurate because of furrow degradation. Pass 9, which was manually steered during the furrow-reforming operation, shows a substantial improvement in accuracy over pass 8, the last pass recorded before the furrows were reformed. For subsequent passes following the furrow-reforming operation, the data shows oscillations in accuracy levels. Overall, the mechanical furrow-guidance system provided fairly accurate guidance over multiple passes on the same row.

Rainfall seemed to be the most significant cause of furrow degradation. Substantial silt accumulation in the bottom of the furrows was observed following intense rainfall. This sedimentation reduced the effective depth of the furrow, thereby decreasing the capacity of the furrow wall to exert corrective forces on the guidance wheel. Variations in machine position also contributed to furrow degradation as the tires strayed from the furrow center, flattening the furrow walls. Further analysis of the data is being done to incorporate rainfall into the statistical model in an attempt to determine how the intensity of rainfall affects furrow integrity. Efforts are also being made to analyze the data to determine how accurate the guidance was for adjacent passes guided from the furrows created by the initial manually-driven pass.

The three-wheeled machine used in this study worked out surprisingly well. The open configuration made it very flexible for positioning equipment and the operator for many different vegetable crop production operations. The wide stance of the machine, straddling two rows while operations using the three-point hitch were conducted on one row, worked particularly well for accomplishing two different operations, one on each row, at the same time. The effectiveness of the furrow-following system in making the machine self-guided is the key that frees up the driver for such multi-tasking, potentially reducing the labor requirements significantly for small-scale operations.
Conclusions

For small to intermediate-size vegetable growers, precision guidance technologies are usually considered too expensive and are rarely utilized. A low-cost mechanical guidance system could be particularly beneficial for smaller-scale vegetable farms because it could free up the driver for performing other functions, thereby significantly reducing manual labor requirements. Experiments were conducted to evaluate a mechanical furrow-following guidance system’s ability to provide accurate guidance for repeated passes on fixed vegetable beds during the course of a growing season. GPS data from the initial manually-steered pass on each row were recorded and used to create a baseline that all subsequent passes on each row were compared to. The furrow-following guidance system performed well during testing, with an average deviation from the initial pass of 1.30 in. [3.30 cm] with a standard deviation of 1.07 in. [2.72 cm].

Experience gained from these experiments and from additional work with the furrow guidance system has revealed areas that require further study. Of particular importance is the issue of furrow quality. Degradation of the furrow with time, both from weathering and from machine operations, can affect both the reliability and the accuracy of the guidance provided by the furrow-following wheel. More work is needed to investigate efficient ways to both create deeper, more pronounced furrows in the first place, and to maintain the quality of those furrows through reforming operations. Efforts at better matching the width and profile of the furrow-following and steered wheels may also help improve guidance accuracy. The effect of side-slope is another area needing further investigation. These tests were conducted on field plots that were fairly flat, but in trials conducted during the 2014 growing season in a field with a 2-6% side-slope, the machine has shown a tendency to drift downhill with repeated passes over the same furrows. Efforts directed at improving furrow quality may help with the side-slope drift issue.

The guidance accuracies achieved in these tests were good enough to make this furrow guidance concept very promising for the application of manually-intensive vegetable production for local markets. The simple guidance system was reliable and accurate enough to allow the machine to be self-steered on fixed vegetable beds, freeing up the driver to accomplish multiple tasks. Work is continuing on improving the system and developing more applications and implements to more fully exploit this capability.
References


