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Automatic Guidance Sensors for Agricultural Field Machines: A Review

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The need for automatic guidance and the problems, both technical and economic, associated with its introduction into agricultural field operations are discussed. Traditional agricultural guidance technologies such as leader cables and mechanical methods are examined as well as more recently proposed techniques. These can be categorized into those which sense local features such as furrows or plant rows and those which work on a large-scale absolute coordinate system. For completely general full automation the latter is preferable. However, the accuracy currently achieved by such systems using radio or satellite navigation technique is relatively poor. This makes a combination approach, using also a short range relative sensing technique such as computer vision, a promising area for research. Optical systems using lasers are capable of providing absolute location with adequate accuracy, but they require further development and will always be limited to line of sight.

1. Introduction

One of the most time consuming tasks in modern agriculture is driving agricultural vehicles. Using census data[1] and average tractor hour requirements given by Nix[2] it has been calculated that approximately 180 M man hours per annum are spent driving tractors in the UK. Some of this time will be spent on the public roads or performing complex tasks but a lot will be taken up by repetitive low speed work on the land. If the driver could be eliminated from these operations, cultivating, spraying and drilling for example, productivity could be massively improved. Furthermore, where the task is unpleasant or potentially hazardous, in orchard spraying for example, a driverless vehicle is particularly attractive.[3] A number of further benefits including reduced overlap, night spraying and variable chemical application rates linked to spatial mapping have been identified by Palmer and Matheson.[4]

Unfortunately there are a number of problems relating to the use of automatic guidance and control in agricultural applications. One of these is that the vehicle usually has to be transported to the field on a public road for which a driver will be required. Once in the field the vehicle may require servicing at intervals, filling a spray tank for example. This problem could be overcome by using one worker to manage the fleet of Automatically Guided Vehicles (AGVs). The control of implements, engine and transmission, presents a number of problems to the designer of a fully autonomous vehicle.

Ploughing, for example, involves a complex interaction of implement depth, gear ratio and engine speed with a soil whose properties may vary across the field. Although work has been conducted on automatic engine and transmission control,[5,6] a fully integrated system incorporating implement control is not yet commercially available.

A further complication applicable to AGVs in general is the requirement for fail-safe devices to prevent collisions with people or objects. The adequate reliability and safety

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Notation

a	Sensor distance ahead of rear axle
d	Half distance between pairs of search coils
L	Distance between front and rear axles
V	Vehicle velocity
k	Constant
k_d	Derivative gain
k_p	Proportional gain
r	Radial distance from leader cable
t	Time
x	Horizontal displacement from datum perpendicular to direction of travel
y	Horizontal displacement in direction of travel
z	Vertical distance above leader cable
γ	Heading error
θ	Steering angle
ϕ_1, ϕ_2	Magnetic flux a distance d to the left and right of the vehicle
ϕ_x	Horizontal component of magnetic flux
ϕ_z	Vertical component of magnetic flux
$\phi(x, z)$	Magnetic flux at coordinates x and z relative to a leader cable

levels which have been reached in the well-ordered factory environment[7] are not so easily achieved on agricultural land. Apart from safety considerations, reliability is an important factor in system design. This is not necessarily easy to achieve in an agricultural environment particularly if the guiding feature is, for example, a row of plants which are subject to natural variation.

The following review starts by examining the information required from a guidance system in order to achieve stable control. The principles of guidance are then reviewed in detail, a summary of which is provided in the Appendix. Finally, the potential of the various options is discussed from both an economic and technical point of view.

2. Controller requirements

A requirement of the guidance system is that it should provide sufficient information for the control system to achieve stability. *Fig. 1* illustrates a tractor attempting to follow a straight line where, x is the displacement from the datum line, y is displacement in the direction of travel and θ is the steering angle relative to the tractor. The speed of the tractor in its direction of motion is V and the distance between front and rear axles is L.

Grovum and Zoerb[8] showed that provided the tractor is following a substantially straight line and that inertia and wheel slip effects are negligible then tractor dynamics can be represented by the following equation:

$$x = kV\int_0^t \int_0^t \theta \, dt \qquad (1)$$

$$\text{where } k \text{ is a constant} = \frac{1{\cdot}01\ V}{L} \qquad (2)$$

They also showed, using analogue computer simulation as well as practical field trials, that in order to achieve stable automatic control of steering, feedback signals incorporating both heading γ and displacement x relative to the guidance path are required. This result applies to all tractor automatic guidance applications so that the equation of a

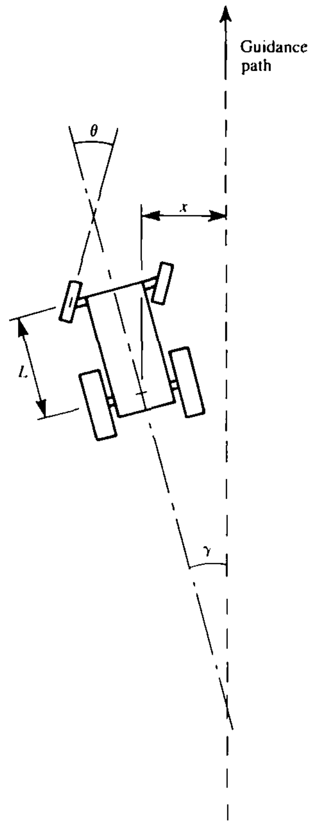

Fig. 1. Tractor guidance geometry

typical controller is:

$$\theta = k_d\gamma + k_p x \tag{3}$$

where k_d and k_p are heading and displacement gains respectively.

Simulations[8] using a simplified model have shown that an automatically guided tractor has the basic characteristics of a linear second-order type system. In particular, increasing the displacement gain, k_p, increases the natural frequency, improving the rate of response but also reducing damping. Increasing heading gain, k_d, increases damping without affecting the natural frequency.

Similar results are obtained when investigating the automatic guidance of crop-spanning gantries.[9] In this case, steering is achieved by increasing the speed of one side of the gantry relative to the other so that θ represents the ratio of these speeds.

In theory, it would be possible to obtain a heading, γ, signal by differentiating a displacement, x, signal. In practice this would be very sensitive to noise. Therefore, feedback techniques where heading, γ, is measured directly are used in most automatic guidance and control systems. There are a number of techniques for doing this all of which are represented in the following review. Displacement and heading can be directly measured separately. Displacement can be measured at two positions on the axis of the vehicle so that heading can be calculated from the difference and displacement from the sum of the measurements. Alternatively a single displacement measurement can be taken by a

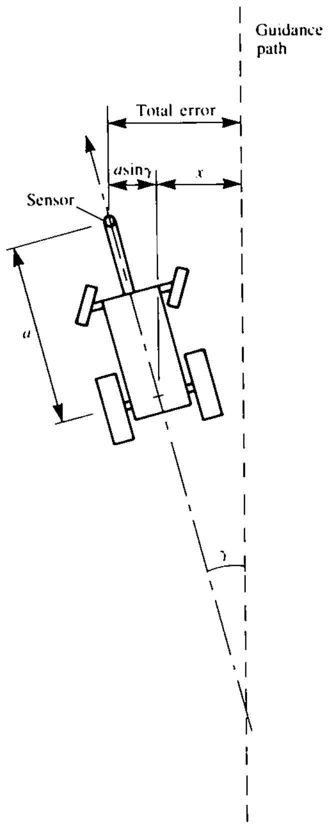

Fig. 2. Geometric addition of heading and displacement errors for guidance using a single sensor

sensor whose position by virtue of geometry incorporates elements of both vehicle displacement and heading as illustrated in *Fig. 2.* The geometry must be matched to the needs of the controller as it is not possible to deduce separate values for displacement and heading. This technique can only be used if the sensor is positioned ahead of the vehicle centre. If the direction of motion is reversed the sign of the heading error element ($a \sin \gamma$) is incorrect and will lead to instability.

For accurate control it is desirable that the error signals and control inputs are linear. However, Liljedahl and Strait[10] have shown, by analysis and simulation, that cruder systems using on/off control can be successful at low speed.

3. Guidance systems

3.1 *Mechanical guidance*

3.1.1. *Following existing features*

Mechanical guidance systems that utilize existing features are generally cheapest as costs are restricted to the sensing and control devices. Drains were used by Kawasaki *et al.*[11] as a guiding feature though more usually the crop or a cultivation furrow are used.

Suggs *et al.*[12] used a feeler spring loaded against tobacco plant stems which activated an electrohydraulic valve which controlled a steering ram. Steering accuracy achieved in field tests was ±50 mm under normal conditions. Richey[13] devised a similar system but used an electrically operated lead screw to move the steering drag-link. Accuracy in this case was ±100 mm at 9·7 km h^{-1}. In both systems steering angle feedback was achieved by mounting the feeler-arm assembly on the steered wheel support structure. The sensing arm extended forward of the steered wheel so that its angle was a function of heading as well as displacement error. If there was a gap in the row of plants longer than the feeler (approximately 400 mm), control was lost.

Kaloev and Liberfarb[14] developed a system in which when the feeler came to a gap in the row the arm vibrated, "searching" for the next stem whilst the vehicle continued on its previous heading. A different type of mechanical crop sensor was developed by Parrish and Goering[15] to sense the presence or absence of alfalfa hay by vertical pressure applied to the sensing arms. The arms which acted on microswitches hung down under gravity from a horizontal pivot. The experimental unit was used to control a windrowing machine at up to 7·2 km h^{-1} giving a root mean square error of between 230 and 300 mm.

Hilton and Chestney[16] developed a tractor self-steering device for out-of-furrow ploughing which followed the previously made furrow. The purpose of ploughing out of the furrow was to avoid soil compaction. Like most mechanical guidance systems it was designed as an aid to manual operation. The driver would make the first pass and headland turns. During subsequent passes the driver was free to concentrate on engine speed, ploughing depth etc whilst the self steering device maintained the correct path relative to the previous furrow. A cross beam attached to the tractor carried a pivoted furrow following arm which projected slightly forward of the tractor and parallel to the furrow. The follower was held firmly down and against the furrow wall by springs. Through a series of linkages the movement of the follower was transferred either to the tractor drag link (for power-assisted steering) or to a control valve (for hydrostatic steering). This system was capable of keeping the front wheels within 40 mm of the desired path. Furthermore, waves in the original furrow were attenuated by successive passes. Changes in soil or surface conditions affect the balance between the plough and tractor lateral reaction forces causing some deviation from a straight path, though not exceeding 6% of the ploughed width. Errors also occur working across a slope of uneven gradient. Commercial systems also exist which follow the ridges formed by some vegetable beds.[17]

3.1.2. *Following specially provided features*

Some soil-engaging sensing arms follow a furrow or slot specifically made for this purpose.[8,17,18] In such systems the first pass is made under manual control during which a guiding furrow is made. Subsequent passes under automatic control follow the guiding furrow and produce a new off-set guiding furrow on each occasion. Grovum and Zoerb[8] used twin sensing wheels at the end of independent trailing links to straddle the marker furrow. When the vehicle moved to one side, one of the wheels dropped down the furrow activating a microswitch. This signal was used to control a d.c. servo motor driving the steering wheel. It is interesting to note that initially they mounted the displacement sensor in line with the rear axle where the signal had little component due to tractor heading. A heading signal was provided by gyro-compass to make the system stable. It was found that by moving the displacement sensor level with the front wheels so that its position was a function of vehicle heading as well as displacement, stability improved to the point that the gyro-compass signal was not required at speeds below 2·4 km h^{-1}. Wilden and Blair[19] proposed a system where a cord buried just below the surface acted as the guidance marker. The tractor drew the cord up out of the ground through a sensing mechanism which steered the tractor using a servo hydraulic valve. A new trail offset by the width of the implement was produced by ploughing the cord in again on the other side. The system, which was found to be accurate to within ±50 mm, has the advantage of low capital cost. Its lack of commercial exploitation is probably due in part to the difficulty in collecting and tensioning the cord. The expected life of the nylon cord is not reported.

Taut above-ground cables are used to guide commercially available linear multi-truss irrigation gantries. This principle provides an accurate and reliable form of guidance but has the drawback of obstructing other operations. It is therefore best suited to wide-span machinery where a relatively small number of wires in uncropped strips are economically justifiable.

Steel rails for gantry system could be regarded as a form of mechanical guidance, though they also provide support. They have the advantage of reliably providing a very high degree of accuracy combined with low vehicle rolling resistance. For reasons of their very high installation costs their use is limited to very intensive horticultural operations, normally within a greenhouse,[20] though field applications have been attempted.[21]

3.2. *Optical guidance*

3.2.1. *Lasers*

Lasers can be used in a number of ways to guide vehicles. The simplest of these is using a fixed beam or plane projected in the direction of travel from the headland. A row of detectors mounted on the vehicle is arranged perpendicular to the laser plane or beam to determine displacement from the desired path. Lawson[22] described a system commercially available in 1985 in which a tractor was guided by a laser projected from a remote-controlled mobile beacon. At the end of each pass the remote-controlled vehicle was indexed to the next row. Like all optical guidance systems it can only operate in an area where the line of sight is unbroken limiting application to relatively flat sites without obstructions such as trees.

The most common use of laser guidance in agriculture is in drainage machinery.[23] Such machines used a horizontal plane to get an accurate depth reference at any position within sight of the source. Such systems while potentially very accurate only provide guidance in one dimension. Alternative laser guidance and measuring systems have been developed which provide spatial information in two or three dimensions. Mizrach *et al.*[24] evaluated the use of a scanning laser system to guide a multi-jointed mobile truss. They used a single laser beam located on the headland which was rotated in a horizontal plane at constant velocity. Four detectors were mounted on the vehicle. Location was calculated on the basis of the angles from the source measured by means of elapsed time from a synchronizing trigger pulse and velocity of rotation of the laser. Static field tests showed the system to be insufficiently accurate, though improvement to acceptable levels was thought possible by the provision of more accurate components.

Shmulevich *et al.*[25] used a single continuous laser split into two beams and directed by two rotating mirrors positioned several metres apart. The target, fitted to the vehicle, consisted of a retro-reflector. The first mirror rotated until the target was hit, causing the reflected beam to be detected and that mirror angle to be recorded; the process was repeated for the second mirror. The beam splitter was also used to split the reflected beams onto a single detector further reducing the number of components (*Fig. 3*). The known distance between the two mirrors and the angles at which the beam struck the target, made it possible to calculate the target coordinates. Mirror scanning speed was limited to 0·8 rad/s by the computing speed available. This was too slow for guiding a multi-jointed truss system travelling at 0·5 km h^{-1}. Accuracy was said to be 150 mm over a 400 × 400 m area.

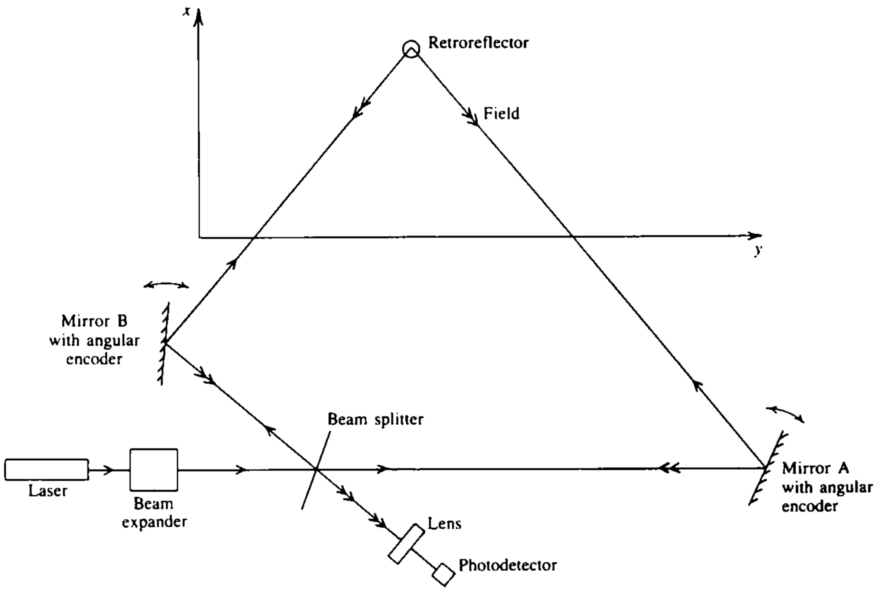

Fig. 3. Laser guidance system developed by Shmulevich et al.[25]

Gorham[26] reported a land surveying technique which could be used to provide vehicle guidance. A source consisting of two lasers fanned into a sector both inclined at an angle of 45° to the horizontal plane was rotated about a vertical axis. The rotation of the lasers was tracked at the source by angle encoders, the information from which was transmitted to the surveying staff using an infra-red beam. The staff incorporating an infra-red receiver carried a number of photo-detectors mounted vertically above one another. By coordinating the inputs from the photo-cells to the beam angle it is possible to calculate the three-dimensional position of the staff. On a prototype commercial surveying unit the calculations were performed by a computer mounted on the staff. A "fix" could be produced within 8 s to an accuracy of ±6 mm in range and ±5 s in horizontal angle (corresponding to ±3 mm at 100 m range). For vehicle guidance purposes this system could be simplified as height coordinates are not usually required though the processing speed would have to be increased in order to control a vehicle travelling at moderate speed.

3.2.2. *Infra-red methods*

Harries and Ambler[27] used an infra-red ranging and triangulation technique in conjunction with furrow following (Section 3.2.3) and dead reckoning (Section 3.6) to allow completely driverless operation to take place. They used the phase difference between the output of an infra-red emitting diode energized by a square wave at 5 MHz and its reflection from retro-reflective posts on the headland to determine distance. The resolution obtained using this system was 0·1 m and the range approximately 20 m. Further information on the bearing of the posts, arranged at 15 m intervals on the headland, was obtained by rotating the output beam at 3·1 rad s^{-1} and recording its angle when a reflection was received. Bearing estimates were to within ±5° of calculated values.

Kawamura and Namikawa[28] used the differences in the reflectance of infra-red radiation between cultivated and uncultivated soils as a means of guiding a tractor engaged in rotary cultivation to within ±50 mm. They used two detectors mounted ahead of the front wheels one either side of the boundary between cultivated and uncultivated soil. With the detectors either side of the boundary the tractor was regarded as being on course. When both detectors were on the same side of the boundary the controller made the required correction. Each detector consisted of a light-emitting diode and a photo sensor which provided an analogue output depending on the soil surface. Using an electronic threshold these signals were converted to logic high or low input signals. The technique was said to be unaffected by weeds or crop residue.

MacHardy[29] proposed that the hot exhaust pipe of a tractor could be tracked by two infra-red sensors at different locations on the headland so providing the necessary information for vehicle guidance. No practical trials were conducted.

3.2.3. *Visible light*

Visible light is not widely used in guidance systems as ambient light can cause interference. To overcome this problem, Harries and Ambler [27] used light modulated at 1 kHz when following a plough furrow (*Fig. 4*). They directed their light source, a band of light perpendicular to the direction of travel, downwards, ahead of the tractor. One array of inclined photocells detects reflections from the uncultivated top of the furrow and another array detects reflections from the bottom. When the light source is equally disposed about the furrow wall both arrays of detectors are equally illuminated. As the vehicle moves to one side the summed outputs from each array become unequal producing a stepwise signal proportional to error. The system was limited to furrow depths of greater than 125 mm though an alternative optical system for shallow furrows has been proposed.[30]

Visible light is also used by some factory AGVs which follow a retro-reflective tape path stuck to the floor.[31] The system also allows changes of route to be made quickly and

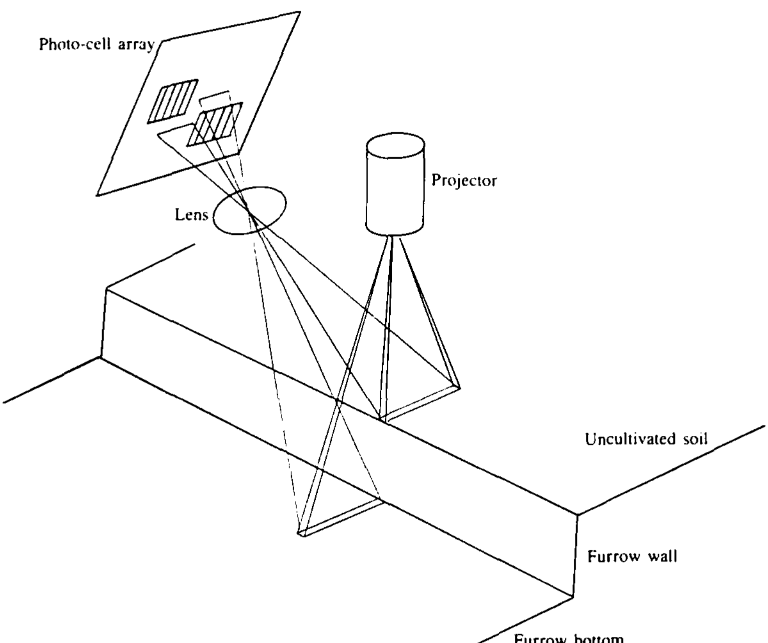

Fig. 4. Optical furrow-following sensor developed by Harries and Ambler[27]

cheaply. The major disadvantage of this system, which rules it out for most agricultural operations, is that the tape must be kept unbroken and relatively clean.

3.2.4. *Image analysis*

Computer analysis of a video image is a technique which has only recently, by virtue of advances in computing technology, become a potentially viable method of obtaining guidance information. Attempts have been made to apply these techniques to a number of different situations including road[32] and factory-based vehicles.[33] The technique has the particular advantage of utilizing the same equipment to sense a variety of different guiding features with only software changes. One example of such a feature is row crops which Reid and Searcy[34] used to develop a statistically based algorithm for clarifying areas of crop canopy and soil background. Their algorithm was successful in this respect except when the image consisted of a high percentage of canopy or soil. Their work did not extend to the determination of row location or vehicle guidance signals.

Gerrish *et al.*[35] used conventional image recognition techniques to extract information on the path of a vehicle from an image looking ahead and tilted down at 17° to the horizontal. They experienced some difficulty determining suitable guidance information from a view of the cut edge of a field of alfalfa. An image of well defined onion rows, however, enabled image offset from the row to be known to ±45 mm and heading to ±0·3°. Some of their image processing routines took several seconds to run but they projected that a vehicle path could be obtained from a ragged but well-defined edge within 1 s. Their system like Reid and Searcy's[34] had not been field tested.

3.3. *Radio navigation*

Radio navigation techniques are very attractive for guidance purposes. They can cover a very wide area and require only a few beacons which can be placed at convenient points. The receiver mounted on the vehicle can be relatively compact.

A large part of the earth's surface is covered by the transmissions from beacons intended for use by aircraft and boats. Unfortunately these systems only locate to within 100 m or worse. An American company started to market a smaller scale radio-navigation system (AGNAV) which located the vehicle within a field.[17] The device, which was intended for use during spraying and fertilizer application operations, displayed guidance information to a driver who controlled the machine. The accuracy achieved with this system which used 1 W transmissions at 154·6 MHz is reported to be ±0·23 m at a 0·8 km range.[36]

Systems using earth satellites for position determination known as global positioning systems are now becoming available. These currently provide[36] a stationary accuracy of 2 to 5 m averaged over 1 to 5 min. Unless accuracy and speed can be substantially improved these systems are unlikely to find application in agricultural vehicle automatic guidance except perhaps in conjunction with some other technique which uses local guidance features for example.

Bonicelli and Monod[37] used microwave reflections from passive beacons on the headland to deduce vehicle position by triangulation. They had a target accuracy of ±1 m, but it is not clear if this was achieved in practice. Hiel *et al.*[38] and Searcy *et al.*[36] both used the same proprietary microwave location unit to monitor vehicle position within the field. They were not attempting to guide the vehicle automatically. The unit which used two or more transponders mounted outside the field gave linear errors of ±1 m between the vehicle and each transponder. The error in a two-dimensional "fix" is therefore dependent on the number of transponders and the relative angles between transponders and the vehicle. In general, microwave systems are limited to line of sight and have proved insufficiently accurate as a sole method of location for automatic guidance.

3.4. *Ultrasonic guidance*

Ultrasonic devices for measuring distance are readily available. They typically work in the range 100 mm to 10 m with an accuracy of 99%. Distance is calculated from the time taken for an ultrasonic signal to reach and be reflected back from the target. As the signal may be reflected back from a number of objects in its field of view only the nearest is recorded. In using such a device it is, therefore, important to ensure that stray foliage, for example, does not come between the sensor and target. It is common practice with such sensors to use the same diaphragm to generate the signal and pick up its reflection. It is for this reason that there is a lower limit to range as some time is required for the change of roles.

Ultrasonics have been used to detect a number of materials for guidance purposes although it is important that they should reflect rather than absorb ultrasonic sound. Inadequate reflection of ultrasound from soil caused Warner and Harries[39] to abandon this method of detecting a plough furrow in favour of optical methods.[27] Bonicelli and Monod[37] also used ultrasonics to guide their ploughing robot, though accuracy and reliability are not specifically reported on. McMahon *et al.*[40] used such a device to sense the position of apple tree trunks in order to guide a harvesting vehicle. Patterson *et al.*[41] used two ultrasonic sensors straddling a row of transplants to guide a planter. Signals from the two devices whose fields of view overlap were compared. If there was no plant present or the plant was central the signals were the same. If they were uneven, a displacement error was indicated.

3.5. *Leader cables*

Leader cables have been in use for several decades. Patents concerning apparatus and applications[42] go back at least as far as 1924. The most popular application of leader cables is in AGVs working in factory and warehouse areas. Leader cables are not widely used in agriculture though they are used in some specialist applications such as the guidance of multi-truss irrigation gantries.

Leader cable guidance is based on the detection of a magnetic field generated by a small low frequency signal (typically 150 mA, 2 KHz). Despite the low intensity of the signal a licence to transmit is required to operate the system in the UK. As the magnetic field is not greatly affected by soil[43] the wire can be buried. Factory-based systems operate with the wire buried a few centimetres below a concrete floor. Most agricultural systems operate with the wire approximately 0·5 m below the surface so that they are unaffected by ploughing. The wire can be conveniently placed at this depth using a mole-plough.[44] Some agricultural users of leader cables have reported problems of loss of wire continuity thought to be due to rodent attack. Commercial systems for guiding multi-truss irrigation gantries are known to use a heavily reinforced cable in preference to the field telephone wire used in earlier systems.

3.5.1. *Vertical sensing coil*

The sensors used on the vehicle consist of a large number of turns of copper wire wound on a ferrite core. The changing magnetic field induces a signal in the coils the magnitude of which varies with signal strength. *Fig. 5* shows the lines of flux around a wire carrying a current in a direction out of the page. The strength of the flux, ϕ, at

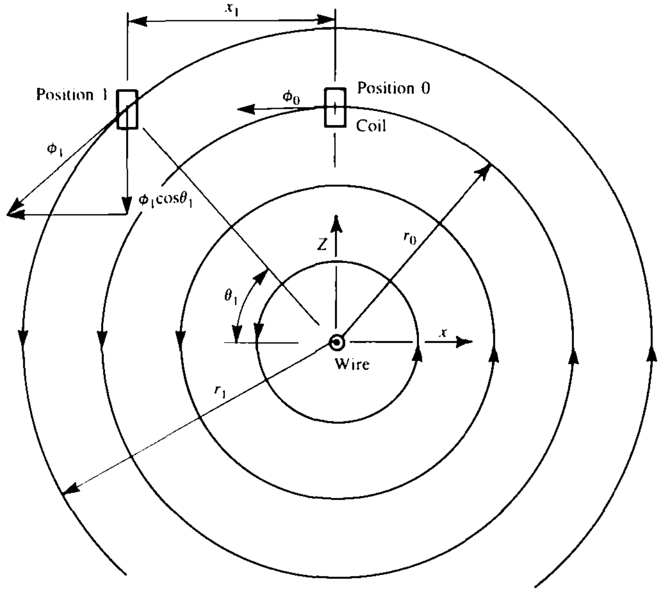

Fig. 5. Flux around a single vertical coil shown vertically above (Position 0) and offset by a distance x_1 *(Position 1) from a wire carrying current in a direction out of the page*

coordinates x and z from the wire varies inversely with radial distance, r.

$$\phi(x, z) = \frac{k}{r} \tag{4}$$

where k = constant.

A wound coil with its axis vertical will pick up the vertical components of flux and the current will be induced in its windings at the same frequency as the signal generator.

The variation in signal strength with offset x has been calculated by Tillett[45] and is illustrated in *Fig. 6.* Within the range of offset 0 to 0·5 m the relationship is fairly linear. It is in this area that most leader cable systems operate.

For the purposes of practical guidance it is necessary to know which side of the wire the coil is on as well as how far it is offset. As the direction of flow of current changes in the wire with each half cycle, so does the direction of flux and the induced current in the coils. Referring again to *Fig. 5,* when the vertical component of flux to the right of the wire is downward the corresponding flux to the left is upward and vice versa. Consequently the a.c. signal generated in a coil to the left of the wire is 180° out of phase with the one on the right. A second coil with its axis parallel to the x-axis has a signal generated in it which does not change in phase from left to right of the wire. Such a coil is used as a reference to detect the change in phase of the signal generated in the vertical z-axis coil and therefore polarity of the offset. Finn-Kelcey and Owen[44] used this principle to control their automatic tractor guidance system which was commercially available in 1969. The coils were mounted forward of the tractor front wheels on a beam parallel with the axle. The coils could be indexed along this beam so that a number of different passes could be made parallel to but offset from a single wire. By virtue of the coils' position ahead of the tractor the signal was a function of heading as well as displacement.

A technique for calculating a separate heading signal used by Young *et al.*[46] Jahns[47] as

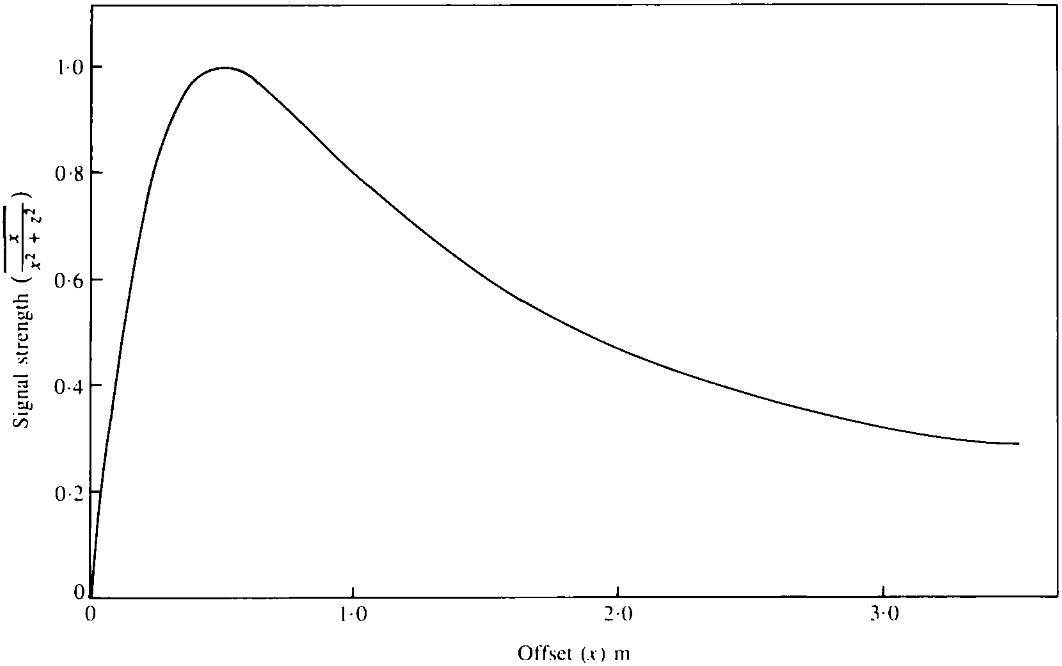

Fig. 6. Single strength vs offset for a vertical coil Vertical height of coil above wire z = 0·5 m

well as Telle and Perdok[48] utilizes a third coil horizontally mounted with its axis parallel to the direction of motion. When parallel to the wire the axis of this coil is perpendicular to the flux and no signal is generated. When the vehicle direction deviates from the wire a signal is generated whose magnitude varies with the sine of the heading angle. The phase of the signal will change through 180° as the heading changes from left to right.

For the purposes of control the signals giving offset and heading errors are combined in some predetermined ratio to provide a correcting signal. Barrett[49] patented a system primarily aimed at factory applications in which the vertical offset and horizontal heading coils were replaced by a single inclined coil. This single coil picks up both heading and offset information, the ratio being determined by its angle to the vertical. A horizontal phase reference coil is then used as previously described to give direction to the net error signal. Puckett *et al.*[50] used this system to guide an AGV for the distribution of forage and concentrated cattle feed. Rushing[51] used a similar principle when guiding an agricultural tractor.

3.5.2. *Balanced pair of horizontal coils*

Jahns[47] developed a system also used by Telle and Perdok[48] using a balanced pair of horizontal coils straddling the leader cable. *Fig. 7a* shows two such horizontal coils mounted with their axis parallel to the x-axis and perpendicular to the wire a distance $2\,d$ apart. They are symmetrical about the wire a distance z above and a distance r from it. The flux, ϕ, at each coil will be the same. *Fig. 7b* shows them offset by a distance x_1 so that the flux in each is different. *Fig. 8* illustrates how the resultant difference in signal strength between the two coils varies with offset.[45] The system is designed to operate in the range 0 to 0·8 m where the relationship between offset and signal strength is fairly linear. A heading signal can be derived by mounting a repeat pair of coils in line with but

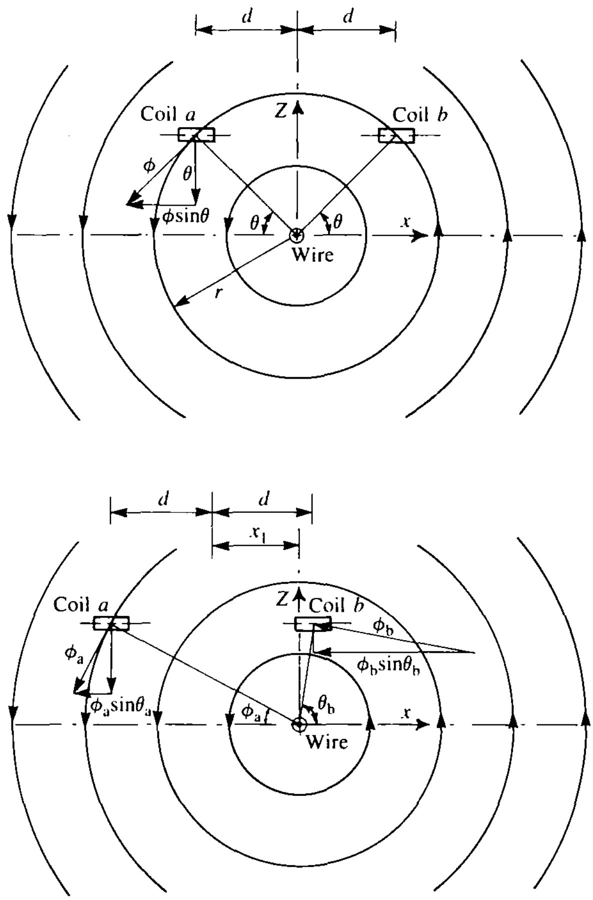

Fig. 7. Flux around horizontal pairs of coils (a) Coils arranged symmetrically about a wire carrying current in a direction out of the page. (b) Coils displaced horizontally by a distance x_1 *from the wire*

ahead or behind the first. In this configuration the sum of the front and rear signals varies with displacement error and the difference with heading.

The practical advantage of the balanced coil pair system described here, over the systems described earlier, is that there is no need to compare the phase of signals. As the centre line of a pair of balanced coils passes over the wire the polarity of the signal changes. The electronic circuits required are therefore less complex and simpler to set up. A disadvantage is that the coils need to be spaced apart giving a less compact system.

It is a common feature of the system described above that they operate with a null point over the wire. The position of this null point will be independent of fluctuations in field strength caused by varying cable depth, field wire current or any other factor. The magnitude of any correcting signal will vary with these factors and have the effect of altering overall control system gain. In general, satisfactory control will be retained over a wide range of system gain and so minor fluctuations in field strength will not have any significant effect.

3.5.3. "*Off wire*" *guidance*

A problem with operating over the wire at all times is that a relatively large number of wire runs are required. Brooke[52] developed a system where the coils could be offset from

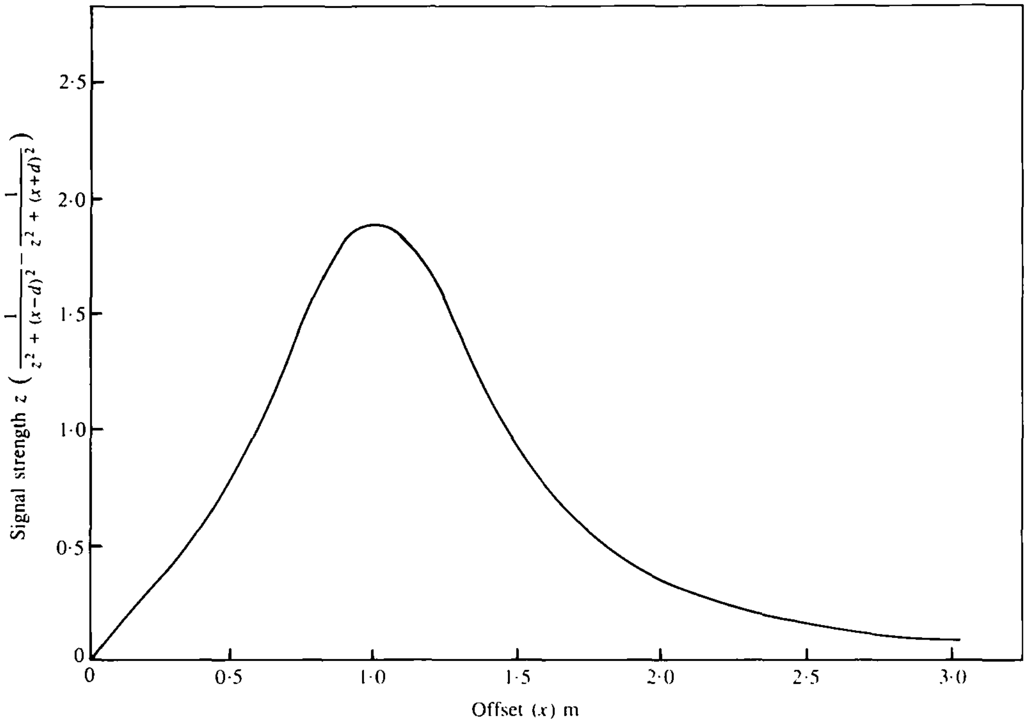

Fig. 8. Signal strength vs offset for pair of horizontal coils. Distance between coils, 2 d *= 2* m*. Vertical height of coils above wire* z *= 0·5 m*

the cable by a distance of up to 30 m and achieve an accuracy of ±300 mm. This system used two coils, mounted either side of the vehicle, with their axis vertical. When offset $x \gg$ height z the field is substantially vertical, and its strength is inversely proportional to x. With the vehicle running at an offset distance, x, from the wire and the coils symmetrically placed on either side a distance $2d$ apart then:

$$\frac{\phi_2+\phi_1}{\phi_2-\phi_1}=\frac{x}{d} \tag{5}$$

where ϕ_1 and ϕ_2 are the field strengths a distance d to the left and right of the vehicle.

Thus, the vehicle offset can be deduced from the ratio of signals in coils 1 and 2. The system is likely to be inherently less accurate than those previously discussed as signal strength gradient is shallower some distance from the wire. A limitation of "off the wire" systems is that they cannot operate in the transition region close to the wire where there is a substantial horizontal component to the field. "Off the wire" guidance depends on a ratio of signals and is not therefore affected by changes in absolute signal strength.

3.6. *Dead reckoning*

It is a feature of some of the previously described techniques that the guidance information is not continuous. Dead reckoning allows some form of guidance to be maintained between "fixes" from the location system. Most dead reckoning systems estimate relative vehicle position by recording the rotation of its wheels and steering angles. This method can be satisfactory on smooth concrete factory floors and has been used on such surfaces by Komatsu and Nakano[31] among others. Patterson *et al.*[41] used a record of the rotation of left- and right-hand wheels of a tractor-towed transplanter to estimate vehicle relative position between "fixes" from an ultrasonic guidance system (Section 3.4). Relative position deduced in this way is most accurate if the wheels are not under any driving load so that slip is minimized.

In order to improve the accuracy of tight headland turns between furrow following passes, Harries and Ambler [27] used a rate gyroscope. By integrating its output tractor heading relative to the start of the turn can be calculated. To improve accuracy further, particularly over long straight runs elapsed distance can be combined with heading information from a compass.

Gilmour[53] found that a gimble-mounted compass was insufficiently damped for this purpose and concluded that a gyro-compass is required. Such devices are commonly used on aircraft and boats for navigation and control purposes. With the exception of a laboratory study by Machardy[29] their high cost has up to now prohibited their use in agriculture.

4. Discussion

Despite a long history of research into automatic guidance the technique is not widely used in general agriculture. The agricultural environment introduces problems of both an economic and technical nature more extreme than those found in manufacturing industry where the technique is relatively common.

It is the extensive nature of agriculture which rules out, on economic grounds, the most common form of industrial guidance, leader cables. Not only do farms cover large areas but every part has to be covered calling for very long runs of wire. Utilization is also an economic problem, each route is covered only a few times in a year as opposed to several times a day within a factory. Cost effectiveness in this respect is also related to vehicle speed. The slower the vehicle travels the larger the saving in driver time. For this reason low speed horticultural operations, particularly multipass hand harvesting are the most likely to benefit. This is particularly true because straight line guidance only is required as the workers travelling on the vehicle can take over steering near the headland.

Low cost devices for retrofitting to tractors which mechanically follow a furrow have been commercially available for a number of years. Their use has been strictly limited for a number of reasons including, reliability particularly in stony soils or where the furrow has become eroded, the requirement to perform headland turns manually, and safety. The latter is particularly important and relevant to any semi-automatic guidance device retrofitted to a conventional tractor, as safe operation relies on the driver being close to the controls within the cab. For many, applications productivity could only be improved if the "driver" performed a productive task sitting or standing on a trailed implement such as a field vegetable transplanter. The cost of equipping conventional tractors with suitable fail safe auxiliary controls for operation out of the cab is high. Specialist vehicles such as mobile packhouses on the other hand can be suitably designed from the outset at modest additional cost.

Tillett and Nybrant[9] analysed the economic aspects of automatically guiding a 9 m span gantry for leaf vegetable production using leader cables. They concluded that leader cable guidance would provide a net annual benefit of £3000 when used on a 30 ha area of leafy vegetables, provided the land was continuously cropped. The effect of a one in three crop rotation with cereals which would require 90 ha to be "wired up" would more than eliminate this benefit.

In general, the extensive nature of agriculture will favour relatively sophisticated vehicle-mounted units which require little land preparation. The average tractor use in the production of 1 ha of cereals is given by Nix[2] as 11 h. Assuming that 90% of this is in the field and neglecting combine harvester time, the maximum annual saving in driver time is $10\,\mathrm{h\,ha^{-1}}$. Assuming the cost of employing a tractor driver to be £5 $\mathrm{h^{-1}}$ the maximum annual saving on a 200 ha arable farm is £10 000. In practice this would be reduced to £7000 by the requirement for some supervision. Although there are about 2000 workable hours in a year,[2] timeliness will require that more than one tractor be suitably equipped. On this basis it is likely that costs will exceed labour saving for the foreseeable future.

There are, however, a number of other benefits which may help to justify automatic guidance. In particular, systems which can map vehicle position within a field can be used to control applications of seed, fertilizer, water, pesticides etc on a spatially variable basis. This reduces input costs and environmental damage. Some of the systems reviewed here have this as the primary application rather than automatic guidance.[36,38] Accurate automatic guidance techniques capable of control to say ± 50 mm might facilitate mechanical weed control or spot chemical treatment in cereal crops for example. Existing tractor implement combinations are virtually impossible to steer sufficiently accurate for this purpose. With increased environmental pressure and product price incentives, mechanical weed control could become economic if the technology were available.

Technical problems result from the relatively unstructured nature of the agricultural environment. Variability in crops and within the soil make implement and engine transmission control a complex area which is likely to add considerably to costs for completely driverless operation. The full potential of automatic guidance cannot be achieved until these problems are resolved. The topography of farm land and the outdoor environment including rain and fog provide additional challenges, particularly for optical systems. Safety too is a particular problem as it may be difficult to exclude unauthorized people.

For automatic guidance to achieve widespread use, it will have to be very flexible and capable of satisfying the technical and economic requirements discussed above. None of the systems reviewed here and summarized in the Appendix achieve this. Leader cables satisfy the technical requirements but are generally too expensive to install. Radio navigation techniques as currently available are insufficiently precise. Scanning laser systems within the limitation of line of sight seem to offer some potential for the future. Systems which rely on specific ground or crop features have the virtue of being cheap to install. They cannot, however, provide reliable general solutions and are unlikely, therefore, to find widespread use. The only exception to this might be image analysis of a view from the vehicle. This might include the use of passive headland markers to provide absolute location within the field. The degree of machine intelligence required to provide complete guidance is beyond that currently developed. However, the rapidly advancing pace of this technology may provide solutions. Ultimately it may be necessary to provide guidance from two sensors, one such as radio navigation to determine where the vehicle is in the field and a second using computer vision perhaps to give the required accuracy relative to crop rows and obstructions.

The most promise for short-term progress in the economic automatic guidance of conventional agricultural vehicles would seem to lie with systems which aid but do not totally replace the driver. These would ease auxiliary control and safety costs but allow the driver to do his task better in some way. This might include spatial variability of inputs, mechanical weed control or faster workrates for example. An alternative direction for research on automatic guidance could lie in the development of an autonomous robot weeder. This robot vehicle could either mechanically destroy or spot apply chemicals.

While there are a number of difficulties in the identification of weeds, the vehicle could be relatively small reducing considerably the safety problems of controlling large agricultural vehicles. Slow speeds might be more easily justified as the robot could work 24 h a day with little supervision.

5. Conclusions

1. Despite the widespread use of automatic guidance in industry very few commercial systems exist in agriculture. This is due to the additional problems, both economic and technical, associated with the extensive and unregulated nature of the agricultural environment.
2. None of the techniques reviewed are sufficiently technically well advanced to economically provide the guidance required for general agricultural field operations.
3. Existing proven automatic guidance technologies such as leader cables are most likely to be economic in intensive, low-speed horticultural operations.
4. It is likely that two methods of guidance will be required in order to provide a general solution to the problems of automatic guidance in agriculture. One such as radio navigation would be used to determine where the vehicle is within the field and a second perhaps using computer vision to give the required accuracy relative to crop rows and obstructions.

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Appendix

Summary of automatic guidance techniques

Guidance type	*Approximate accuracy*	*Reliability*	*Compactness*	*Approximate cost*	*Agricultural applications*
Mechanical					
(a) Sensing of crop (Refs 3, 10, 12–15)	Variable, typically ± 50 mm	Very dependant on unbroken row of plants	Mechanical feelers protrude and are vulnerable	Potentially very low cost	Low speed straight line operation at a late stage of crop development particularly harvesting
(b) Sensing of a furrow (Refs 8, 16–18)	Typically ± 50 mm relative to previous furrow	Quite reliable	As above	As above	Low speed straight line operation after first manual pass
(c) Sensing of stretched or buried lines (Refs 11, 19)	± 20 mm for fixed features, ± 50 mm for buried lines	Quite reliable	As above	Low cost sensing equipment, but high site preparation costs	Where features already exist eg. drains or where the cost and inconvenience of stretched wires is acceptable
(d) Steel rails or concrete tracks (Refs 20, 21)	± 10 mm or better depending on installation accuracy	Very reliable	No ancillary equipment	Low vehicle cost, very high site preparation costs	Only suited to very intensive operations e.g. under glass
Optical					
(a) Laser (fixed beam or plane) (Refs 22, 23)	Only limited by diameter of beam and size of detector (approximately ± 1 mm)	Very reliable (based on drainage machinery)	Compact with detector set high on the vehicle	Commercial system available at £10 000	Straight line guidance where high accuracy is important and bed changes are infrequent e.g. planting out orchards and fruit
(b) Laser (rotating beam) (Refs 24, 25, 26)	± 150 mm to ± 5 mm depending on system and speed	Not proven	As above	Not known, but likely to be expensive	Capable of guiding all movement including headland turns, though the field must be relatively flat
(c) Infra-red to sense cultivated and uncultivated soil (Ref 28)	± 50 mm under good conditions	Not proven	Detectors mounted low down in front and behind	Not known	Straight line operation after first manual pass
Using Retroflective beacons (Ref 27)	$\pm 5°$ on bearing ± 100 mm on range over the range (4–22 m)	Not proven	Detector set high up and centrally on vehicle	Not known	As a supplement to furrow following guidance etc to give an absolute location within the field near the headland

(d) Visible light to sense the edge of a plough furrow (Refs 27, 30)	±50 mm	Dependant on unbroken furrow	Components overhang tractor	Not known	Straight line operation during ploughing after first manual pass
(e) Image analysis (Refs 32–35)	Potentially accurate	Dependant on continuity of guiding feature and robustness of algorithm	Compact with a single camera looking forward	£5000 for guidance hardware alone	Very wide potential application in following continuous features such as furrows, row crops etc
Radio Navigation (Refs 17, 36–38)	±0·3 m or worse	Very reliable	Very compact	Commercial system marketed for US $3500 in 1979	Accuracy limits use to operations on grassland or on crops at an early stage of development
Ultrasonic (Refs 37, 39–41)	99% over a range 0·1 to 10 m	Reliable where the surface is a good reflector and stray material cannot obstruct	Sensors are compact but require mounting close to feature being followed	Individual sensors cost approximately £100. System costs are not known	Guidance along a well-defined row of plant material possibly a furrow wall
Leader cable (Refs 9, 42–52)	±5 mm in factory environment, ±5 cm in agriculture (for on wire operation)	Good, though the life of cheap field telephone wire is unknown	Dependant on system, but generally compact	Sensors and control equipment £6000 £100–£200 ha^{-1} to lay cable[9]	Requires intensive operations where the same path is followed many times in one year to justify high cost ha^{-1}
Dead reckoning (Refs 27, 29, 31, 41, 53)	Very poor except over short distances where little wheel slip occurs	Good within limitations of accuracy	Compact	Relatively low cost except where gyro-compasses are used	Useful as an addition to absolute location and guidance techniques which cannot provide continuous information