Agricultural Automatic Vehicle Guidance from Horses to GPS: How We Got Here, and Where We Are Going

Presentations

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Agricultural Automatic Vehicle Guidance from Horses to GPS: How We Got Here, and Where We Are Going

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Abstract. *Automatic guidance based on GPS is a rapidly expanding technology in the area of precision agriculture. Its adoption is fueled by a quick return on investment, ease of operation and installation, as well as the availability of lower-cost system options. This report covers the history of the development of vehicle guidance from the early days of guidance to current and future applications with a focus on GPS-based automatic guidance. It also reviews GPS basics, the different correction sources typically used in agriculture, as well as future developments we can expect in Global Navigation Satellite Systems.*

Keywords: *Automatic guidance, Automatic steering, GNSS, GPS, Manual guidance, Vehicle guidance.*

1. History of Vehicle Guidance

Steering a farm vehicle is an extremely demanding task. The operator must drive on the desired path so as to not run over crops while minimizing overlaps and skips and continuously monitoring the operation of the equipment. The result is fatigue and poor driving performance, especially at night or in dusty conditions. These are some of the reasons for manual and automatic steering.

There is a long history of creating inventions to help a vehicle/implement driver space his planted rows uniformly. Starting in the 1870s, there started appearing numerous patents regarding row markers, foam markers, aids for manual steering, automatic steering sensors, and autosteering systems. Appendix A contains a survey of historical patents and is intended to give a bit of insight into how previous generations solved these problems. One of the most interesting of the early inventions (1913) was the Big Four tractor and its furrow-following automatic steering aid, shown in figure 1.1.

In two review papers, Jahns (1976, 1983) reviewed nearly 300 papers and 100 patents related to automatic guidance in agriculture. None of the techniques that Jahns examined were sufficiently robust to meet the needs of agriculture, and he said that "no universal system has been found." Jahns finally speculated that advances in computing power might "make a universal guidance system for agricultural vehicles by image recognition feasible."

Tillett (1991) described a variety of techniques, including sensors for following existing features (furrow followers and crop sensors, both mechanical and optical) and a wide range of navigation systems including optical, electromagnetic, and radio techniques. His two conclusions were:

"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."

With the arrival of GPS in the mid-1990s, many early adopters were soon routinely using GPS for manual steering. It was apparent that the most of the limitations of the previous techniques were not present with GPS.

2. History and Description of GPS

The Global Positioning System (GPS) is a worldwide radio-navigation system that consists of a constellation of 24 or more satellites, a number of ground stations, and millions of users. The GPS was developed by the U.S. Department of Defense starting in the 1970s as a military system (Parkinson and Spilker, 1996). Because of political and economic realities, it was opened to civilian use in the 1980s. In 1995, the system reached full operational capability; since that time, GPS has had a significant effect on agricultural practices (Buick, 2006).

GPS receivers have several levels of accuracy: modest handheld receivers costing less than $100 can determine your position to within 15 m (table 2.1). Slightly more expensive receivers using a second signal can position within 1 m using differential GPS, and the most accurate GPS receivers using a technique called real-time kinematic (RTK) positioning that can position within a few centimeters (Trimble, 2007).

To produce a GPS position, a GPS receiver receives signals from a minimum of four satellites. These GPS signals from the satellites are collected by an antenna, amplified,

Figure 1.1. Big Four tractor with automated steering.

Table 2.1. Typical GPS accuracies.

	"Autonomous" GPS	Differential GPS (DGPS)	Real-Time Kinematic (RTK)
Position	15 m or less (often much less)	1 m or less	2 cm or less
Velocity	0.5 km/h or less		
Time	Within 100 ns of Universal Coordinated Time (UTC)		

and converted to digital timing signals and satellite orbital data that are used to calculate the user's position.

The accuracy of GPS is affected by a number of error sources. Some of these errors are correctable by the use of differential GPS (DGPS), while other errors are not correctable. The most important uncorrectable error sources of GPS are caused by the receiver and antenna design, and multipath interference in the user's local environment. The most important DGPS-correctable errors are ionosphere-induced signal distortions, satellite timing errors, and satellite ephemeris errors. GPS errors also depend on the method of differential correction. The relative errors of a GPS generally grow with the time of observation. For example, the FAA Wide-Area Augmentation System (WAAS) is only rated to be a 5 m system; however, for short intervals of time, it can easily produce 0.5 m relative positioning accuracy. Figure 2.1 shows the relative error versus time for different correction techniques.

The availability of GPS depends on having a minimum number of visible satellites. Having more visible satellites provides a slight increase in accuracy and a big increase in availability. If one or more satellites (SV) are blocked by an obstruction, such as a building or tree, the user's receiver will still be able to compute a position as long as sufficient GPS SVs are available.

The orbital period of a satellite is approximately 12 h, so a user will see the satellites continuously moving. At any time, some satellites are rising while others are setting, and the number of visible satellites increases and decreases throughout the day. Figure 2.2 is a plot of elevation and number of visible satellites available for a user at 37° 23' N 122° 02' W for a 24 h period.

Each GPS satellite transmits a coded timing signal with its assigned pseudo-random number (PRN) code. The receiver decodes each of these timing signals with a specially constructed correlator dedicated to each signal. The correlator recovers the timing of the incoming signal for each satellite and compares this time measurement with the internal clock in the GPS receiver. The GPS satellites are synchronized so that they transmit their timing signals at the same instant, and the signals travel to the user's GPS receiver at the speed of light. The delay in the time of arrival of a satellite signal at the antenna depends on the distance of the

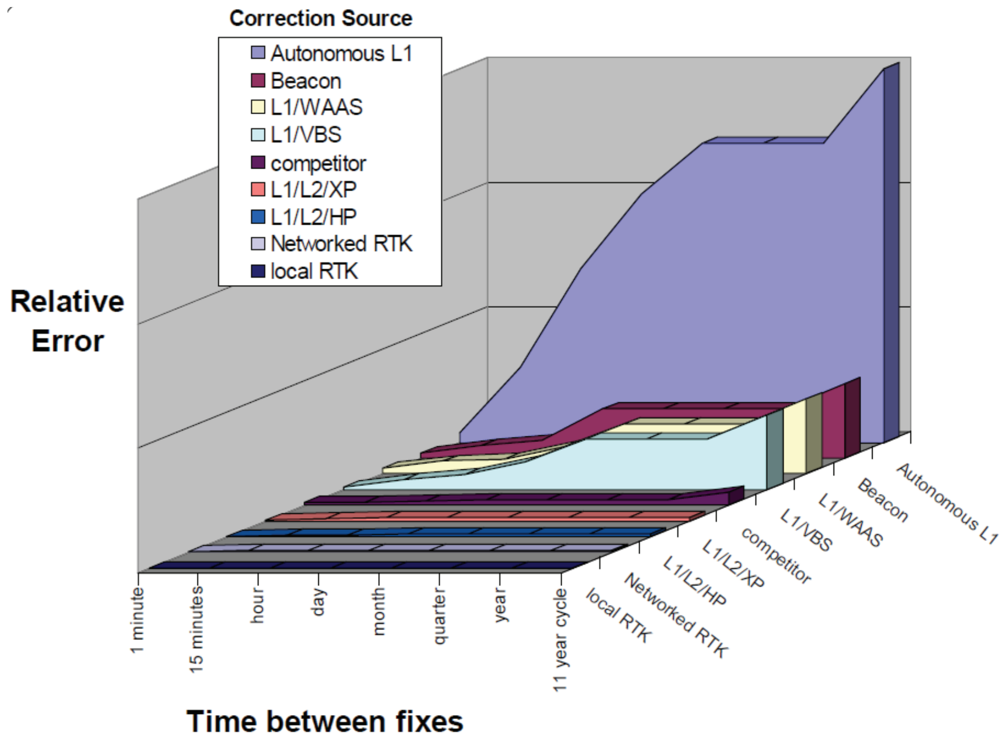


Figure 2.1. Accuracy vs. time vs. correction type.

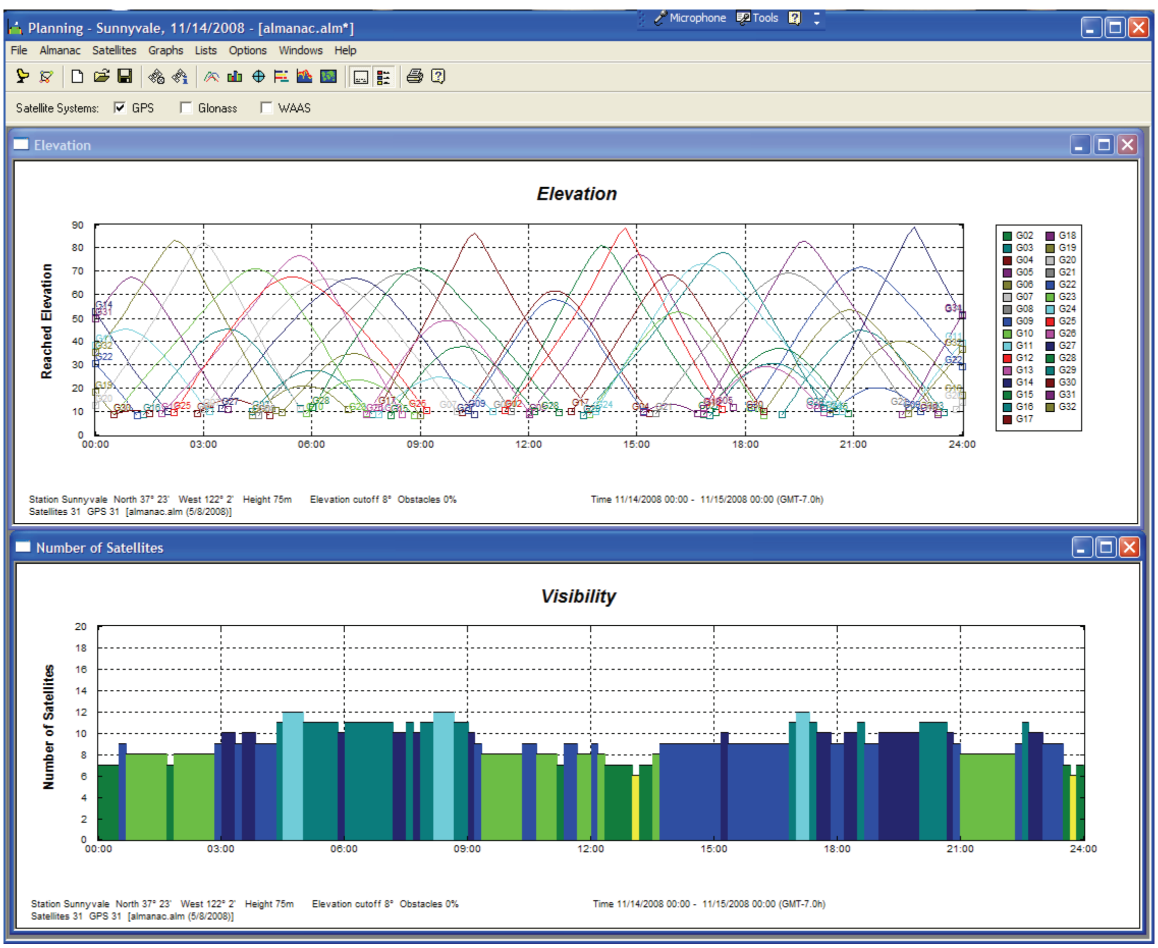


Figure 2.2. GPS satellite elevation and visibility.

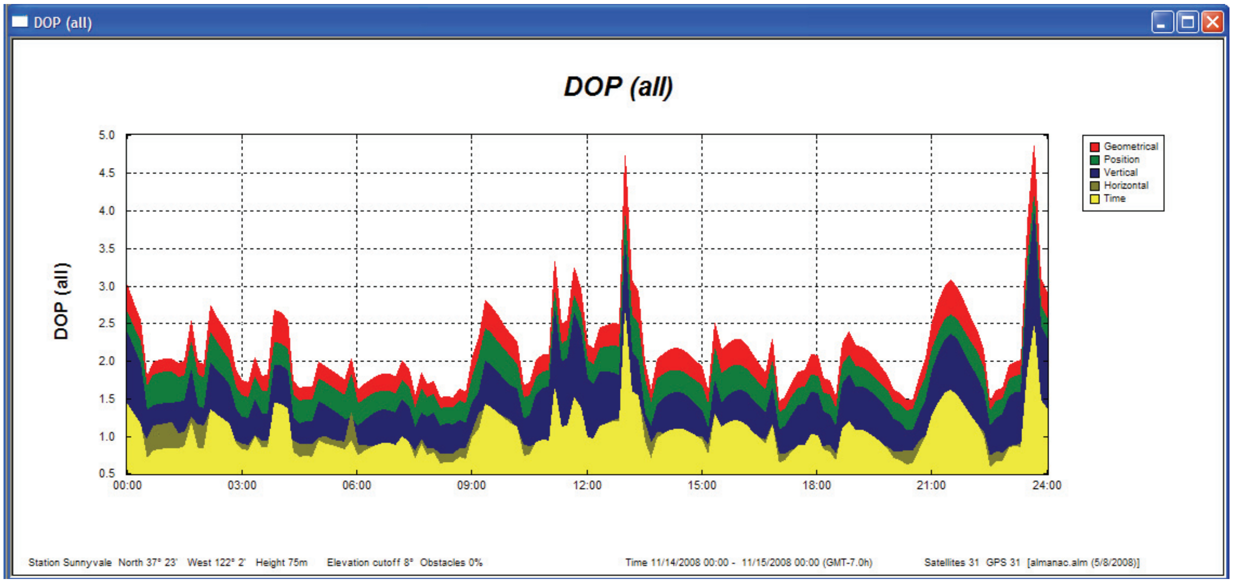


Figure 2.3. GPS dilution of precision (DOP) for time, horizontal, vertical, position, and geometrical.

satellite from the receiver (distance = time of flight × speed of light). The geographic coordinates of the receiver are computed using the time of arrival measurements for each satellite and the broadcast locations (ephemeris) for each satellite. This rather complicated computation is done by the microprocessor embedded inside a GPS receiver. The computation result is the determination of position, velocity, and time (PVT).

Causes of Reduced GPS Performance

Several factors can affect GPS performance and therefore guidance performance in the field. Some errors of GPS are correctable, and other errors are not correctable. The following sections describe the key variables that affect GPS guidance system performance.

Satellite Constellation and Geometry

The positions of the satellites in the sky and their movements influence GPS performance. Dilution of precision (DOP), including the subcategories of horizontal DOP (HDOP) and vertical DOP (VDOP), is a measure used to indicate good or bad satellite geometry: high DOP indicates poor satellite geometry, and low DOP indicates good satellite geometry. Furthermore, the blocking of some satellite signals to the GPS antenna by tall trees or buildings increases DOP and reduces GPS accuracy. GPS position errors caused by high DOP are not correctable. To obtain the best performance from a GPS receiver, the user should locate the antenna on the top of the vehicle to obtain an unobstructed view of the sky.

For guidance applications, users need to minimize horizontal error. Horizontal error is roughly proportional to HDOP. For land-leveling applications with an RTK GPS receiver, users need to minimize vertical error. Vertical error is roughly proportional to VDOP. Figure 2.3 shows the DOP values over a 24 h period.

Atmospheric Conditions

The ionosphere and troposphere layers of the atmosphere can introduce errors to GPS performance because a change in density of the atmosphere changes the speed of the GPS signal. This effect varies at different times of year and in different locations. Ionosphere effects are more noticeable at high latitudes because the GPS signal has to pass through the ionosphere at a more oblique angle. A main factor affecting the ionosphere is high sun spot activity, which increases atmospheric sources of error. For most of 2008, the sun has had relatively few sunspots. Sun Spot Cycle 24 started in late 2008, and by 2011 the number of sunspots will have increased significantly (figure 2.4). GPS position errors caused by ionosphere or troposphere variability are partly correctable by the use of differential correction. Because ionosphere errors increase with distance from the reference station, the user should choose the correction source with the closest reference stations to obtain the best performance during periods of high ionosphere activity.

Selective Availability

Selective availability (SA) was an intentional source of error in the GPS system introduced by the U.S. Department of Defense (DoD). This was removed in May 2000. Today, the U.S. DoD has another means of jamming the GPS system if required during times of combat. SA errors are correctable with the use of a correction signal. Local in-theater jamming of GPS by the military may prevent ordinary, non-military receivers from working.

Quality of GPS Receiver and Antenna Components

The components within a GPS receiver and antenna have a significant effect on the performance of the GPS receiver. If important components, such as the receiver's quartz oscillator, are low quality, then there will be more noise in the GPS position. High-quality GPS receivers ex-

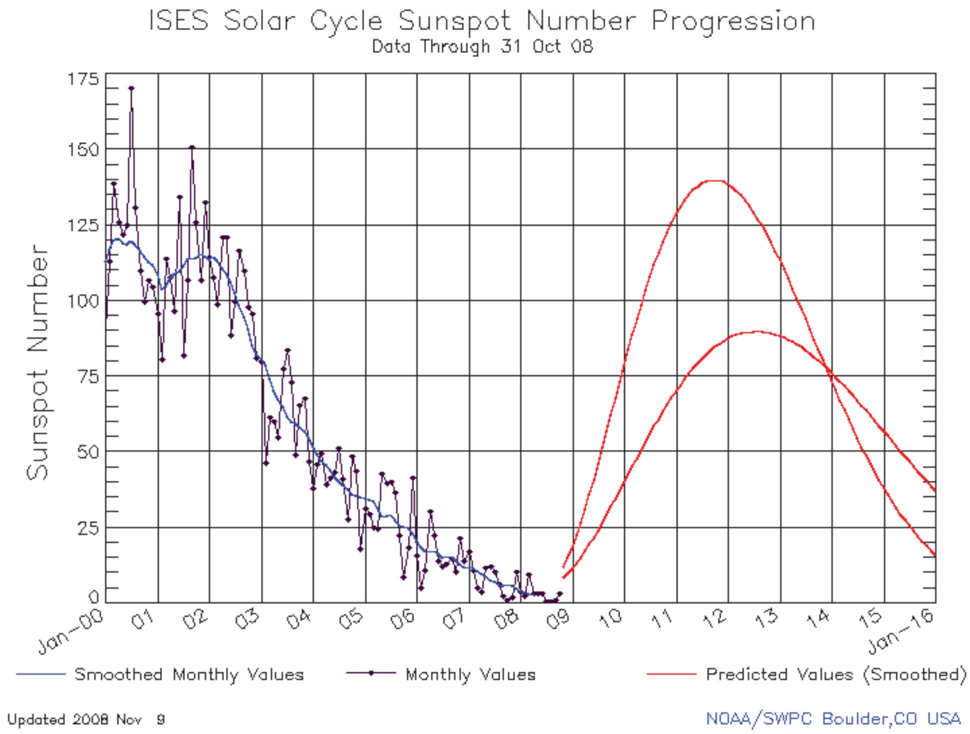


Figure 2.4. Number of sunspots observed and predicted.

Figure 2.5. Examples of two antennas: a very good geodetic-quality antenna with excellent multi-path rejection, and a very low-cost patch with poor multipath rejection.

perience less self-generated noise and provide a more consistently accurate position output. GPS position errors caused by the receiver design or components are not correctable.

Multipath and GPS Interference

The presence of tall buildings or certain reflective objects close to the GPS antenna can cause reflection of the GPS signal. This results in a phenomenon called multipath interference. Trees and other objects can also interfere with or block the GPS signal on its trajectory from the satellite to the GPS receiver.

GPS errors caused by multipath interference are generally not correctable. Some manufacturers utilize digital signal processing (DSP) algorithms to mitigate some of the effects of multi-path interference. If a receiver is in a local environment with severe multipath interference, then there is little that DSP algorithms can do. To minimize multipath interference, the user should location the antenna as high on the vehicle roof as possible and away from other communication antennas. Table 2.2 shows the magnitude of typical GPS ranging errors.

Filtering and Smoothing Algorithms in GPS Systems

Many GPS receivers and guidance systems have software that adjusts the performance to smooth variations. This includes filtering or smoothing in the software or firmware code to reduce the effects of satellite constellation and geometry changes. Inappropriate or excessive filtering may prevent the receiver from responding to sharp turns or may prevent an automatic steering control system from operating properly.

Table 2.2. Typical GPS ranging errors.

Error Source		Autonomous GPS	Differential GPS	RTK
User range errors (URE)				
System errors	Ephemeris data	0.4 to 0.5 m	Removed	Removed
	Satellite clocks	1 to 1.2 m	Removed	Removed
Atmospheric errors	Ionosphere	0.5 to 5 m	Mostly removed	Almost all removed
	Troposphere	0.2 to 0.7 m	Removed	Removed
	Typical URE	1.7 to 7.0 m[a]	0.2 to 2.0 m	0.005 to 0.01 m
User equipment errors (UEE)				
	Receiver	0.1 to 3 m	0.1 to 3 m	Almost all removed
	Multipath	0 to 10 m	0 to 10 m	Greatly reduced

[a] Ephemeris and clock errors are somewhat correlated and typically total less than the sum of the ranges for each.

Radio Frequency Interference (RFI)

There are many potential sources of electromagnetic noise that can affect GPS receiver performance. Sources include electronics, two-way radios and motors within an agricultural vehicle, power lines, microwave data links, and radar transmitters.

Tilt Compensation for and Roll

Terrain can have a significant effect on GPS performance. The advantage of adjusting GPS positions for terrain is most apparent with automated guidance systems because the accuracy improvement due to tilt compensation is not masked by driver error. The benefits of tilt compensation are large, for example, a GPS antenna mounted 3.5 m above the ground on a tractor will have an error of 6 cm for every 1° of roll.

Differential Correction Sources

Agricultural use of GPS has significantly expanded with the development of widely available differential corrections. Today there are four main types of differential correction available:

- DGPS radio beacons (e.g., U.S. Coast Guard DGPS beacons along major waterways).
- SBAS (Space-Based Augmentation Systems) such as WAAS (U.S. and parts of Canada and Mexico), EGNOS (Europe), and MSAS (Japan).
- L-band (e.g., Fugro's Omnistar differential service, and Thales Landstar differential service).
- Dedicated base stations and extensions of these.

GPS ranging errors for autonomous GPS and differential GPS are compared in table 2.2 for different error sources.

DGPS Radio Beacons

Approximately 40 countries worldwide offer radio beacon DGPS services to mariners and users in a wide variety of applications including mapping, surveying, agriculture, and vehicle tracking. Members of the International Association of Lighthouse Authorities (IALA) broadcast data free of charge in the Radio Technical Committee for Maritime Communications (RTCM) standard format. Depending on the user's equipment, these services can provide sub-meter DGPS accuracy, and provide reliable coverage to users on land, at sea, and in the air.

In some countries (e.g., Argentina), commercial services offer DGPS radio beacon transmission in agricultural areas Although DGPS radio beacons are only specified to meet 10 m absolute accuracy, numerous performance measurements with a nearby DGPS radio beacon usually have less than 0.5 m with a good-quality GPS receiver. In the U.S., DGPS from ground-based transmitters is sometimes referred to as national differential (NDGPS).

Advantages and disadvantages of using radio beacons include:

- It is a free service.
- It is available in at least 40 countries, but the coverage may not be ubiquitous.
- It is less obscured by objects, as the signal frequency tends to "hug" terrain and continue to travel over objects. DGPS beacon signals in the 300 kHz band propagate from the transmitter antenna to the user via a ground wave. This ground wave is generally unaffected by terrain and local foliage.
- It is best to operate within 150 km of the radio beacon for optimum performance.
- Accuracy degrades as the receiver moves away from the beacon reference station by approximately 1 m for every 160 km, depending on the ionosphere effects caused by sun spot activity.
- Beacon signals are susceptible to man-made (electrical noise) and natural interference (lightning). Since this beacon technology uses waves in the 285 to 325 kHz band, the interference is similar to that experienced by an AM radio.

SBAS (Space-Based Augmentation System)

Free satellite differential correction services are available in the U.S. as the Wide-Area Augmentation System (WAAS), in Europe as the European Geostationary Navigation Overlay Service (EGNOS), and Japan as the MTSAT Satellite-based Augmentation System (MSAS). These services broadcast in the GPS band and can be received using most standard GPS antenna/receivers, allowing for a very economical GPS hardware design. The accuracy of these free satellite services varies. The WAAS service in the U.S. is fully operational for safety-critical operations such as aircraft navigation and is specified to achieve 7 m absolute accuracy. Agriculture users have found WAAS to be a reliable source of correction, with an absolute accuracy of better than 1 m and a much better pass-to-pass accuracy. The EGNOS service in Europe and the MSAS service in Japan are designed to provide performance in their regions similar to that of the WAAS in North America.

Advantages and disadvantages of SBAS systems include:

- SBAS systems are free services (WAAS in North America, EGNOS in Europe, and MSAS in Japan).
- Usually a simple firmware update is required to activate a GPS receiver to receive the SBAS signal (if it is not already activated).
- The ionosphere models (i.e., software models in the system to reduce the effects of ionosphere errors) used in the WAAS system are relatively good, but they suffer during solar flares, which can cause transient variations in the ionosphere with resulting larger errors. The ionosphere model takes 12 min to download from the WAAS satellite; when the model has been updated in the receiver, there may be a small position jump.
- During periods of high ionosphere activity, such as during sunspot peaks in the solar cycle, the WAAS ionosphere models are not as accurate compared to when the sunspot numbers are low.
- Performance and signal reliability in outer regions of the coverage area (with WAAS, this is southern Mexico and northern Canada) may be reduced.
- The signal is line-of-sight, so it can be easily obscured by objects (e.g., tall buildings and trees) as compared to radio beacon signals, which are not as easily obscured.
- WAAS does not have a high-accuracy option similar to the Omnistar and Starfire systems.

L-Band DGPS

The two major suppliers of commercial L-band satellite-delivered sub-meter accuracy services are Fugro with its Omnistar service and Deere with its Starfire service. Fugro developed the Omnistar system to serve the very demanding offshore positioning industry associated with oil exploration and extraction. Omnistar provides almost complete worldwide coverage. The Starfire service is based on the Jet Propulsion Laboratory (NASA) system. Both of these commercial service providers have a high-accuracy offering that uses dual-frequency receivers and antennas for performance in the decimeter range (10 to 30 cm).

Advantages and disadvantages include:

- Almost complete global coverage
- Since these are commercial services, they are reliably maintained.
- L-band correction signals are less susceptible to equipment noise and electronic interference than radio beacons.
- Each service has a subscription fee.
- L-band satellite signals use line-of-sight and are more easily obscured than radio beacon signals.
- L-band services are more susceptible to ionosphere disturbances compared to ground-based services.

Dedicated-Use RTK Base Stations and RTK Networks

In agriculture today, real-time kinematic (RTK) GPS receivers are most commonly used for field topographic mapping for land leveling or drainage, or for automated vehicle guidance systems. Table 2.2 compares the GPS ranging errors for autonomous GPS, differential GPS, and RTK. Notice that significant sources of error are removed with RTK. Small residual errors remain, however, and these errors are caused by ionosphere disturbances.

Dedicated RTK base stations can be used to provide cm-level accuracy corrections (1 cm + 1 part per million (ppm) error in the horizontal, and 2 cm + 1 ppm error in the vertical). RTK accuracy notation includes an additional ppm error descriptor because RTK errors tend to increase as the receiver moves away from the base station. One ppm error is equal to 1 mm at 1 km. A radio link transmits the RTK data from the base to the GPS receiver. RTK receivers determine the number of wavelengths to the satellites (called a “fixed” solution). If the ionosphere errors or the distance to the base station are too large, then RTK receivers can fail to produce a fixed solution and remain in float, with an increased error. The typical specified range to a RTK base station is 10 km for a reliable fixed solution. The actual range for a reliable fixed solution varies depending on the state of the ionosphere. The range can be considerably greater during low sunspot activity. In cases of extreme solar storms with a very disturbed ionosphere, users may experience a significantly reduced operating range; fortunately, this does not happen often.

Typical RTK correction transmitters are specified have a 10 km range. The reliable distance at which a user can receive corrections from a base station depends on the transmitter power, the height of the transmit antenna, the terrain (e.g., hills) and obstructions (e.g., trees).

Arrays of RTK base stations are sometimes set up to cover regions that have a dense number of users. These RTK base station arrays work independently of one another; however, they are accurately surveyed relative to each other. The base stations are dispersed across an area with overlapping coverage “circles,” approximately 10 km apart. The coverage “circles” from each base station overlap each other at a radius of approximately 6 to 8 km. This gives users the ability to switch base stations as they move out of range of a base station. The array can be set up to cover any shaped area.

RTK virtual reference system (VRS) is a type of high-accuracy network. It uses a much more advanced approach than the RTK array described above. RTK VRS base stations are on the same coordinate system and are surveyed relative to each other; additionally, the data from each reference station is collectively used to provide a larger coverage area with fewer reference stations and improved ionosphere modeling. RTK VRS network base stations are placed at intervals of ~70 km from each other, encompassing a large area. Data is collected at each station and then sent to a central location for data processing. The data is processed to determine a "network solution" that allows for corrections, including ionosphere and troposphere errors within the network service area. Ionosphere and troposphere errors are greatly reduced by the VRS algorithms; however, small errors remain and will be seen during times of high ionosphere activity at larger distances from a network reference station. Typically, the RTK VRS data is transmitted to the user via cell phone. This allows for more freedom of movement, not restricting the user to a certain distance from the base. The user can move within the RTK VRS network without the need to switch base stations.

There are numerous RTK VRS networks operating in the world (e.g., Germany, Austria, Japan, Australia, and selected areas of the U.S.) supplying RTK cm-level correction over wide areas. For high-accuracy survey applications, these systems are typically operated by government agencies and referred to as a CORS (continuously operating reference station) network. The two primary suppliers of the systems used by these networks are Trimble (Network VRS brand) and Leica (SmartNet brand). RTK VRS networks are suitable for deployment in areas of high-value crops, where cm-level accuracy is required.

Other GNSS and Modernization Plans for GPS

There are a number of global navigation satellite systems (GNSS) besides the GPS in the U.S. For example, Russia has a system called GLONASS, Europe has the Galileo System, Japan has the Quasi-Zenith Satellite System (QZSS), and China has the Compass System (table 2.3). Each of these GNSS operates on similar principles to GPS and has an interworking strategy with GPS. In addition, GPS is undergoing a modernization program with the planned launch of new satellites with additional capability. This increase in the number of satellite systems with more capable satellites will improve both the availability and accuracy seen by users who purchase new GNSS receivers capable of using these improvements.

Increased Availability

With more satellites, a user will have a decrease in periods of high DOP caused by satellite failures or blockages, such as caused by trees on the edge of a field. Users will not be susceptible to having a single satellite failure cause their DOP to increase.

Increased Accuracy

The most important increase in performance of the new GNSS is additional satellite carrier modulations and additional operating frequencies. The original GPS satellites have two broadcast frequencies, L1 (1575.42 MHz) and L2 (1227.60 MHz). The L2 signal is modulated with the military P(Y) code. The current generation of satellites now being launched has an additional civilian modulation called L2C, which allows for an improvement in the operation of RTK receivers. The next generation of GPS satellites will

Table 2.3. Summary of public sources for DGPS corrections.

System	Name	Areas Covered	Frequencies	Status
Public Beacon Services				
NDGPS	Nationwide DGPS service	Continental U.S. and parts of Hawaii, Alaska, and Puerto Rico	285 to 325 kHz	Operational
Satellite-Based Augmentation Systems				
WAAS	Wide-Area Augmentation System	Continental U.S. and southern Canada	GPS L1	Operational
EGNOS	European Geo-Stationary Navigation Overlay Service	Europe	GPS L1	Partially operational
MSAS	MTSAT Satellite-Based Augmentation System	Japan	GPS L1	Operational
QZSS	Quasi-Zenith Satellite System	Japan	GPS L1, L2, and L5	R & D
GAGAN	GPS-Aided Geo-Augmentation System	India	GPS L1	R & D
Public Internet-Based Service				
CORS	National Continuously Operating Reference Station system	Continental U.S.	Internet and cell phones	Operational

have an additional frequency called L5 (1176.45 MHz) with an L5C (civilian) modulation. The L5C signal is transmitted at higher power than the original L1 signal.

With the addition of these signals and modulations, the GPS receivers capable of receiving them will be able to more accurately compute the magnitude of ionosphere disturbances and will therefore be capable of more accurate positions. This improved accuracy will have a larger effect during periods of high ionosphere activity, such as during the peak of the solar sunspot cycle in 2011-2012. The magnitude of the increased accuracy that a user will realize will be on the order of 0% to 50%. For example, a GPS receiver, operating with no differential correction, might have an L1 only positioning accuracy of 10 m; with the addition of both the L2C and L5C signals, an autonomous receiver will have an accuracy of around 5 m, a 50% improvement in accuracy. For an RTK user who is using an L1/L2 or L1/L2/L2C receiver, the addition of L5C will have a modest increase in accuracy. Near a base station, an RTK user may not realize any improvement with the use of L5C. Users of VRS (network RTK) will see improvements during periods of high ionosphere activity with the use of L5C, and the magnitude of the improvement will depend on the spacing of the reference stations in the network.

GPS Block III

GPS Block III is the follow-on to the current GPS system and is intended to be available through 2030. Block III satellites will provide more power and increased accuracy compared to the current Block II satellites. A new signal will be broadcast, L1C, which is intended to be compatible and interoperable with the planned Galileo system. The first Block III satellites are expected to be launched in 2013.

3. Manual Guidance and Lightbars for Agricultural Vehicles

Ground-based manual guidance appeared around 1995. Most of the companies that started selling in this market had already been selling products since the early 1990s in the aerial spraying market, where the high need for implement guidance meant that customers could tolerate higher early adopter prices. With the advent of lower priced, higher accuracy GPS receivers, manufacturers started selling their products to the ground-based manual guidance market, too.

The main components for manual guidance are:

- The GPS receiver.
- A user interface capable of displaying cross-track error information and receiving user input, such as the desired pass spacing and the location of the first guidance line.
- Path-planning algorithms capable of computing a cross-track error relative to a guidance line.

The system works as follows. When driving the vehicle, the driver manually makes steering adjustments to minimize the cross-track error displayed. The cross-track error is typically displayed in the form of LEDs, and the display device is usually called a lightbar (figure 3.1). The first systems to come out supported relative simple guidance patterns, typically straight parallel lines and adaptive curves. With time, manual guidance systems have grown in sophistication, and now higher-end models include color LCDs, 3D display modes, and additional functions such as logging, feature marking, and other more advanced mapping functions (figure 3.2). Modern systems also offer different GPS correction sources, typically from autonomous or WAAS based to L-band or higher.

Typical GPS accuracy used for manual guidance ranges from 5 or 10 cm to 30 cm pass-to-pass. Typical drivers are not able to follow guidance more accurately than about 10 cm, so having a very precise GPS source that is more accurate than this is not justified. At the high end, at least 12 inches of accuracy is needed in order for GPS guidance to provide better accuracy than traditional methods like row markers.

- GPS manual guidance adoption was very fast. Several reasons exist for the fast adoption of GPS-based guidance.
- Reduced skips and overlaps.

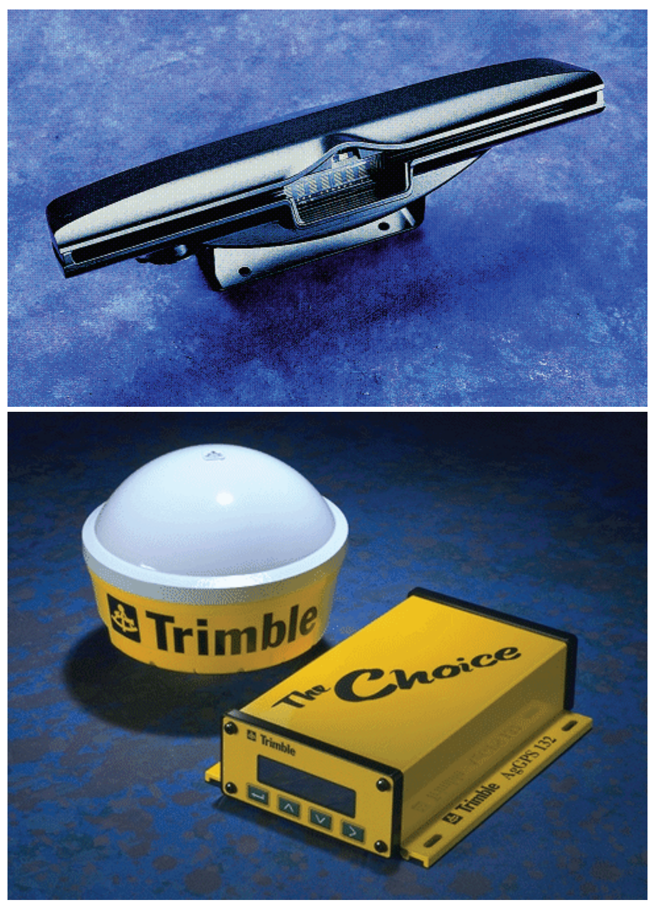


Figure 3.1. Early lightbar guidance: Trimble PSO.

Figure 3.2. Modern full-featured manual guidance system: Trimble EZ Guide 500.

- More accurate, less expensive, and more reliable than pre-existing guidance technology (row markers and foam markers). Additionally, GPS lightbars can be moved from one vehicle to another, providing higher return on the guidance equipment investment.
- Ability to operate at night and in low-visibility conditions without accuracy degradation.
- Ability to guide to fixed line guidance.

To explain this last point, it is important to review the two guidance modes: prior pass guidance and fixed line guidance.

Prior Pass Guidance

In prior pass guidance, *each* guide line follows a prior pass offset by a given distance. The first pass is typically called a "guess row." This method of guidance is the one naturally used by drivers in the absence of guidance devices. Examples of devices that that produce these guidance patterns are row markers and furrow or edge detectors.

This method of guidance can be useful when following a particular feature in a field, such as a water way or an irregular boundary. However, a limitation can arise due to error accumulation when unintended oscillations are introduced in one pass. The following pass will then tend to amplify these oscillations, making the eventual result undesirable. Farmers using this type of guidance typically end up leaving a gap between passes when error accumulates above tolerable limits, leading to wasted land.

Fixed Line Guidance

In fixed line guidance, each line is offset from a reference initial line (typically called the A-B line or the A-B curve) by a given offset distance multiplied by an integer. The offset distance is typically the implement width, and the integer is the pass number. The position of each line is independent of prior passes, and it is perfectly determined once the A-B line and offset distance are defined. An example of this is parallel line guidance in a regular field or concentric circular guidance in a pivot-irrigated field. One of the advantages of fixed line guidance is that error does not accumulate, making passes more accurate than prior pass guidance and rows easier to follow in subsequent operations.

Up until the appearance of GPS for guidance, very few practical methods for fixed line guidance existed. Fixed line guidance is a natural fit for GPS, where an A-B line and subsequent guidance lines can be easily defined and followed, without having the error in one pass accumulate to the next. This advantage allows for more accurate overall results. Note that GPS-based guidance can also be easily used for prior pass guidance by recording each pass and then, at the end of each row, computing a next pass line based on the recently recorded line.

4. GPS-Based Automatic Guidance

Automatic guidance started appearing on tractors around 1997. The first system was sold in Australia by a company called Beeline. Shortly after, Integrinautics and Trimble Navigation also introduced automatic guidance systems. Today, automatic guidance has been applied to tractors, self-propelled sprayers, combines, and towed implements.

- The main components of a modern GPS-based automatic guidance system include:
- The GPS receiver.
- A user interface capable of displaying cross-track error information and receiving user input, such as the desired pass spacing and the location of the first guidance line.

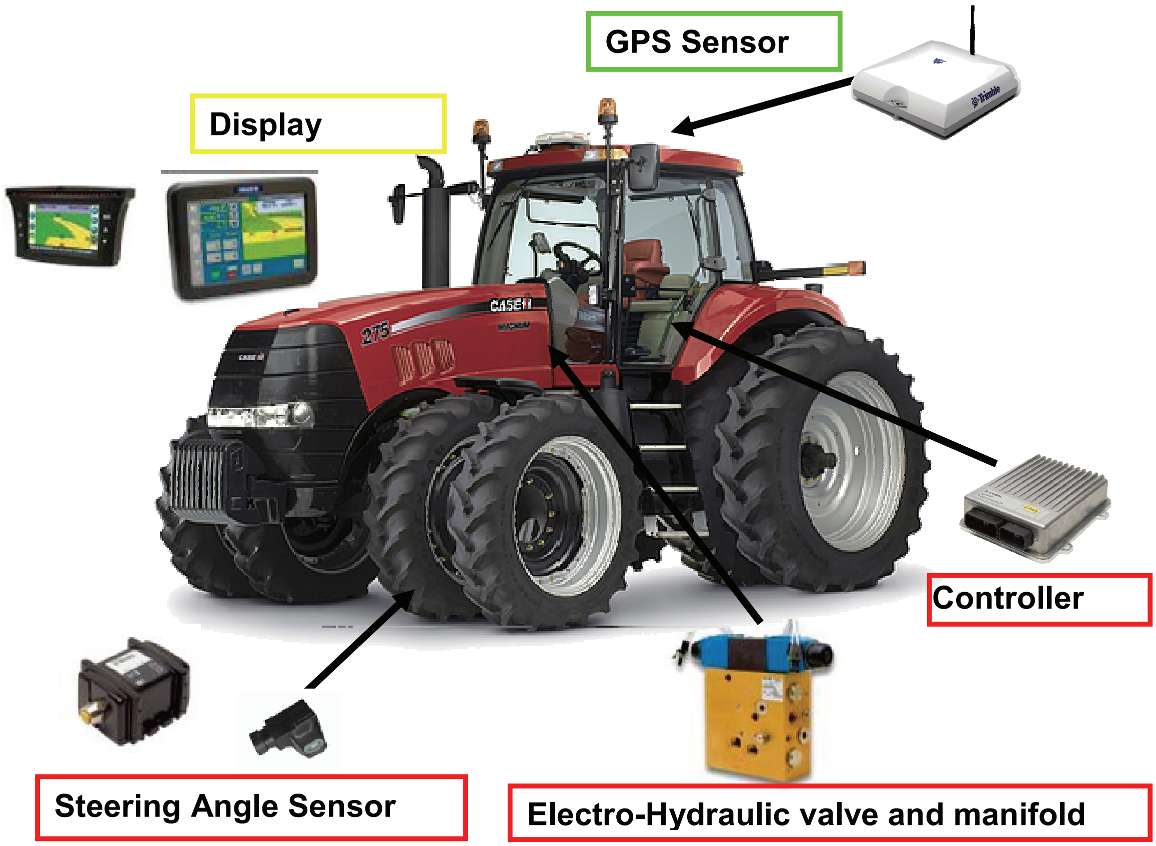


Figure 4.1. Main components of an automatic guidance system.

- Path-planning algorithms capable of computing a cross-track error relative to a guidance line.
- Vehicle steering actuators and manual override detector.
- Manual override sensors.
- Steering angle sensors (optional).
- Control algorithms and controller.
- Terrain compensation (optional).
- Other vehicle sensors such as wheel speed, reverse sensor, etc.

These components are explained in more detail on the following pages.

An automatic guidance system is similar to a manual guidance system, except the task of steering is done by a controller running controls algorithms and not the driver. The driver will typically push an engage button to allow the system to take control, guiding the vehicle to the closest guidance line. Manual control is typically resumed by simply moving the steering wheel.

When the system is engaged, the controller sends signals to the actuators, which then steer the vehicle to a path such that the cross-track error is minimized. For high-accuracy applications, a terrain compensation unit corrects the GPS position for the vehicle's attitude, and a steering angle sensor measures the current turning angle of the steerable wheels, which is used by the controls algorithm as an additional input facilitating closed-loop control.

Automatic guidance, like manual guidance, followed a very fast adoption path. Although the complexity and cost of an automatic guidance system is higher than a manual guidance system, an automatic system brings numerous additional benefits:

- Increased accuracy. Driver error is reduced by having a controller drive the vehicle, reducing the error in high-end systems to typically less than 2.5 cm. Some benefits of this are:
  - Reduced skips and overlaps. It is common for users to reduce the number of passes needed to cover a field by 5% to 10% when using a high-accuracy automatic guidance system. This saves chemicals, fuel, time, machine depreciation, etc., in every field operation.
  - The driver's particular driving skill does not affect performance. All drivers are now capable of producing the best results. This benefit is particularly liked by older drivers, who may not be able to drive as accurately as they once did.
- It allows higher-accuracy GPS correction, such as RTK, to be used effectively.
- Increased operating speed while maintaining high accuracy. For example, it is possible to drive a sprayer

down crop rows at high speed without risking crop damage, even when the crop is so tall that the ground cannot be seen.

- Ability to concentrate on important tasks. By removing the need to drive the vehicle, operators can focus on the more complex operations occurring behind the vehicle.
- Reduced fatigue. Driving a vehicle with high accuracy and at the same time controlling the different vehicle and implement operations can be exhausting. Having an automatic steering system take over steering can reduces operator fatigue.
- Increased vehicle utilization: This results in improved efficiency due to reduced skips and overlaps, faster operating speeds with reduced fatigue, and the ability to operate at nights. By working more efficiently and faster, a farmer can do more work with the same number of vehicles. A side benefit is the ability to more accurately time farm operations. For example, a farmer who knows that rain is approaching might decide to continue to work at night to finish planting before the rain arrives.
- Enable new farming practices, such as strip till, no till, drip tape irrigation, mixed crops, controlled traffic, and prescription application of seed and chemicals.

Typical Components of Modern GPS Automatic Guidance Systems

Vehicle Steering Actuators and Manual Override Detector

Steering actuators take the output commands from the control algorithms and alter the course of the vehicle. This is typically achieved by moving the steerable front wheels of a row crop tractor or sprayer, or the back wheels of a combine or swather, changing the articulation angle of the articulated vehicle, or differentially changing the speed of the tracks on a tracked vehicle. Different actuators are commonly used in automatic guidance.

Hydraulic actuators are typically proportional electro-hydraulic valves mounted in manifolds. The valves are typically solenoid valves, in which a current is passed through the valve coils to move a central spool. In proportional electro-hydraulic valves, the movement of the spool is roughly proportional to the current passed though the coils. The spool movement is used to control the direction of flow and the flow rate of oil. In the case of a row crop tractor, this controlled oil flow is used to actuate hydraulic steering cylinders, causing the tractor's steerable front wheels to move. Using similar techniques, vehicles using independent drive hydraulic motors (like sprayers) or even vehicles using variable-displacement pumps (like tracked tractors) can be steered.

Other types of valves include closed loop valves that use a linear voltage differential transformer (LVDT) to measure and control the exact placement of the spool and match it very closely to the commanded position. The use of a closed-loop spool position control allows these valves to be very precise and consistent with respect to the expected flow/current relationship.

Most typical hydraulic interfaces also include a manual override system to detect when the user has initiated a steering command by moving the steering wheel of the vehicle, indicating that the user wants to take control of the

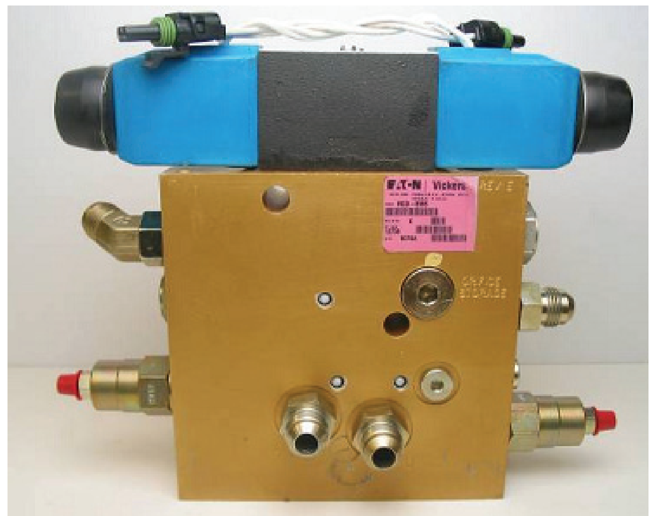


Figure 4.2. Electro-hydraulic valve and manifold used for automatic steering.

Figure 4.3. Precision machined spool used in electro-hydraulic valves.

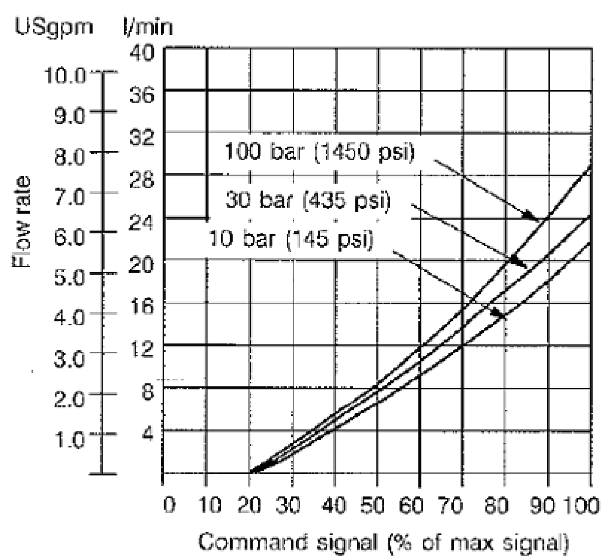


Figure 4.4. Flow vs. command signal curves for a typical electro-hydraulic valve.

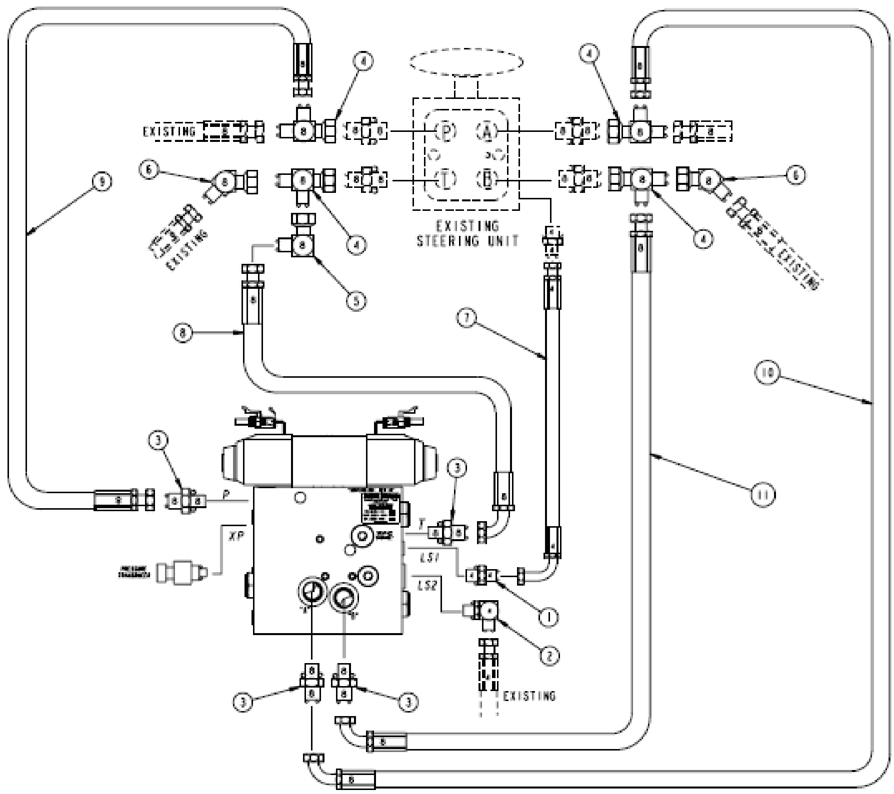


Figure 4.5. Diagram showing how to tie in the electro-hydraulic valve and manifold to a vehicle.

Figure 4.6. Caterpillar MT using automatic guidance over CAN network.

vehicle. This is typically achieved by using a pressure sensor in the steering load sense line or a flow sensor monitoring flow in or out of the manual steering valve (hand pump). Other override sensors commonly used include steering angle sensors mounted directly in the steering column that can detect when the steering wheel is moved.

Fly-by-Wire and CAN-Based Steering

Over the last few years, several agricultural vehicles have started to be factory equipped with *fly-by-wire and CAN-based steering* systems, in which steering commands can be passed to the vehicle steering control system via electronic commands. In particular, CAN (controller area network) based electronic steering is becoming more popular. In this case, when the system in engaged in automatic steering mode, the vehicle is set to receive CAN commands from the automatic guidance controller, and the desired turning radius is sent using pre-defined CAN commands to the vehicle's steering controller. The steering controller is then responsible for making the changes to the vehicle steering. Manual override signals and actual measured steering turning radius are also frequently passed back to the automatic guidance controller over the CAN network.

This scheme is conceptually simple and elegant, and it will likely continue to gain popularity, especially after standards continue to be defined and adopted. This is the only steering system type that does not require a parallel and redundant hydraulic system to support manual and automatic steering. The cost to incorporate automatic steering for CAN-based systems is the lowest of all approaches, with no compromise of performance.

Electric Motor Drive

Electric motor drive systems were introduced fairly recently to GPS automatic guidance, with the first system, the Trimble EZ-Steer, appearing in December 2004. In these systems, the actuators move the vehicle's steering wheel using a small electric motor. These systems are sometimes called assisted steering systems. These systems have become very popular, and today they rival, if not surpass, the number of hydraulic and fly-by-wire steering systems being sold.

Using an electric motor actuator to move the steering wheel to steer the vehicle has the advantage of being less intrusive. Installation time is typically shorter and usually requires less skill than a hydraulic installation. In addition, typical installations require fewer parts, which makes the electric motor system more economical. Some systems, such as EZ-Steer, can be easily moved from one vehicle to another.

Since many of the steering wheels for vehicles used in agriculture are similar to each other, another advantage is that creating interfaces for many vehicle types is usually simpler than for hydraulic interfaces. It is fairly common to find installation kits for large numbers of vehicles for most electric motor based systems.

A limitation of typical electric drive actuators is that the time it takes to turn a vehicle by a given angle is usually slightly longer than when using a hydraulic or fly-by-wire system. This limitation is driven by the practical size of the electric motor and the maximal practical speed at which a steering wheel can be turned in a safe manner. This means that a vehicle usually takes slightly longer to make corrections, which can lead to slightly lower accuracy than with hydraulic and fly-by-wire systems.

Given its lower cost, some manufacturers of electric motor drive systems have taken a further step to reduce the cost by removing the steering angle sensor from the steering wheel (see description of steering angle sensors below). Although the steering angle can be estimated from other inputs, this is usually not quite as accurate as measuring the steering angle directly. This leads to a small degradation in reaction time and accuracy. However, this also allows manufacturers to produce even simpler systems that are lower cost.

Manual override of these systems is usually achieved by monitoring the electric motor's current. In an electric motor, the drive current is related to the load on the motor: a large current means a high load. When a driver grabs the vehicle's steering wheel, a high load is produced, which results in a high current that the system can detect.

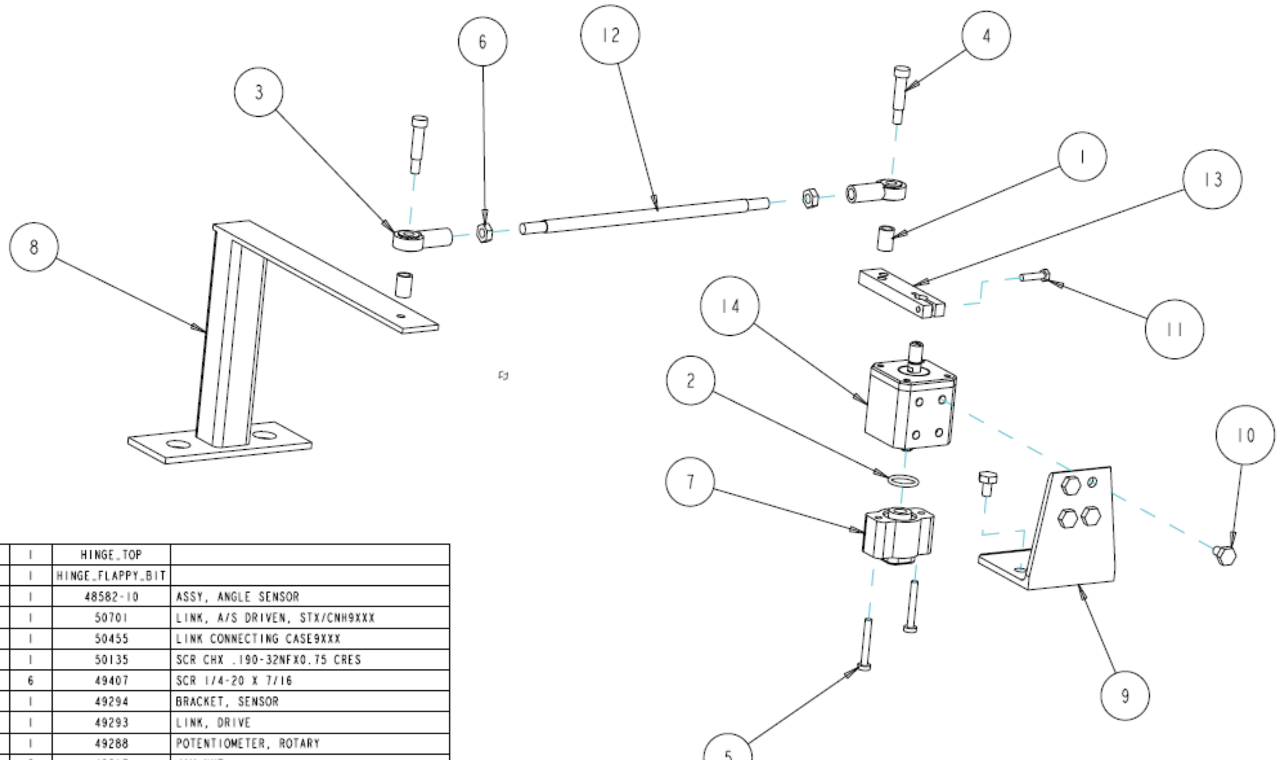
Steering Angle Sensors (Optional)

Steering angle sensors measure the angle that the steerable wheels make with the main axis of the vehicle, or in the case of articulated vehicles, the articulation angle. This angle is important, as it defines the direction that the vehicle will take (assuming no slippage) and provides excellent closed-loop control.

As mentioned above, a steering angle sensor is not always required, as it is possible to estimate this angle from other sensors and measurements. An example is by measuring or calculating the relationship between a given amount of movement of the steering wheel and the corresponding movement of the steerable wheel.

There are several ways to measure the steering angle. Some of the most commonly used are *rotary steering potentiometers and Hall-effect sensor*s. Both these devices measure the steering angle directly. A potentiometer is a device that varies its resistance as it is turned. A Hall-effect sensor does the same thing but uses a magnetic field to generate a small current in an electrical conductor. These devices are typically installed either directly over the king-pin or main axis of the articulation or linked to it though rigid linkages. A table or transformation function is then generated to translate voltages measured to actual steering angles.

Figure 4.7. EZ-Steer system by Trimble. The foam wheel makes contact with the vehicle's steering wheel.



ITM	QTY	PART NUMBER	DESCRIPTION
16	1	HINGE_TOP	
15	1	HINGE_FLAPPY_BIT	
14	1	48582-10	ASSY, ANGLE SENSOR
13	1	50701	LINK, A/S DRIVEN, STX/CNH9XXX
12	1	50455	LINK CONNECTING CASE9XXX
11	1	50135	SCR CHX .190-32NFX0.75 CRES
10	6	49407	SCR 1/4-20 X 7/16
9	1	49294	BRACKET, SENSOR
8	1	49293	LINK, DRIVE
7	1	49288	POTENTIOMETER, ROTARY
6	2	43317	JAM NUT
5	2	41346	SCR 10-24X1.25 SLT PAN HD
4	2	41345	SHOULDER BOLT, 5/16 X 1
3	2	41337	ROD END
2	1	41335	O-RING SEAL SENSR
1	2	40913	SPACER

50454_ROB_DWG

Figure 4.8. Typical steering angle sensor assembly.

Figure 4.9. Steering angle sensor measuring cylinder extension in a combine.

Although these devices are simple and effective, a difficulty is that installation over the kingpin is not always possible. When this happens, linkages are usually used. Depending on the exact design of these linkages, they can be more or less exposed, leading to a failure point.

Linear Sensors and Smart Cylinders

Linear sensors use a variety of technologies to transform length change into a voltage. A common approach is to use a variable-resistance linear potentiometer. An advantage of these sensors is they are usually easier to mount into a vehicle, leading to more reliable installations than using linkages.

A variation of linear sensor is the smart cylinder, in which the sensor is mounted inside a hydraulic steering cylinder. In this case, the hydraulic cylinder that actually moves the steerable wheels or articulation is replaced by a smart cylinder. In either case, just as in the case of rotary sensors, a table relating measured voltage and steering angle can be generated.

Terrain Compensation (Optional)

Terrain compensation has become a popular option in modern auto-guidance systems to compensate for the effect that varying terrain can have on the vehicle and on measured GPS positions. In particular, the effect of roll can be very significant and, if uncompensated, can be the major source of error.

In most systems, the GPS receiving antenna, which is the location from which GPS positions are calculated, is installed on the roof of the vehicle. This leads to antennas

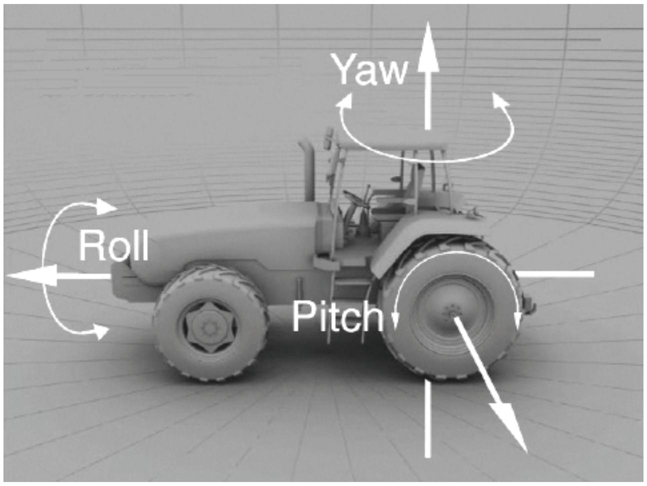


Figure 4.10. Roll, yaw and pitch in a vehicle.

being 3 to 4 m above the ground, allowing the GPS antenna to have an unobstructed view of the sky and the GPS satellites.

In order to guide the vehicle, the control algorithms must calculate the position of a point called the "control point." Given that the actual work done by most agricultural vehicles (e.g., planting, tilling, or harvesting) occurs at ground level, the control point is usually defined as a point at ground level or close to it. The control algorithms must therefore translate the GPS coordinates measured at the roof of the vehicle to the control point.

In the absence of a terrain compensation system, the best that can be done is to assume that the control point is directly below the GPS receiver. However, in the presence of a side slope, this can be inaccurate. When the antenna is at a height of 3 m (about 9 ft), 1° of roll corresponds to 5 cm (about 2 in.). See equation 4.1:

$$Roll\_offset\_dist = height \times Tan(roll\_angle)$$

Equation 4.1. Roll compensation distance.

When terrain compensation is available, the vehicle's roll, yaw, and pitch (also referred to as the vehicle's attitude) can be measured and compensated. Roll is usually the main effect that needs to be compensated and where the largest gain is. However, yaw and pitch can also have an effect in the presence of slippage (crabbing), tight turns, and up/down hills and can be important to achieve high accuracy.

Inertial Sensors: Accelerometer and Rate Gyros

Inertial sensors are sensors that measure changes in inertial forces. At the time this report was written, the most common type of inertial sensors used were micro-electromechanical system, or MEMS (also referred to as micromachines in Japan and micro systems technology, or MST, in Europe) accelerometers and MEMS rate gyroscopes (sometimes simply called gyros). MEMS refers to a class of devices composed of very small structures created on semiconductors. The structures are between 1 to 100 μm in size (i.e., 0.001 to 0.1 mm). MEMS accelerometers measure linear acceleration, and MEMS rate gyros measure the change in rotational speed.

Typical structures in inertial sensors include cantilever structures such as multiple microscopic thin walls and valleys that deflect by minute amounts when subjected to inertial forces such as linear acceleration or rotational acceleration. These small deflections are accurately measured using different techniques, including capacitance measurements, which are then amplified to produce output readings.

MEMS inertial sensors are typically small, with some being as small as a few millimeters. They also come in a variety of prices and performance levels and can be found in many applications, including automobile air bag deployment and dynamic stability control, camera image stabilization, and consumer devices such as the Nintendo Wii and Apple's iPhone. Their design and construction make most of these devices very reliable, rugged, and relatively accurate. The global market for MEMS devices totaled about $40 billion in 2006, according to the report Global MEMS/Microsystems Markets and Opportunities by Yole Development and SEMI (2008),

Using accelerometers and gyros, it is possible to measure the six degrees of freedom, i.e., *X*, *Y*, and *Z* translations and rotations around these axes, or yaw, roll, and pitch.

Multiple GNSS Antennas

Another method used to measure a vehicle's attitude is to install an array of antennas on the vehicle's roof and then very accurately measure the positions of the antennas relative to each other. In simple terms, if two antennas are mounted on the roof, one on the left side and one on the right side, then their relative heights will indicate the vehicle's roll and their relative forward positions will indicate the vehicle's yaw. Using three antennas, with the third antenna mounted forward of the other two, it is possible to measure pitch.

Path Planning

Path planning is a generic term used to describe the set of algorithms that determine where the vehicle should be guided. Most modern automatic guidance systems support a variety of guidance patterns to match planting practices.

Some examples of these patterns include:

- Parallel (or straight) line guidance, in which each new swath is parallel to a master line (usually referred to as an A-B line) and offset perpendicularly to it by a given amount called the swath width. This is an example of fixed line guidance, as mentioned in the prior section.
- Curves, in which the original swath is curved and each point of the new swath is offset from the previous swath by a given perpendicular distance (the swath width).
- Adaptive curves, a pattern similar to curves, but if the user takes manual control, the new path is recorded and acts as a master swath for the next pass.

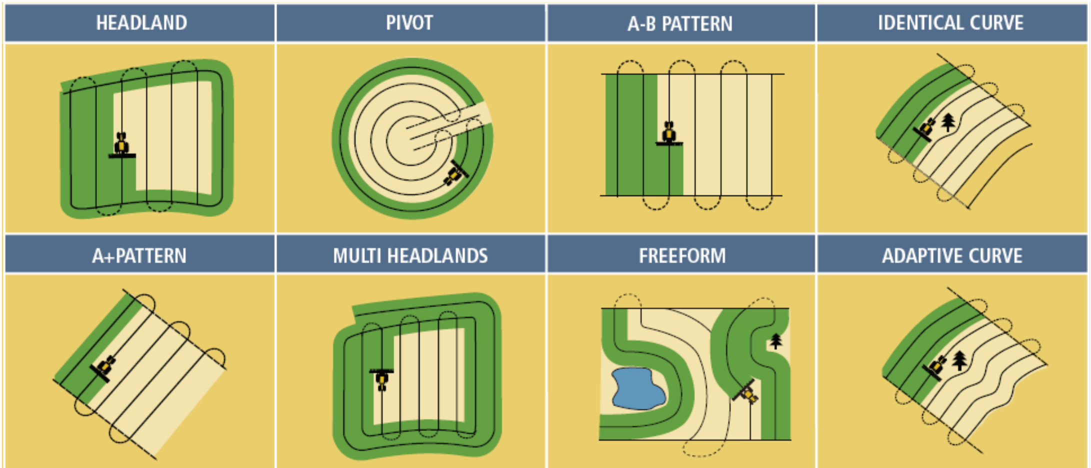


Figure 4.11. Example of the different guidance patterns offered by a modern guidance system.

- Pivots, in which the swaths are concentric circles separated by the swath width.
- Spirals, in which each swath grows concentrically by the swath width. This pattern does not need to be limited to circular spirals; in some cases, rectangular or arbitrary shapes are used.

Path planning algorithms calculate the desired path and the cross-track error. Once a guidance pattern is selected, the user is typically required to define the first pass. Depending on the selected guidance pattern, this is accomplished in a specific way. For example, when using parallel guidance, the user is asked to drive to point A, at the beginning of the first pass and press “mark A.” The user is then asked to drive to point B, a point along the first pass, and press “mark B.” This defines the first line. The user is then asked to enter a swath (or implement) width. This defines the distance between lines. In some systems, the user can also define a field boundary, which can be helpful for additional functions like end-of-row warnings, area calculations, remaining field area, etc.

In curved guidance, a similar procedure is followed, except instead of defining a straight line by selecting points A and B, the user is asked to drive along the first pass while the system records the points along it that define the curve. Additional curves are then defined by using algorithms that create lines that maintain a set distance equal to the swath (or implement) width. Equidistance is an important consideration in curves, as each subsequent swath should maintain a fixed distance to the next swath that is equal to the implement width. When possible, the implement width should not vary along curves; otherwise, skips and overlaps would be created. In order to maintain equidistance, curves cannot be parallel or exact to each other. Instead, curves have varying turn radii (figure 4.12).

When the guidance lines are defined, given a vehicle position, the path-planning algorithms can calculate the closest swath and corresponding cross-track error. Some algorithms also calculate the heading error, which is the angle between the current vehicle heading and the heading of the swath.

Control Algorithms

Control algorithms use the cross-track error and heading error calculated by the path-planning algorithms to calculate the steering corrections that the vehicle must then apply in order to minimize cross-track error and heading error. There are many existing algorithms used to accomplish this. Some common approaches are discussed below.

Tuning-Based Control Algorithms

Tuning-based control algorithms (Franklin et al., 1990; Levine, 1996) assume a fundamental structure for the tractor's motion (kinematics) in response to the steering angle. A typical example is the ubiquitous PID algorithm, consisting of a proportional, an integral, and a differential component (figure 4.14).

The PID algorithm assumes that the tractor’s kinematics can be approximated as a first- or second-order differential equation. However, no attempt is made to establish the actual parameters of that differential equation, that is, by explicitly developing a model for the tractor kinematics. It is assumed that a suitable choice of P, I, and D gains will result in acceptable behavior of the tractor. Those gains are established by trial and error (tuning). Once established, they need not be retuned for the same tractor.

Model-Based Control Algorithms

A parametric model for the tractor’s kinematics is the basis of the model-based method. Typically, a linearized “small-signal” differential equation model is used. One such model is shown in equation 4.2:

$$\frac{d}{dt}(heading) = \frac{speed}{wheel\_base} \cdot steering\_angle$$

$$\frac{d}{dt}(lateral\_position) = speed \cdot heading$$

Equation 4.2. Model based differential equation.

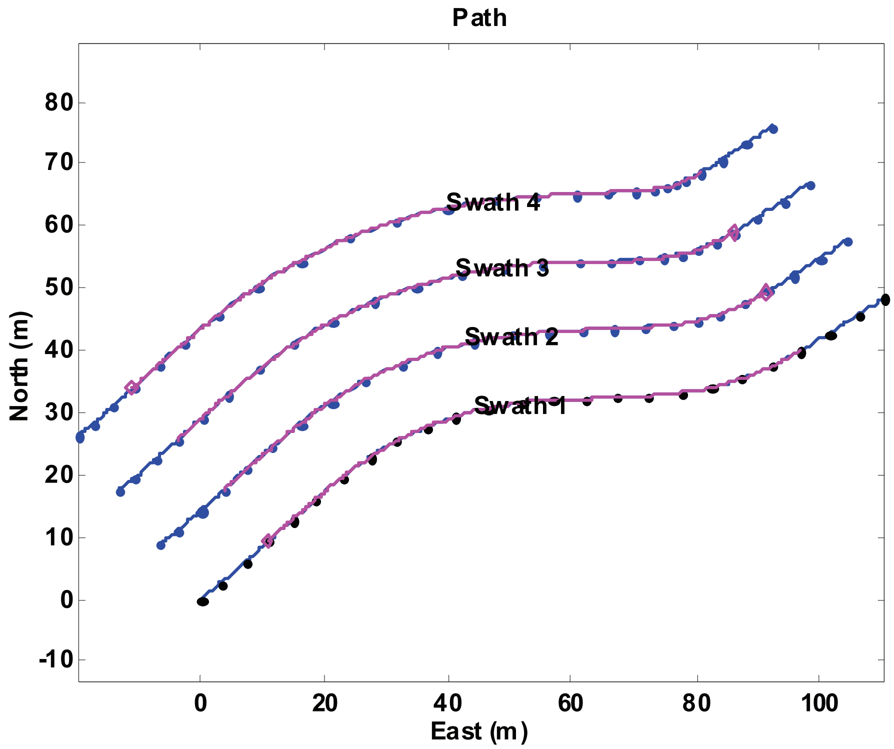


Figure 4.12. Example of curved swaths. Note how the turning radius changes with each swath.

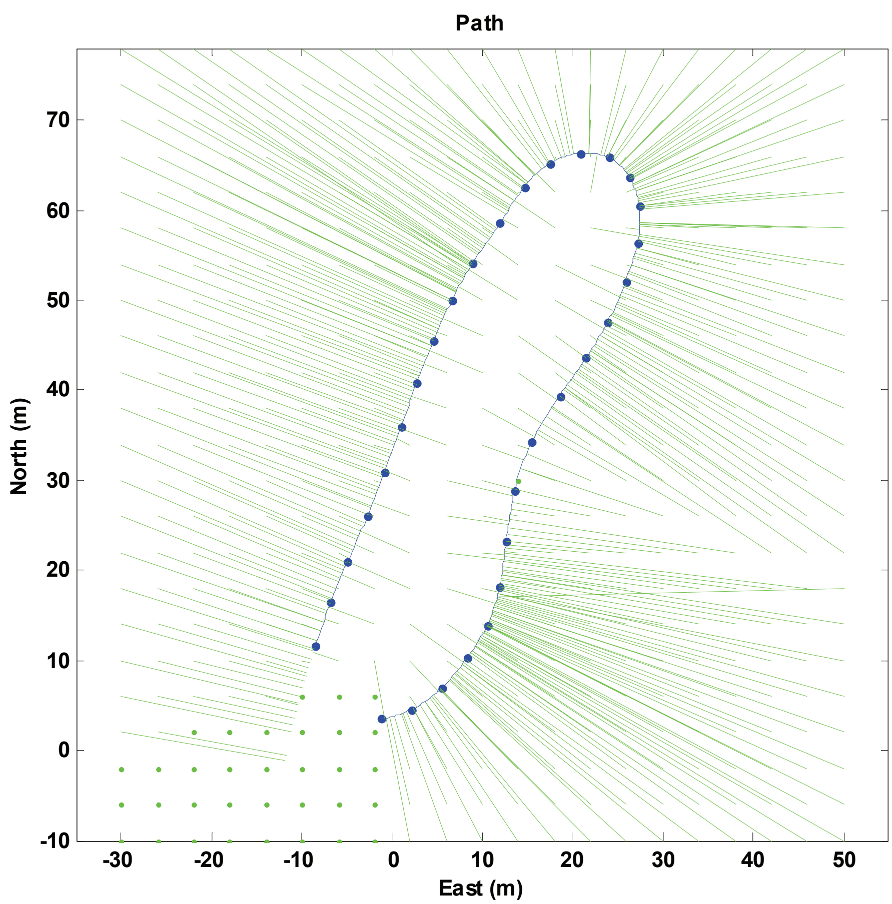


Figure 4.13. Given a vehicle position and a guidance line, algorithms can calculate the cross-track error as shown.

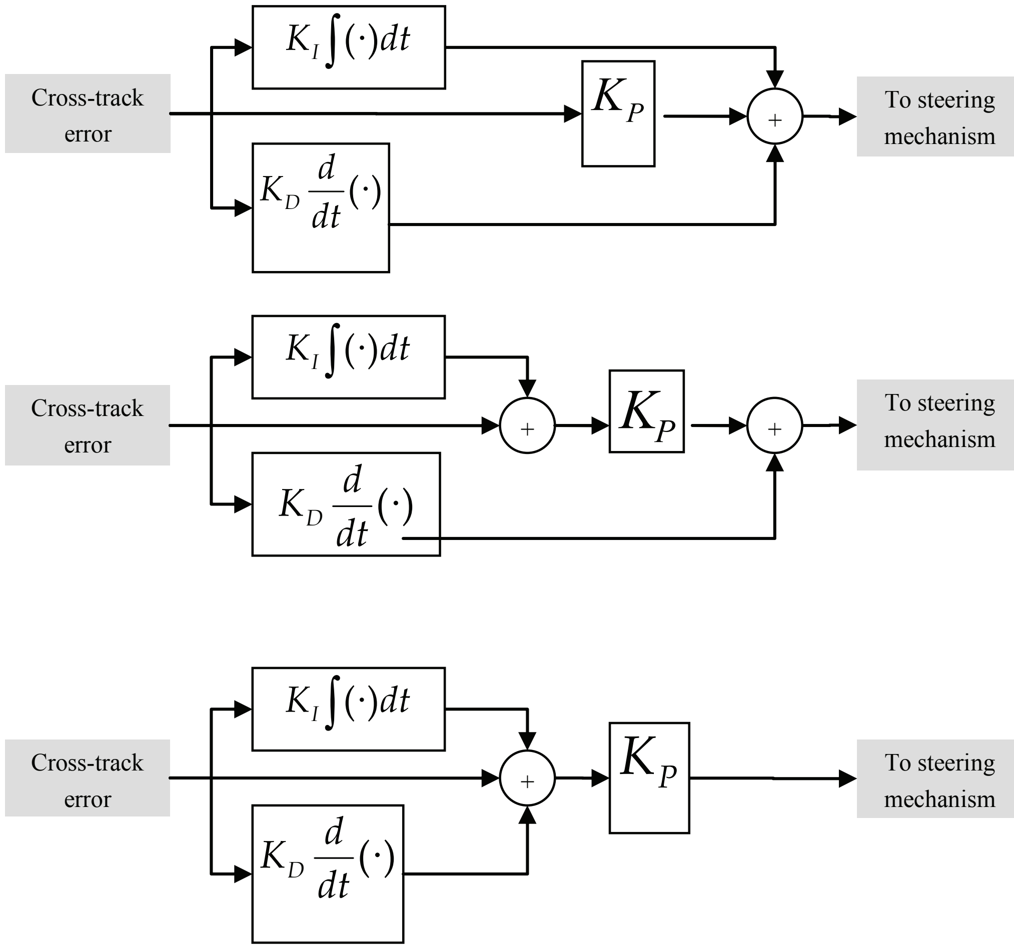


Figure 4.14. Different gains for the PID algorithm provide different intuitive "feel" while tuning.

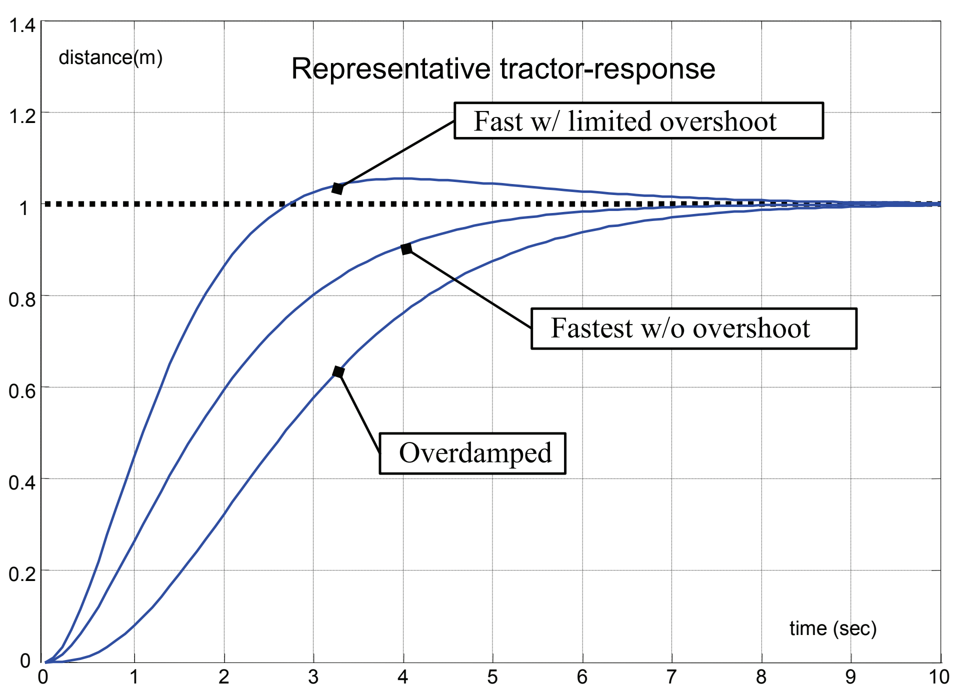


Figure 4.15. Typical response types for a tractor with a wheel base of 1 m, traveling at a speed of 1 m/s.

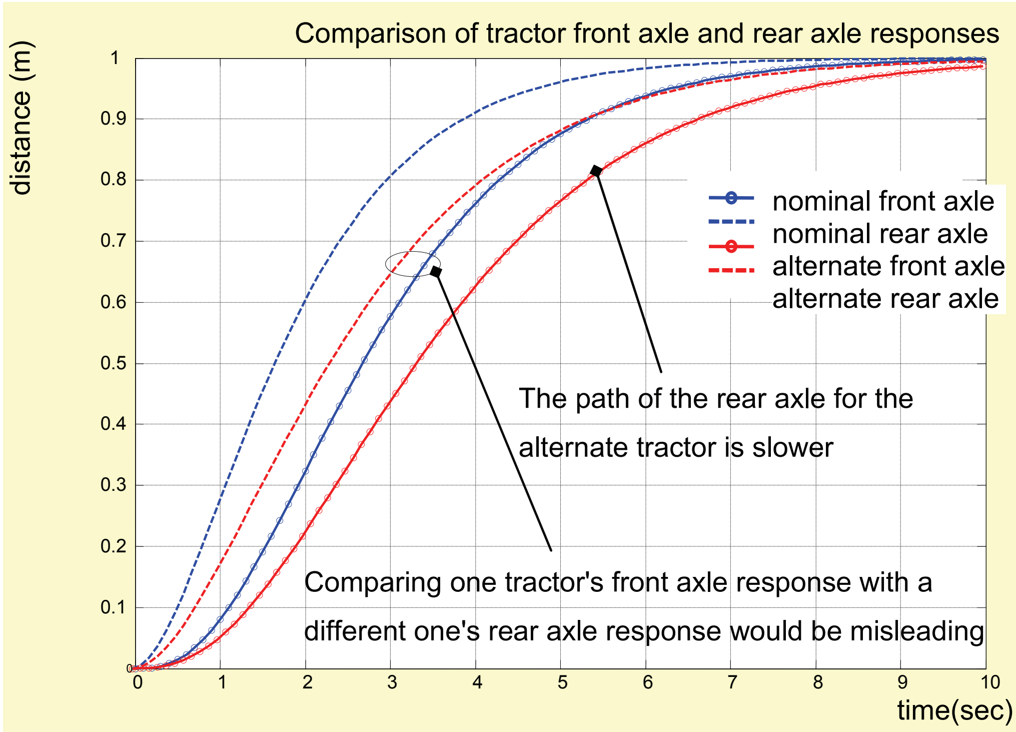


Figure 4.16. Comparing the front-axle response to the rear-axle would be misleading.

The design then keeps the parameters (*speed* and *wheel_base*) explicitly in the solution. One advantage of this method is that the control performance can be maintained at any speed and for any tractor of different wheel base.

For either PID or model-based designs, parameters are chosen to yield a fast settling time with little or no overshoot. Typical responses are shown in figure 4.15, normalized for speed and wheelbase (1 m/s and 1 m, respectively).

Control Point Considerations

The behavior (response) also depends on the placement of the GPS antenna, and the difference is not necessarily obvious to the operator. For instance, an antenna placed over the front axle would register a comparably good response when plotted (figure 4.16, dashed line versus dotted line). At that same time, the rear axle would prescribe a lethargic response.

Methods have been developed to accommodate the difference between the antenna's preferred position and the practical position. For instance, the top of the cab is often the practical place for the antenna, but not necessarily the best location for the preferred tractor response.

Additional Considerations

No matter what design method is used, there are a number of difficulties to overcome. One limitation on control performance is imposed by the steering actuation. Every steering hydraulic system has a limit on its steering rate and on its lock-to-lock range. The control algorithm must take into account that the steering cannot be moved faster than at a certain maximum rate and nor past a maximum angle.

A poorly designed or poorly tuned controller will have difficulty moving the vehicle smoothly to the A-B line. These problems become particularly noticeable when the vehicle is relatively far away from the A-B line, which requires the controller to make large corrections. The tractor may cross the A-B line several times before locking on. In extreme cases, it may never recover and become unstable, resulting in an automatic disengagement, accompanied by an alarm to the operator.

The minimum safe turn radius for any given speed must also be handled properly. At higher speeds, the control algorithm may restrict the maximum steering angle to avoid the chance of lateral instability.

5. Implement Guidance

A recent expansion to the area of automatic vehicle guidance is the use of automatic implement guidance. This is a natural extension because, after all, the implement is the actual device doing the field work. It is possible for the vehicle to follow the desired path but have the implement completely off its desired path. The cause for this are side forces acting on the implement caused by operation on a side slope, vehicle attitude and slip, and unevenness of the ground drag on the implement.

Many large and heavy implements, especially those commonly used on side slopes, have had provisions for steering for many years. For example, steerable potato planters are available from several manufacturers. More recently, automatic guidance of implements has become

Figure 5.1. Test results of automatic vehicle and implement steering in a 12° slope field. Without automatic steering, the implement would have sagged down 60 cm. With implement steering, this is limited to 2.5 cm.

more common. Companies like Orthman Manufacturing, Sunco, and others have created systems that guide implements automatically or semi-automatically. In recent years, these systems have been tied to GPS-based steering systems, providing remarkable results, like the ones shown in figure 5.1.

Towed and Three-Point Hitch Implements

Different compensation techniques are required, depending on whether the implement is mounted on a three-point hitch or towed behind the tractor. Towed implements are particularly susceptible to lateral drifts for various reasons. For example, along lateral slopes, a towed implement will slip downhill behind the tractor due to the lateral component of the implement's weight. Other factors also cause the implement to wander. For example, asymmetrically loaded implements will not follow the tractor's path.

For many applications, it is best if the implement is also controlled, not just the tractor. Controlling the implement and not controlling the tractor is not recommended, because the operator would have to spend substantial effort to maintain the tractor heading at least in the vicinity of the path without destroying the rows. Therefore, typically, an implement controller is used in addition to a tractor controller.

The advantage of implement control becomes immediately evident on rolling hills. The lateral component of the implement's weight causes the implement to slip downhill behind the tractor. The schematic representation in figure 5.2 shows how a towed implement drifts as the slope changes.

While one may think that a three-point hitch would avoid implement weaving, that is not quite the case. Suppose the tractor's rear axle is the "reference point" of the tractor's autopilot. In that case, a yaw (crab-walk, inevitable along slopes) in the tractor's attitude will result in an offset, albeit small of the implement's path (figure 5.3). The implement can also drift due to other reasons, such as asymmetric geometry of the implement and asymmetric variations in forces acting upon it.

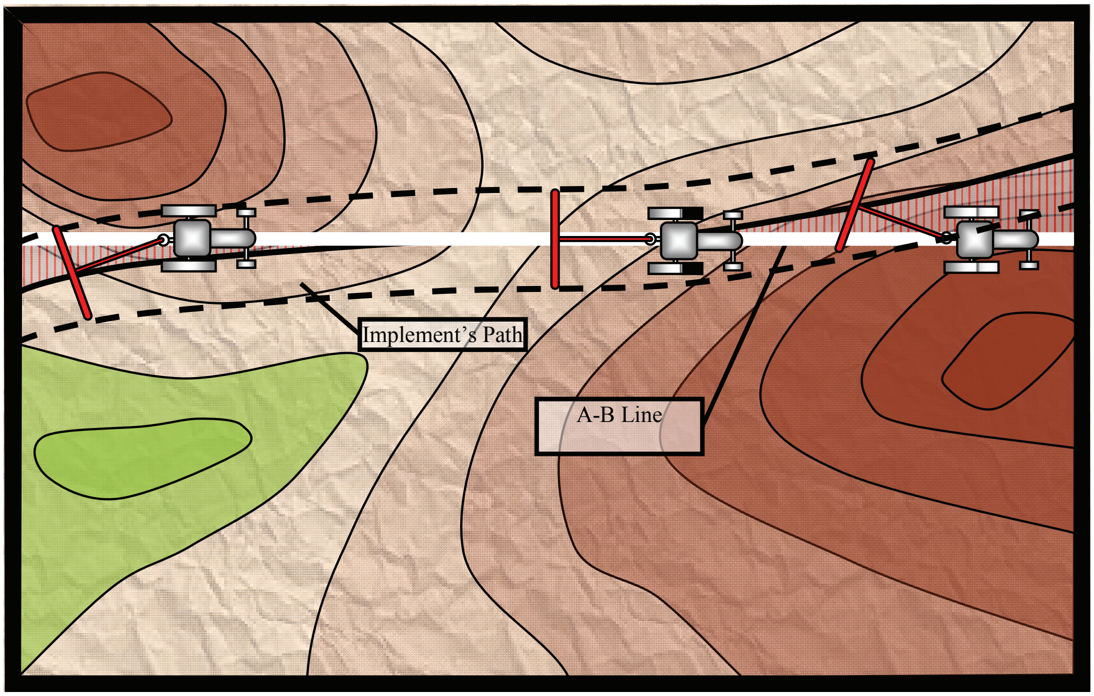


Figure 5.2. Changing slope causes the implement to drag downhill.

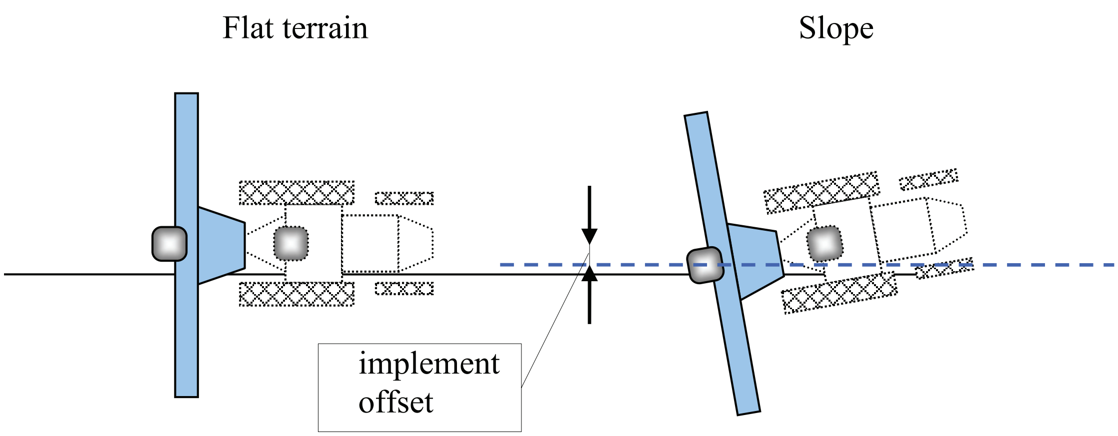


Figure 5.3. Three-point hitched implement exhibiting offset when tractor yaws on slope. Note that the tractor GPS is on the A-B line in both cases. Depending on the terrain and required precision, a three-point hitched implement can also benefit from implement control.

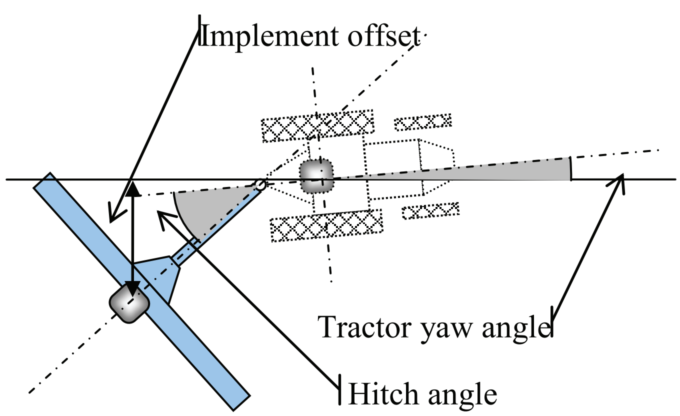


Figure 5.4. Implement position determined from tractor position and heading and implement hitch angle.

Steering Options

Towed implements, such as some potato planters, can have their own independent steering mechanisms. Alternatively, there are "steerable frames" or carriages, which are attached to implements, such as the Orthman Tracker IV shown in figure 5.1. Another popular method is steering by a movable hitch. A steerable implement offers great advantage where implement wandering is undesired. There are various control algorithms depending on the steering mechanism and the sensors available.

Typical steering mechanisms are:

- Laterally movable hitch.
- Carriage with coulter wheels.
- Steerable tires.

Position Measurement

The current position of the implement is easily measured with a GPS antenna. Other indirect methods are also possible. For example, knowing the tractor's position and attitude (yaw) and the tow angle allow the calculation of the implement's position (figure 5.4). However, such convoluted methods are prone to inaccuracies, because they are indirect and complex. Furthermore, they necessitate a "yaw" measurement of the tractor. Nowadays, its relatively low cost makes the GPS antenna the sensor of choice.

Actuation Considerations

Actuators to steer implements vary in their speed and range. The coulter wheel method, such as the method employed by Orthman's Tracker IV, is almost instantaneous in attaining a new angle, and correction starts immediately. Laterally movable hitches also respond quickly, but the total range of motion can be relatively small. However, tires of heavy equipment, such as potato planters, are relatively slow to turn.

Further considerations that affect the control performance are the range of actuation (lock-to-lock) and whether or not there is a measurement for the actuation position available.

The speed of actuation does not necessarily translate to a fast recovery of implement offset. For instance, coulter wheels start moving the implement immediately, while a lateral hitch offset causes a protracted repositioning of the implement over a distance.

Steerable Implements

Laterally Movable Hitch

Although there are many variations of laterally movable hitches, they all rely on moving the tow point off-center. When the implement is off-track, the hitch is moved in the opposite direction.

A PID controller will achieve satisfactory performance by applying a correction proportional to the current offset (P-term). For example, if the implement is off by 1 cm, the hitch is moved by 1 cm in the opposite direction. For various reasons, the 1 cm offset of the hitch may not result in complete correction. Instead, there may be a residual offset left. The I term forces the hitch to move farther for such persistent errors.

While the above explanation makes sense qualitatively, finding suitable values of how much P and I gain to apply is not trivial and depends on the dynamics and geometry of the actuation and the implement. Furthermore, those factors are speed-dependent. A model-based algorithm would incorporate the characterization of the actuation, the imple-

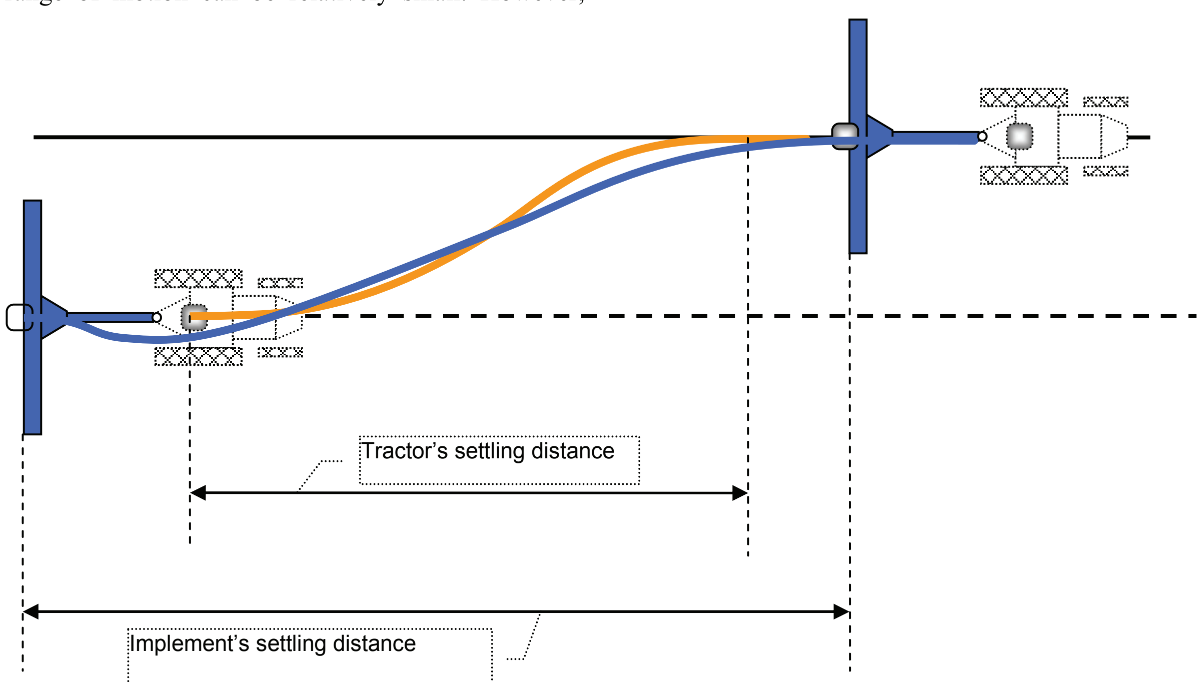


Figure 5.5. Applying a trim change to the tractor initially causes the implement to move in the opposite direction, but eventually it lines up behind the tractor (ideal case). The distance required for the implement to settle is substantially longer than that of the tractor.

implement, and the effect of speed. This would provide a "universal" control algorithm, which is adaptable for changing speed, different implements, and different actuation methods.

Wheeled Implements

The effect of steering wheels (tires or coulter disks) is almost immediate. Tires exhibit a greater "slip angle" along slopes than coulter wheels, which cut into soil and provide a greater sideways resistance to slip. Nevertheless, other than the magnitude of such effects, the principle of steering, and consequently control, are the same for both.

Qualitatively, upon an offset of the implement, the wheels are turned toward the A-B line. As the offset gets smaller, the steering angle is reduced in proportion. This action (P term) will not quite ensure zero error. The residual amount is "shaved-off" by repetitious increase (I term) of the steering angle until the error is zero. Thus, one could get a system to work adequately with a PID algorithm. However, the model-based solution is more universal because the gains attained from the analytical solution account for variations in tractor speed, steering angle, actuator latency, and more.

Passive Implement Steering

Passive implement steering means that the implement does not have its own steering mechanism. Instead, it can be kept on-line by moving the tractor away from the A-B line. Obviously, this necessitates that the tractor is off the A-B line. Hence, this method has limited application and is useful only where the tractor's offset can be tolerated.

Control of the passive implement requires that the tractor provides the actuation. In that sense, it is similar to controlling the implement with a movable hitch. Instead of the tractor staying on path and the hitch moving left and right, the whole tractor will need to move to achieve that same effect.

Given the latency of tractor movement, it should be clear that a significantly lesser performance (greater time to get to the A-B line) can be achieved. Nevertheless, this method relieves the operator from continually making "trim" adjustments, and provides a reasonably improved performance for mild slope variations and systematic offsets, such as asymmetric loads or design.

Thus, control of passive implements can be achieved in a manner similar to movable hitch methods for active implement steering. However, achieving performance better than manual "trim" requires much more complex considerations. For example, the hitch actuation (tractor's realignment) is much slower. Annoyingly, it may also exhibit a reverse reaction. That is, when the tractor is first steered away, the hitch will initially move in the opposite direction, albeit slightly. This often manifests itself as a further delay in command and actuation.

Nevertheless, the qualitative solution remains the same: Move the tractor off the path by an amount proportional to the implement error, which is anticipated to put the implement on the path (P term). After that, if the implement is still off, keep increasing the tractor's offset in proportion to the residual error (I term).

6. System Performance

The main performance parameter for a guidance system is the measurement of the cross-track error, as defined above. A group under ASABE's PM-54 Committee led by Professor Viacheslav I. Adamchuk of the Biological Systems Engineering Department of the University of Nebraska at Lincoln is currently working on a standard definition and procedure to measure cross-track error and auto-guidance performance. This group is focusing on measuring the cross-track error at the drawbar in steady state when the vehicle is following a straight path.

Easterly and Adamchuck (2008) presented a paper at the 2008 ASABE International Meeting describing the results obtained when using the procedure of the proposed standard, with a camera mounted over the drawbar pivot point that is capable of making measurements with an accuracy of 2 mm with respect to a fixed line in the ground. The test vehicle used in this experiment was a John Deere 8030 series wheel tractor with mechanical front wheel assist using a Trimble AgGPS RTK Autopilot™ autosteering system. The results showed the measured cross-track error to be 23 mm or less 95% of the time when driving at speeds of 1 m/s and 2.5 m/s. At speeds of 5 m/s, this error grew to 44 mm 95% of the time.

Table 6.1. Auto-guidance (cross-track) error estimates. "Inner" end marks refer to measurements taken 30 m after the vehicle had started going in a straight path and represent steady-state behavior. "Outer" end marks refer to measurements taken almost immediately after a turn and include some settling behavior. "Pass-to-pass" refers to measurements taken within 15 min, while "long-term" refers to measurements taken after 24 h.

Test Speed (m/s)	Error Type	End Marks	Signed Error (mm)		Unsigned Error (mm)	
			Mean	SD	Median (50%)	95%
1	Pass-to-pass	Inner	1	12	8	21
		Outer	1	11	7	20
	Long-term	Inner	0	11	8	21
		Outer	0	11	7	20
2.5	Pass-to-pass	Inner	-1	9	6	17
		Outer	-1	11	7	22
	Long-term	Inner	0	10	6	19
		Outer	-2	12	8	23
5	Pass-to-pass	Inner	-3	20	14	40
		Outer	-3	32	20	68
	Long-term	Inner	-5	21	14	44
		Outer	26	21	20	69

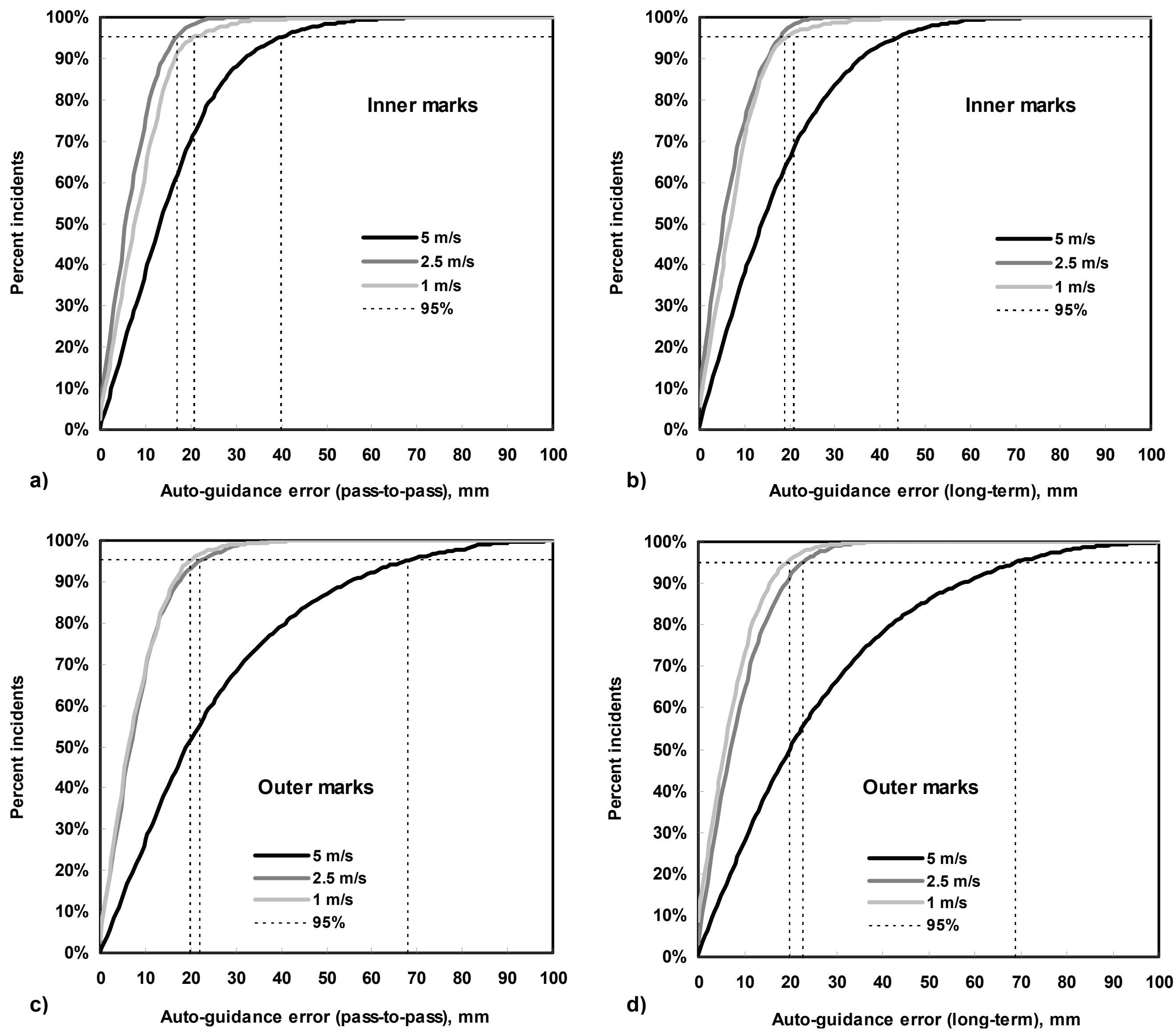


Figure 6.1. Cumulative distribution of unsigned cross-track errors, including: (a) pass-to-pass using inner marks, (b) long-term using inner marks, (c) pass-to-pass using outer marks, and (d) long-term using outer marks.

7. Autonomous Vehicles

We are firm believers that, in the future, fully autonomous vehicles will be capable of farming land with minimal supervision. The harder question to answer is when this will happen. Safety and legislation will play large roles in this development. There is certainly quite a bit of interest from growers in the development of autonomous vehicle technologies. Labor shortages, especially for high-value crops like fruits and vegetables, are driving up production costs in the U.S., and it is getting to the point that many producers are becoming unable to compete. Fruit and vegetable picking for the fresh market is one of the areas where this labor shortage is hitting hardest.

In the short term, two trends are emerging: tandem vehicles or vehicle fleets, and swarms of small vehicles.

Tandem Vehicles or Vehicle Fleets

The idea here is to have a single operator control multiple vehicles. The second vehicle follows the first vehicle a set distance and offset laterally, the third vehicle (if there is one) follows the second, etc. This requires that the vehicles be in communication with one another and with the person monitoring the operation in one of the vehicles of the fleet or monitoring the operation from the side. This approach could be quite well suited to large fields like the one pictured below.

Figure 7.1. An operation suitable for automation.

Figure 7.2. A swarm of small autonomous vehicles scouts a field (used with permission of Prof. Simon Blackmore).

Swarms of Small Vehicles

In this approach, each vehicle has far greater autonomy. Instead of using large vehicles, which can be potentially more dangerous, the tasks are carried out by a swarm of smaller vehicles, all operating in coordination with each other. Professor Simon Blackmore (Blackmore, 2007) created a rendering of what this approach might look like (figure 7.2). Each vehicle could operate throughout the day. The small vehicles could also be modified for different tasks, from planting to cultivating to harvesting.

Small vehicles bring several advantages, including safety, greater autonomy and efficiency, and lower cost. They could also perform tasks that today are not possible to do in large-scale agriculture. One such task could be fruit picking at the right time. Currently, most harvesting is done all at once. With autonomous small vehicles, it could possible to harvest only the fruit that is ready for harvesting.

8. Conclusion

Guidance of agricultural devices is a topic that has challenged engineers for over a century. The state of the art has progressed tremendously, from early devices suitable for visually lining-up horse-drawn implements, through row markers that were widely used for most of the past century and are still used, to manual and automatic GPS-based guidance. The task for engineers in the field of guidance has just started, with little over a decade since the first GPS automatic guidance devices started appearing.

As the earth's population grows, and earth's resources are consumed and reduced, techniques for sustainable agriculture will become more prominent than in the past. Agriculture today is not only challenged with feeding and clothing the world's population, but also with providing renewable fuels and even cleaning the atmosphere, while facing loss of agricultural land to urban areas and droughts. As agriculture faces these challenges, agricultural engineering and technology will be essential. Guidance and, in the future, full automation of vehicles and agricultural processes will play an important role.

Acknowledgements

The authors would like to thank Dr. Gurcan Aral for his contributions to sections 6 and 7, and Doug Brewer, Dr. Roz Buick, Greg Price, Professor Viacheslav I. Adamchuck, Dwight R. Easterly, and Professor Simon Blackmore for their help creating and reviewing this report.

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Appendix:
A Selection of Patents Related to Agricultural Vehicle Guidance

Row Markers

An early design for a row marker was disclosed by Smith (1870) in patent 108,644. The side view of the "Improvement in Land-Markers for Corn-Planting" is shown attached to a horse-drawn plow. The marker bar can be positioned to either side of the plow, pivoting around its middle. The object of this invention was "to furnish an improved marker for attachment to plows, to mark the land for the next row, so that the rows may be at an equal distance apart throughout their whole length."

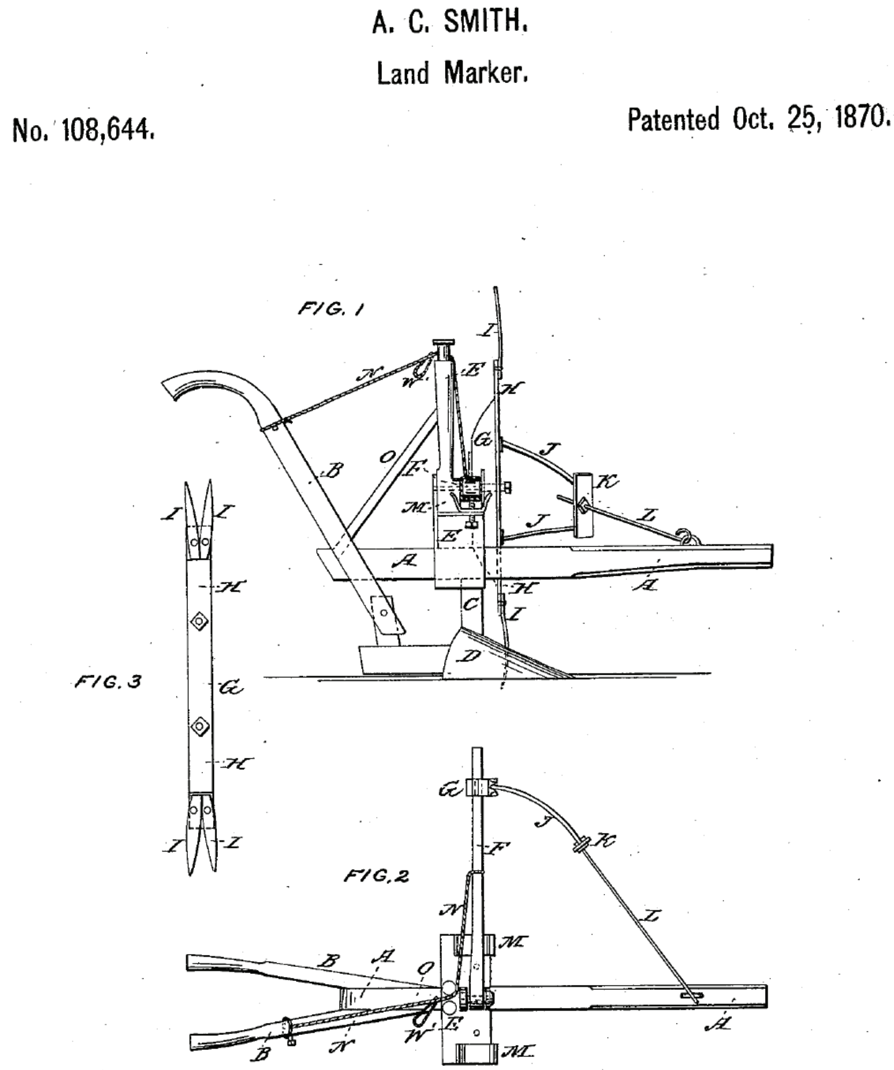

Figure A.1. Land marker.

Many improvements in planters with row markers soon appeared in patents. For example, in patent 172,566, Holly (1876) disclosed a corn planter with a disk-shaped row marker (item G in the drawing).

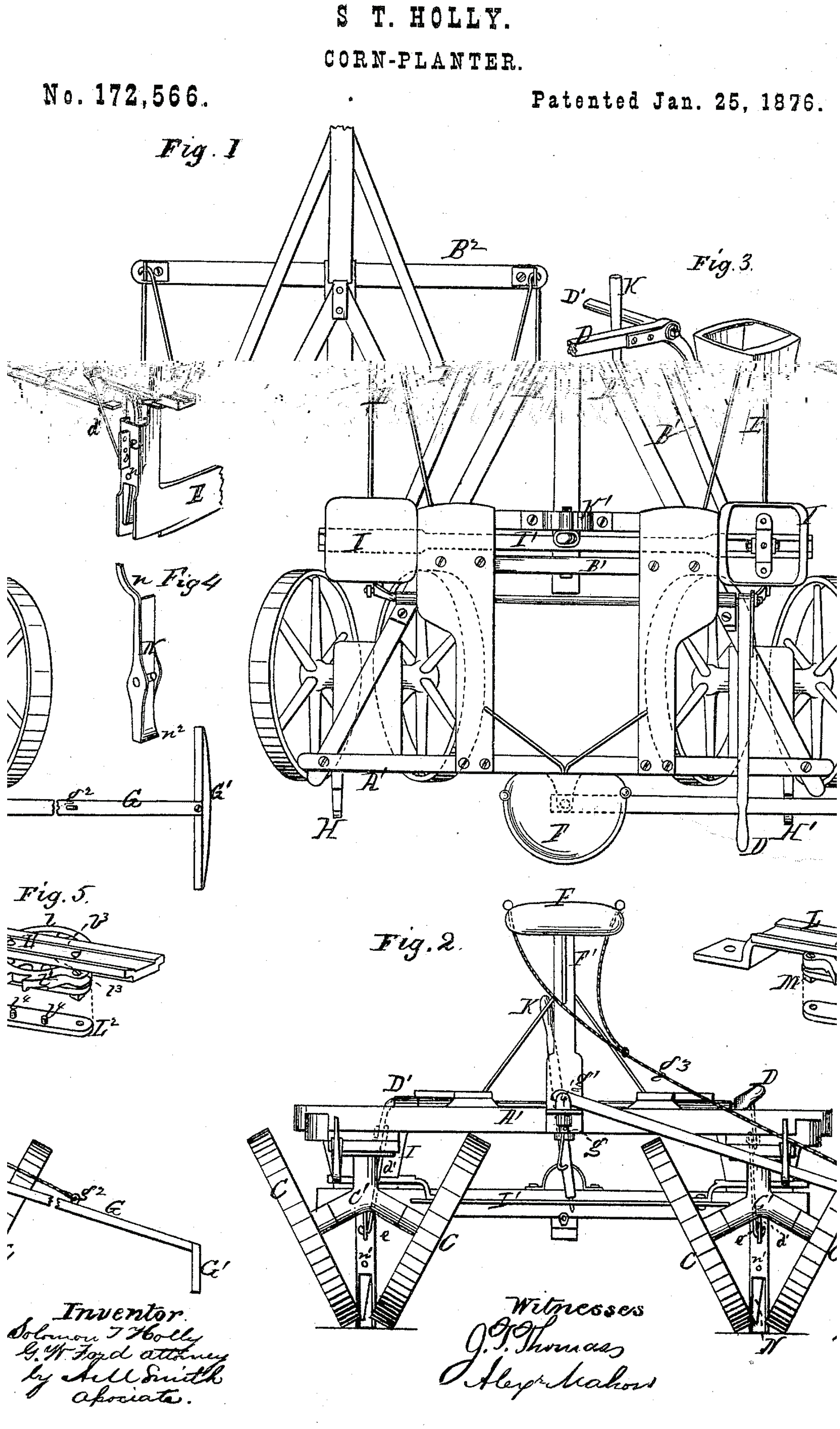

Figure A.2. Corn planter.

In patent 1,080,425, Davis (1913) disclosed an improved marker attachment that could “be secured readily and quickly to the beam of an ordinary beam plow in such a manner that it may be swung from one side to the other.”

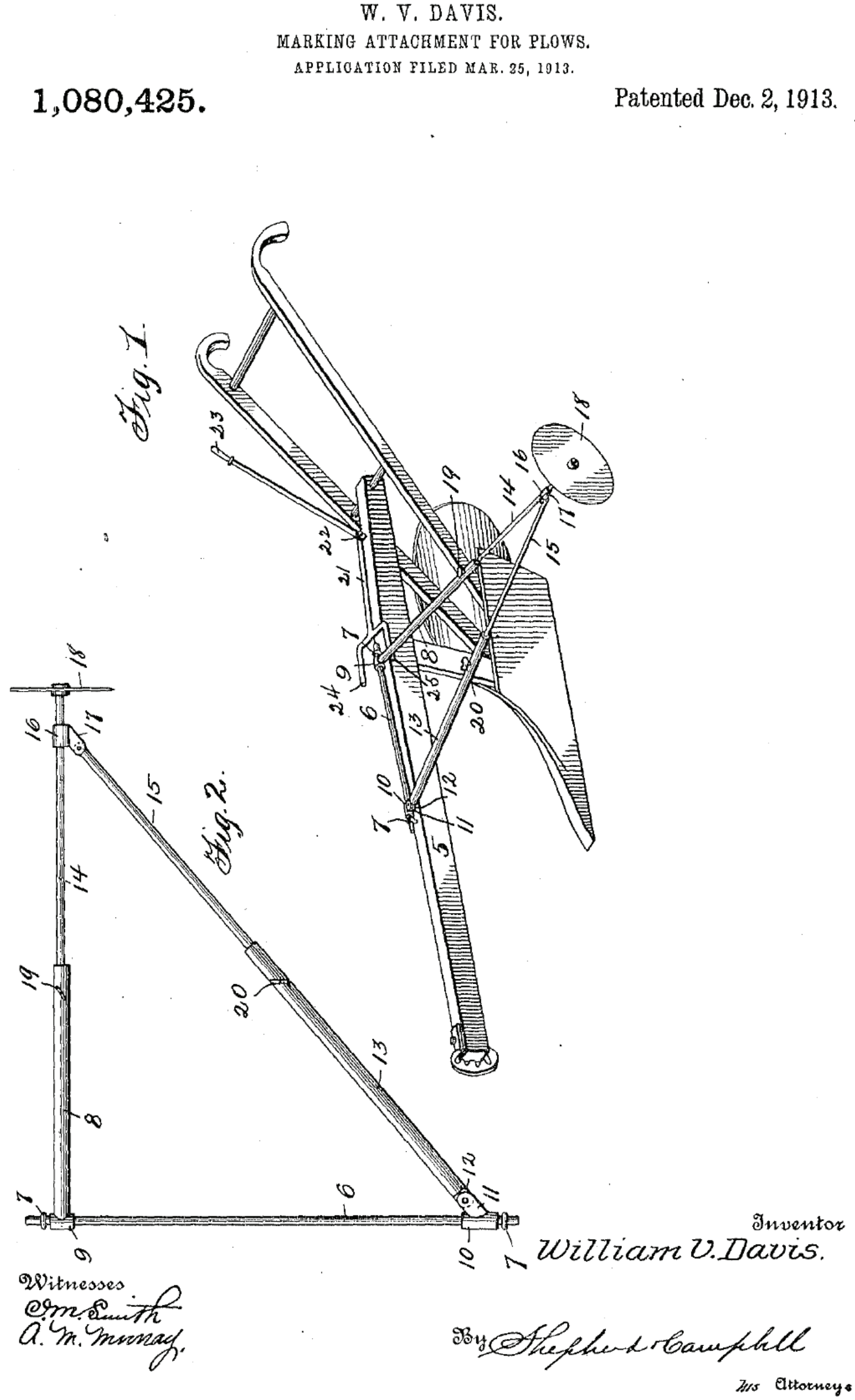

Figure A.3. Marker attachment for plows.

Although steam and internal combustion engines for tractors were available, in patent 1,363,412, Hanson (1920) disclosed a row marker for a corn planter, "which is light in action so as to avoid the usual objectionable drag on the horses."

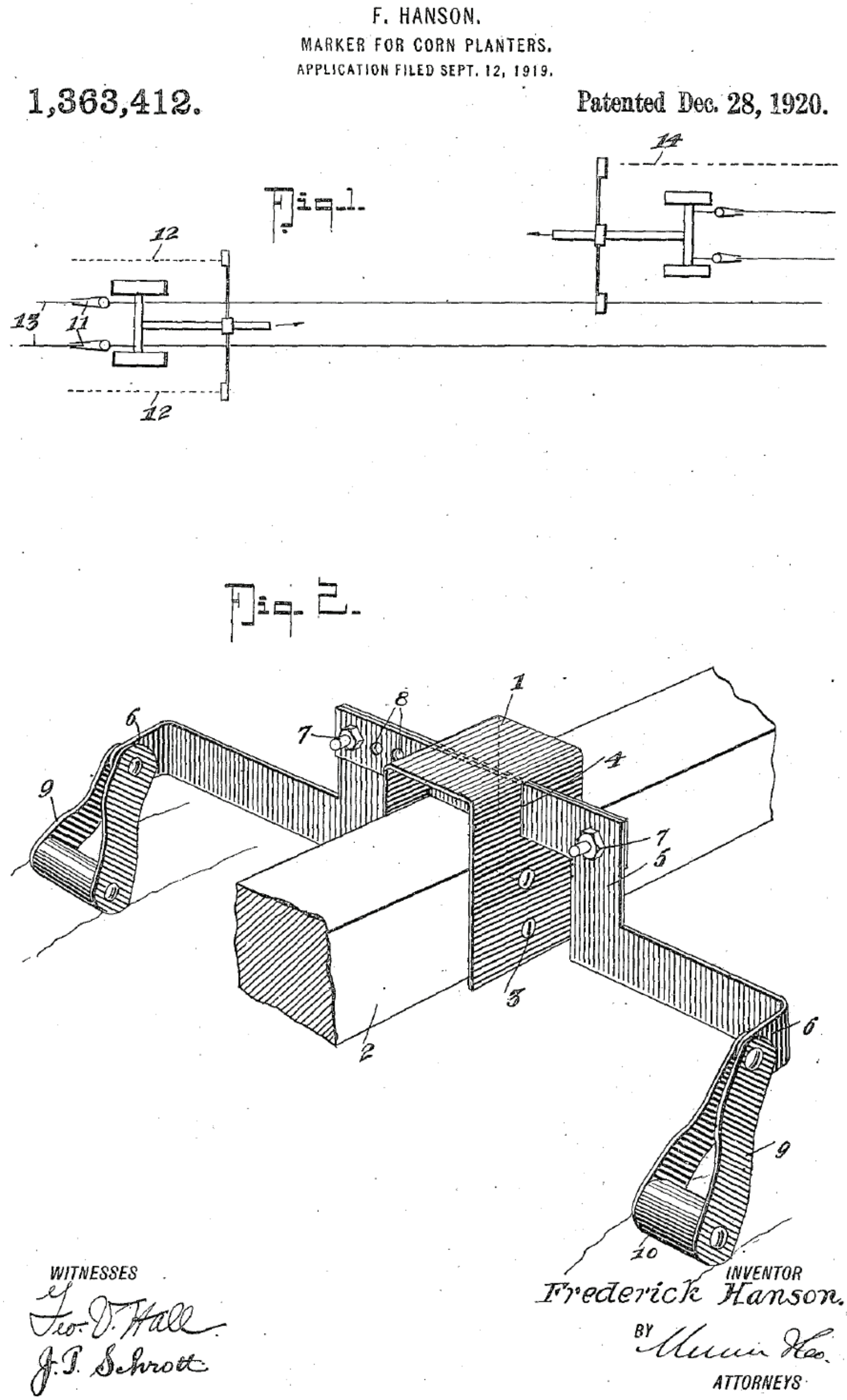

Figure A.4. Marker for corn planters.

In patent 1,911,219, White (1933) disclosed a "power operated marker arm," which will allow the "driver to devote most of his attention to steering the tractor as the end of the field is approached, and there is no necessity for stopping the tractor when the turn is about to be made."

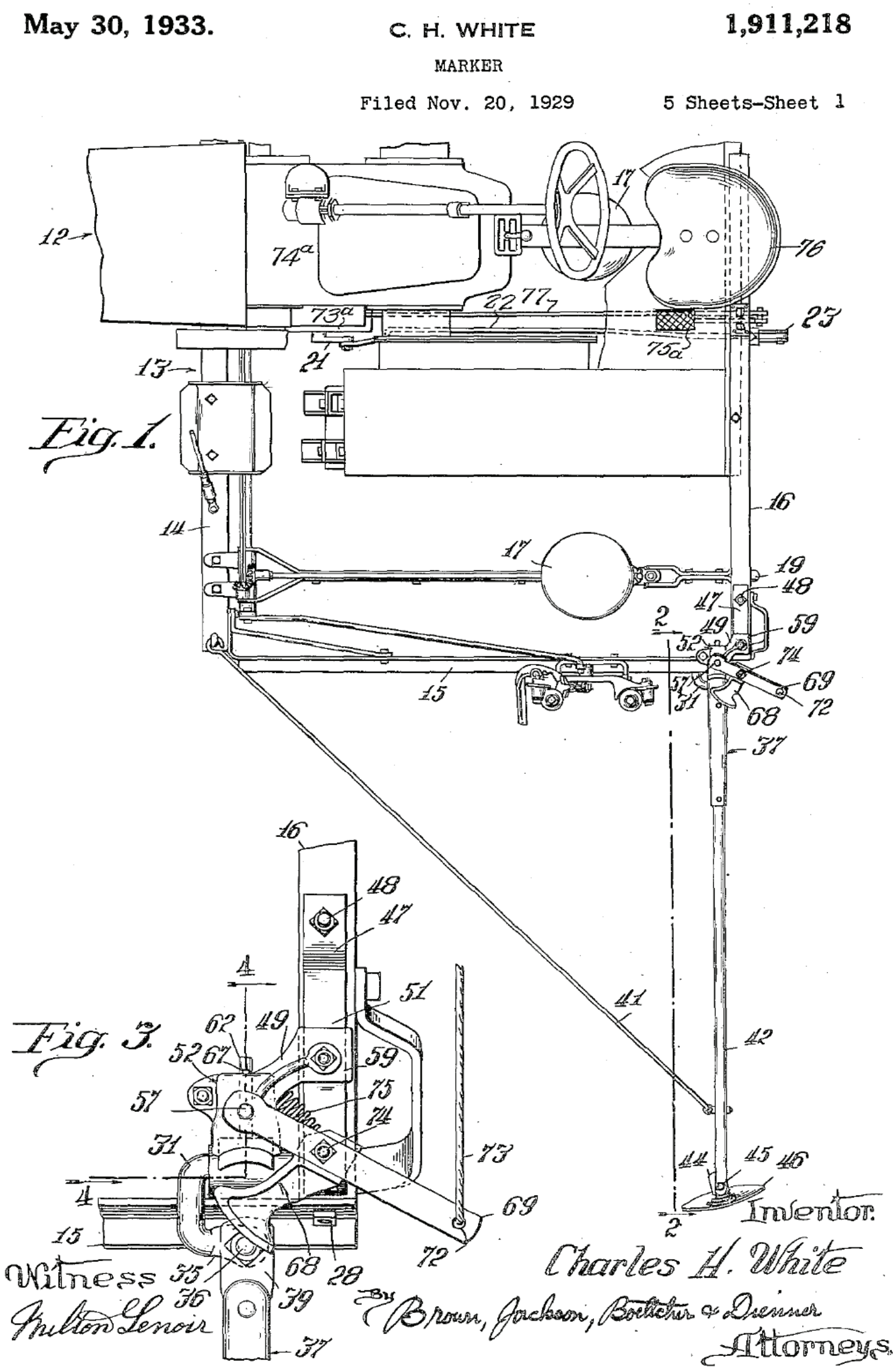

Figure A.5. Marker.

In patent 2,657,623, Allen (1953) disclosed an elevating means for a row marker that "will be automatically raised when the plows are raised out of working position by the power lift of the tractor."

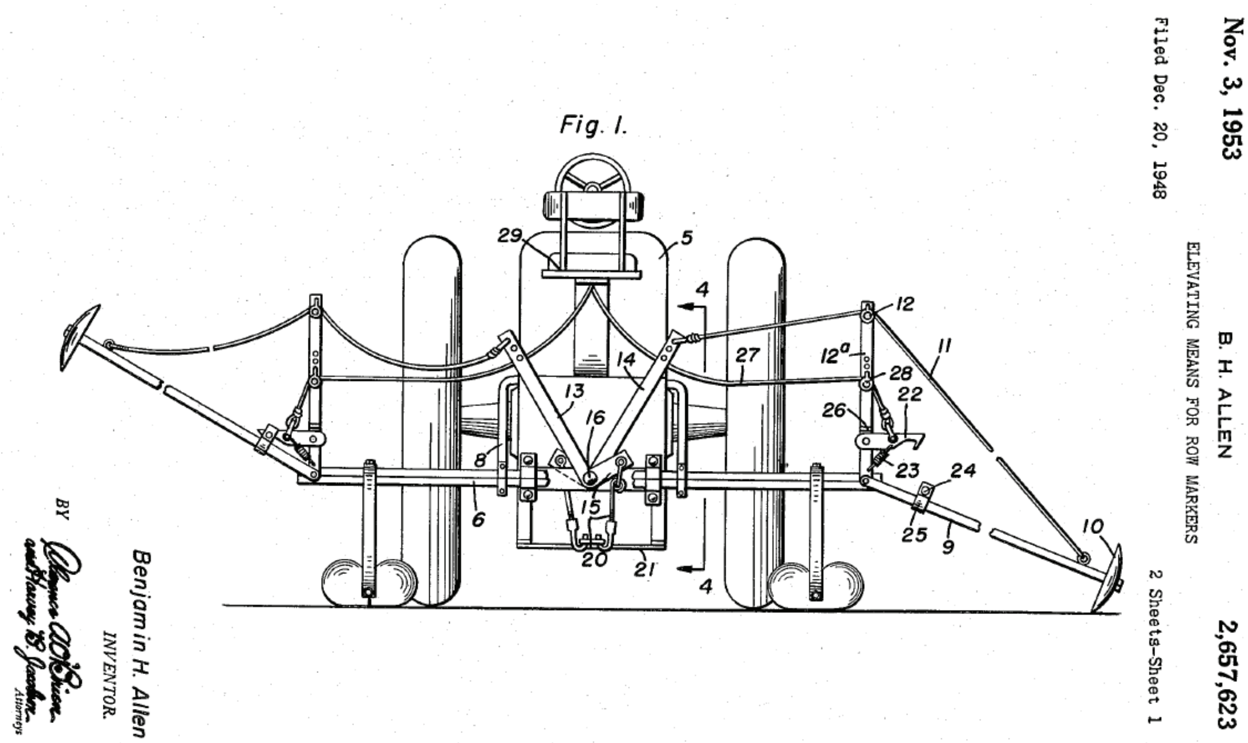

Figure A.6. Elevating means for row markers.

In patent 3,072,200, Yerkes (1963) disclosed a lateral folding row marker "that will permit the marker disk to float vertically, and still can be folded up to reduce implement width."

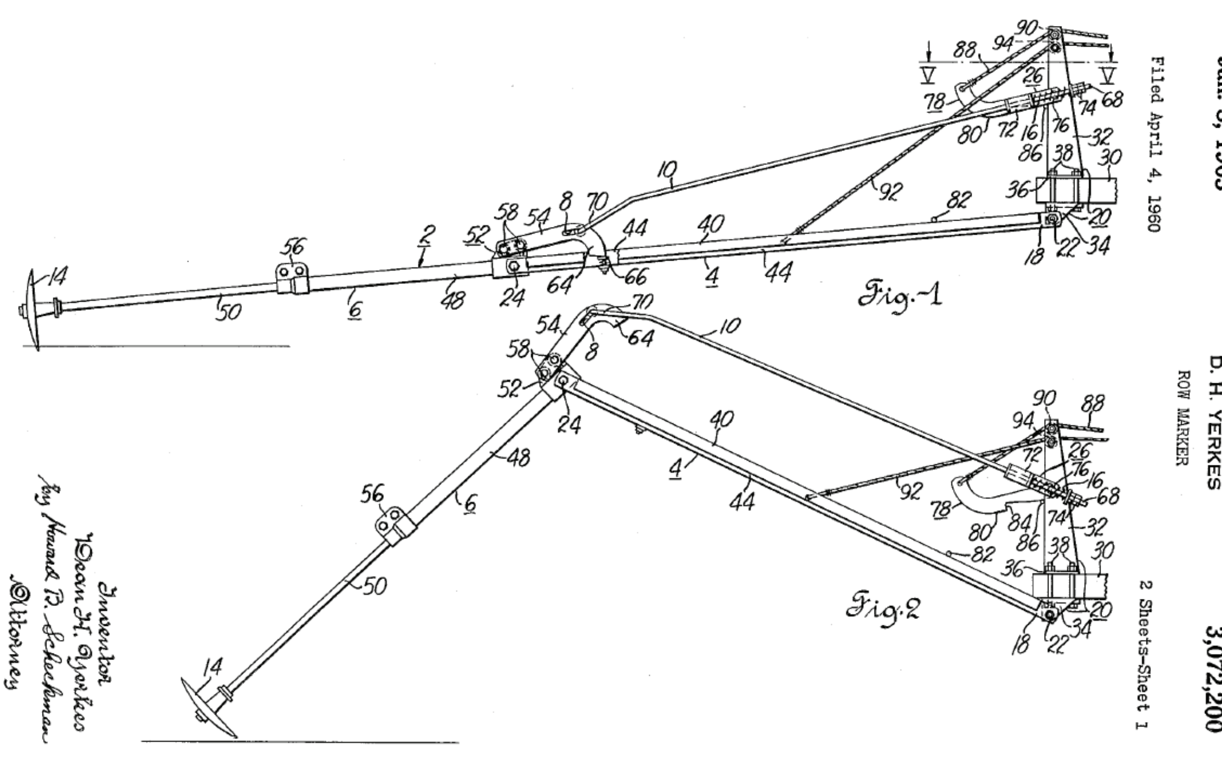

Figure A.7. Row marker.

In patent 3,250333, Day (1966) disclosed a hydraulically operated row marker.

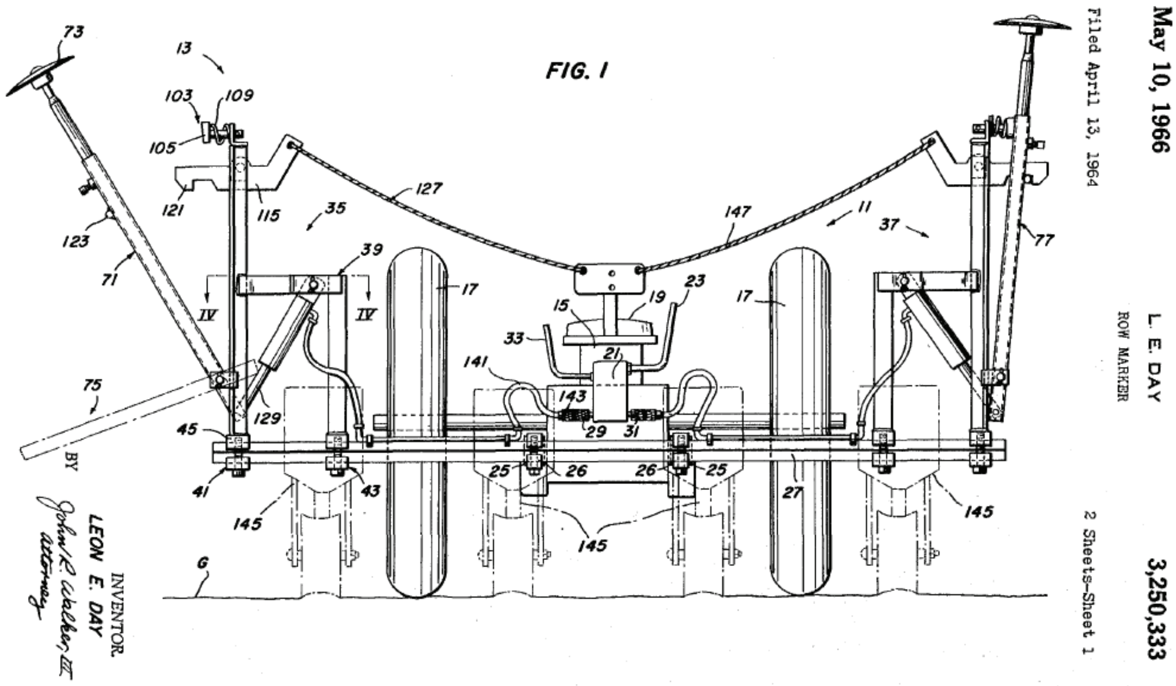

Figure A.8. Row marker.

As implements became wider, the problem of folding the row marker was of great interest, and improvements to row markers continued to the age of GPS. Patent 4,986,367 (Kinzenbaw, 1991) was issued as the initial GPS satellites were being launched. Numerous other patents with small improvements to row markers have been issued, and will continue to be filed and issued even though row markers are somewhat redundant on GPS-equipped vehicles.

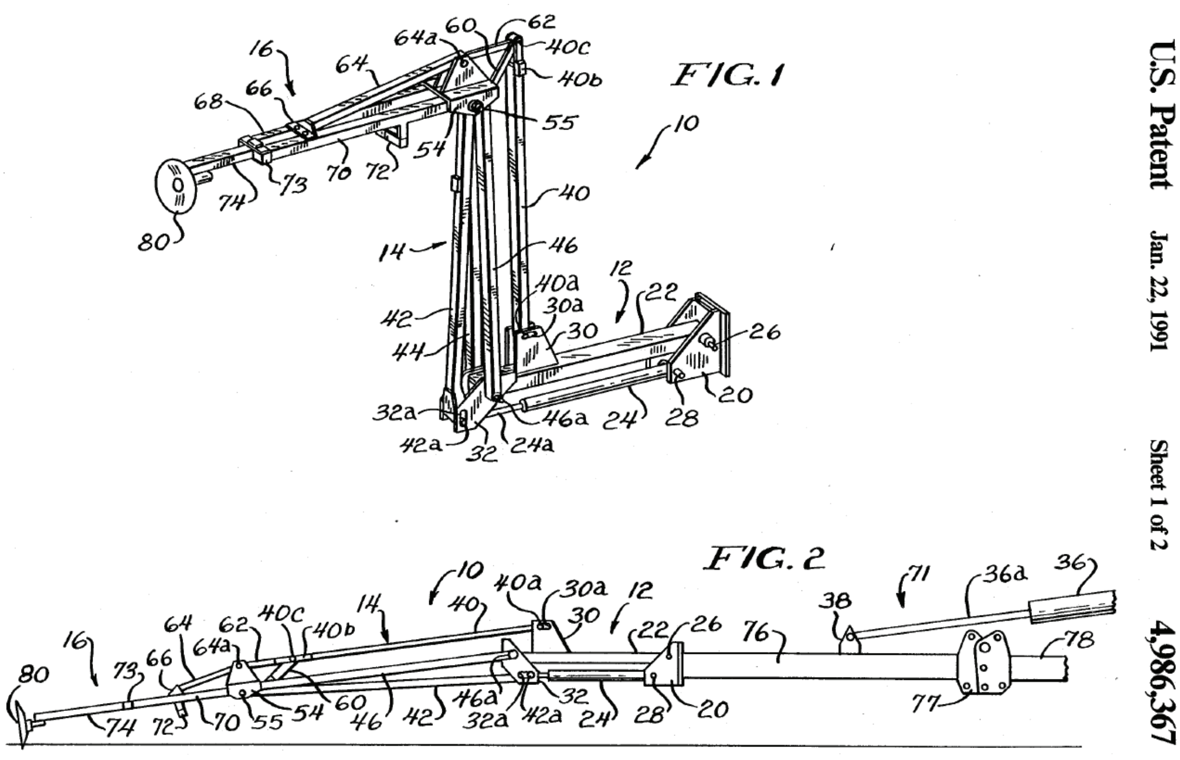

Figure A.9. Folding row marker.

Visual Sighting Aids

In order to use row markers efficiently, it is necessary to follow a previous row or mark from the marker disk on a previous pass. Numerous patents have addressed this issue. The following are some of the more interesting visual sighting patents. In patent 1,373,873, Allen (1921) disclosed an invention to aid the driver in steering a farm tractor and cultivator in close proximity to the crops.

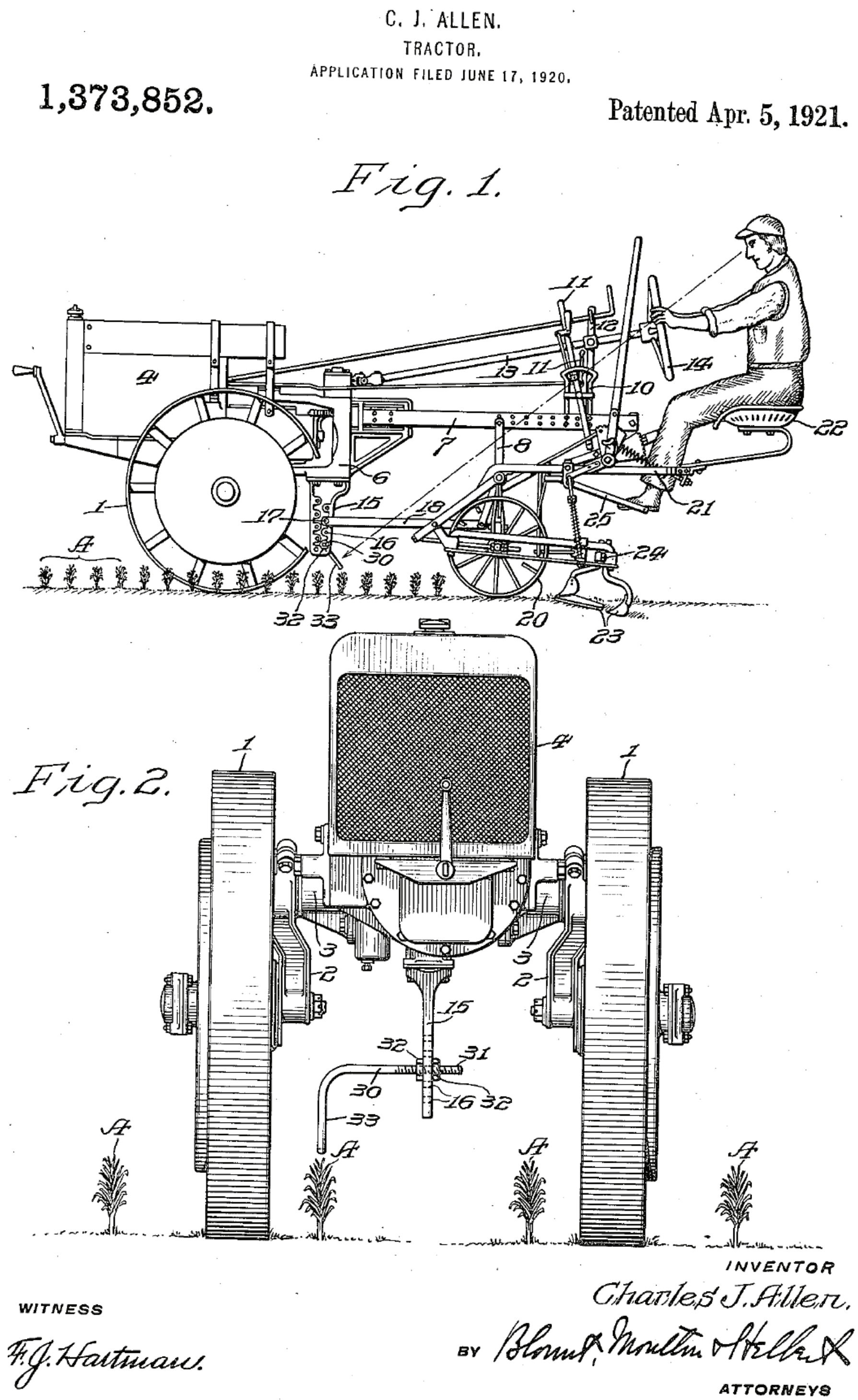

Figure A.10. Tractor.

In patent 2,538,112, Maier (1951a) disclosed a planting sight for farm tractors to facilitate planting crops in equally spaced rows. This device used a pendulum weight to allow the farmer to use the device on a side hill.

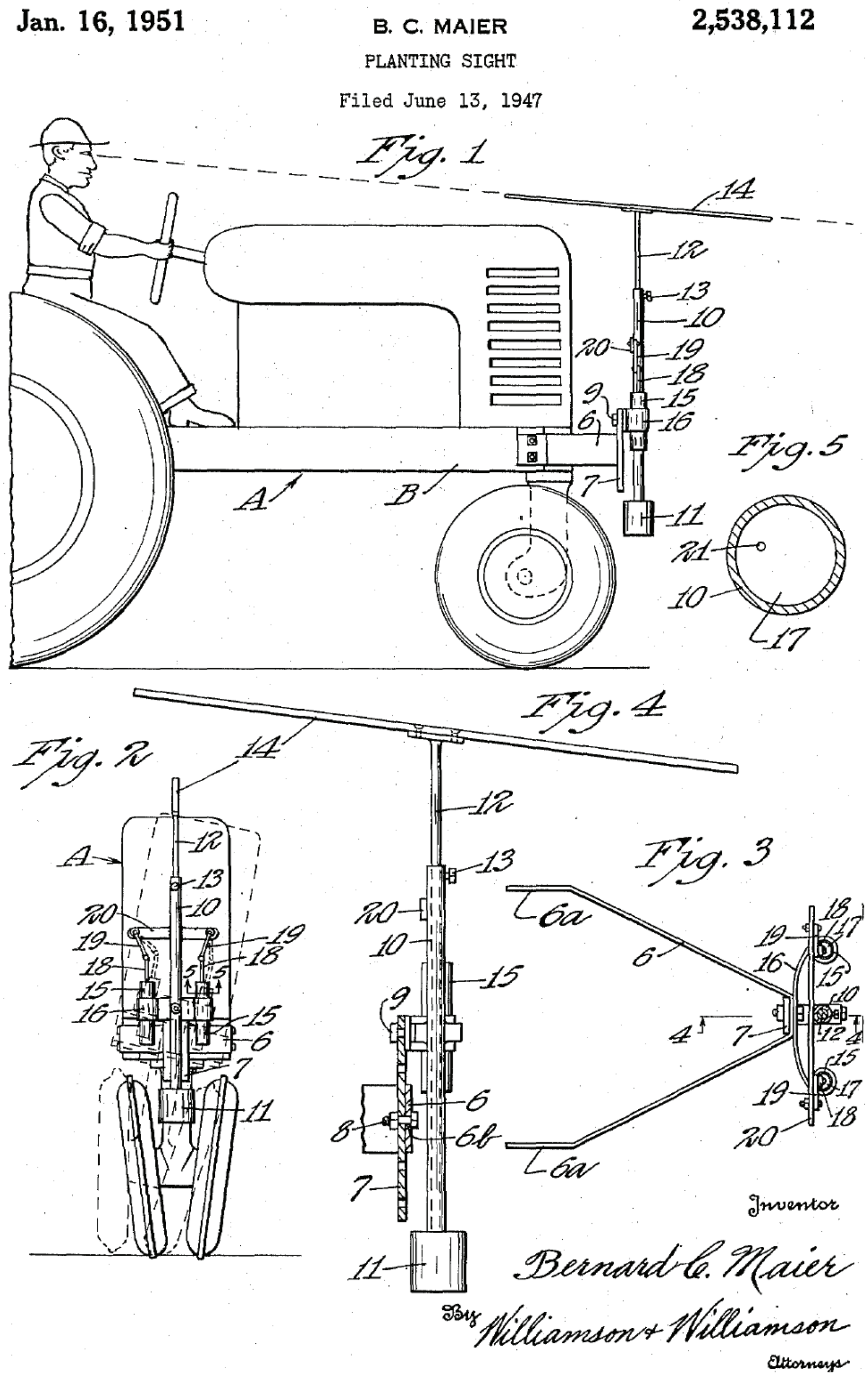

Figure A.11. Planting sight.

In patent 2,548,226, Maier (1951b) disclosed a planting sight attachment for farm tractors “to permit a farmer operating the tractor to sight along the aligned bubbles and maintain the tractor in predetermined relation to the previously planted rows, regardless of the terrain over which the tractor is traveling.” This device used front and rear curved bubble levels to allow the driver to more accurately follow the desired path.

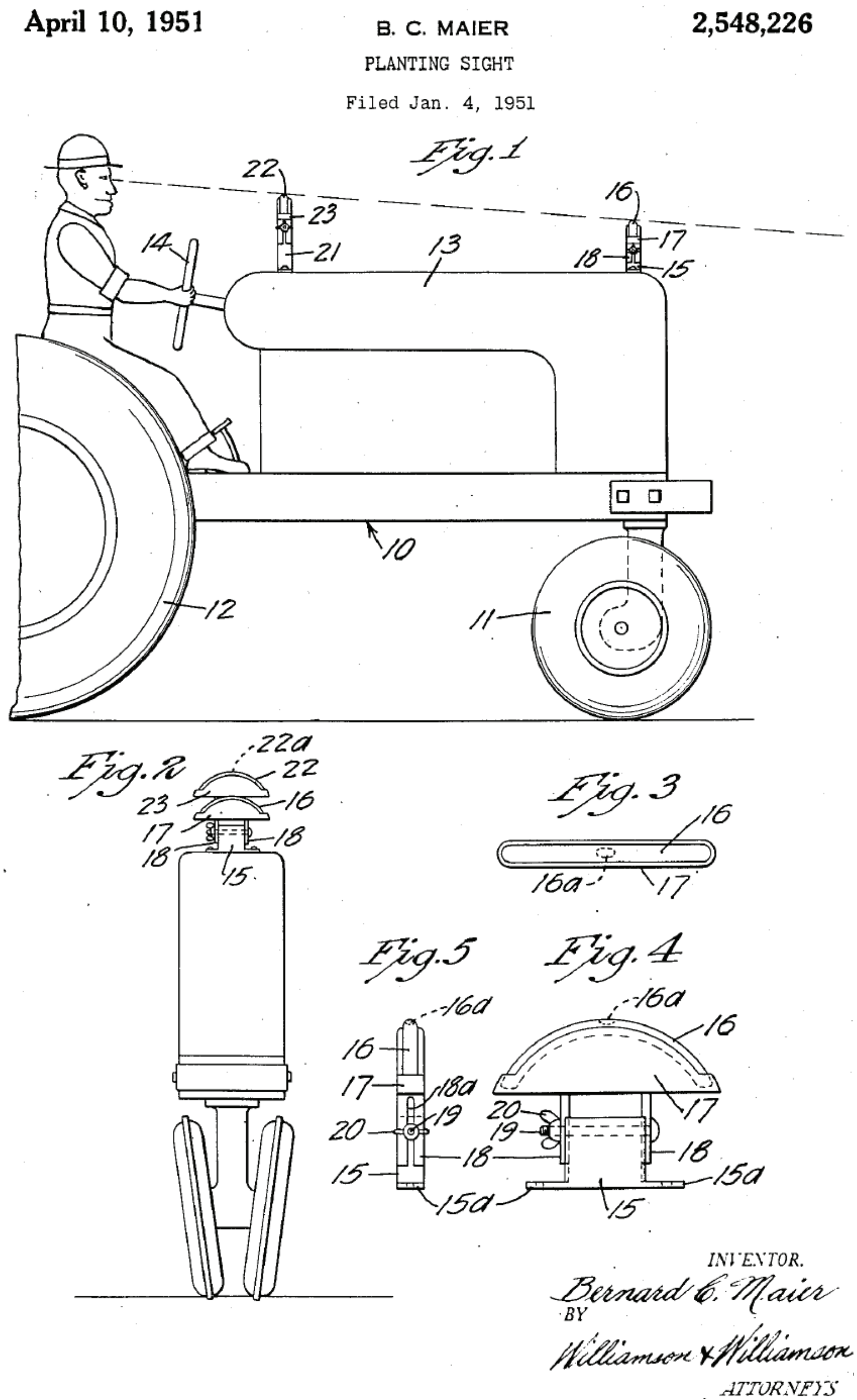

Figure A.12. Planting sight.

In patent 2,555,954, Bruflat (1951) disclosed a gravity-actuated visual sighting device to allow proper alignment of the tractor while cultivating on a hillside.

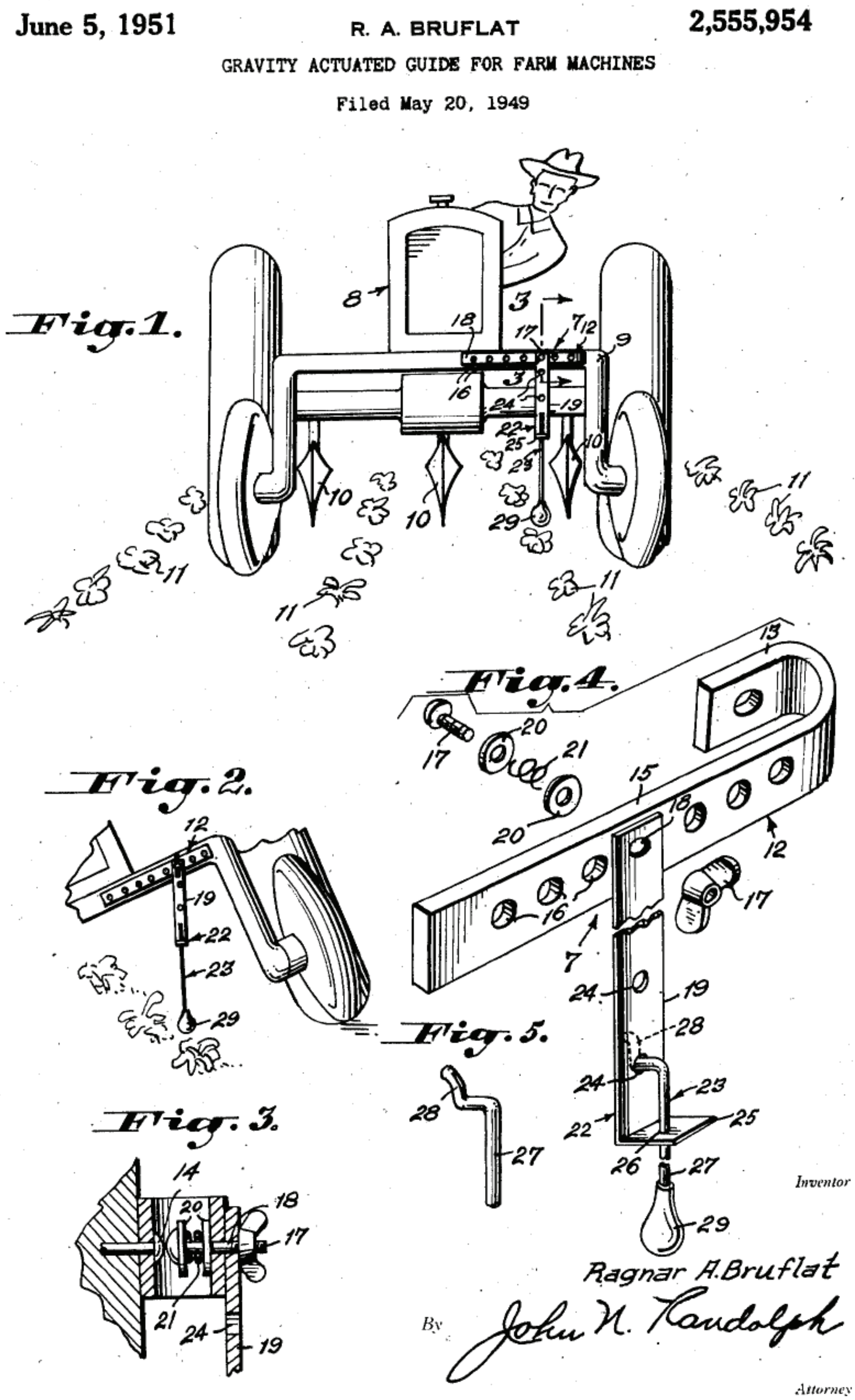

Figure A.13. Gravity-actuated guide for farm tractors.

In patent 2,827,704, Hunsicker (1958) disclosed an adjustable sighting device for spacing crop rows. This may be the ultimate in low-cost solutions.

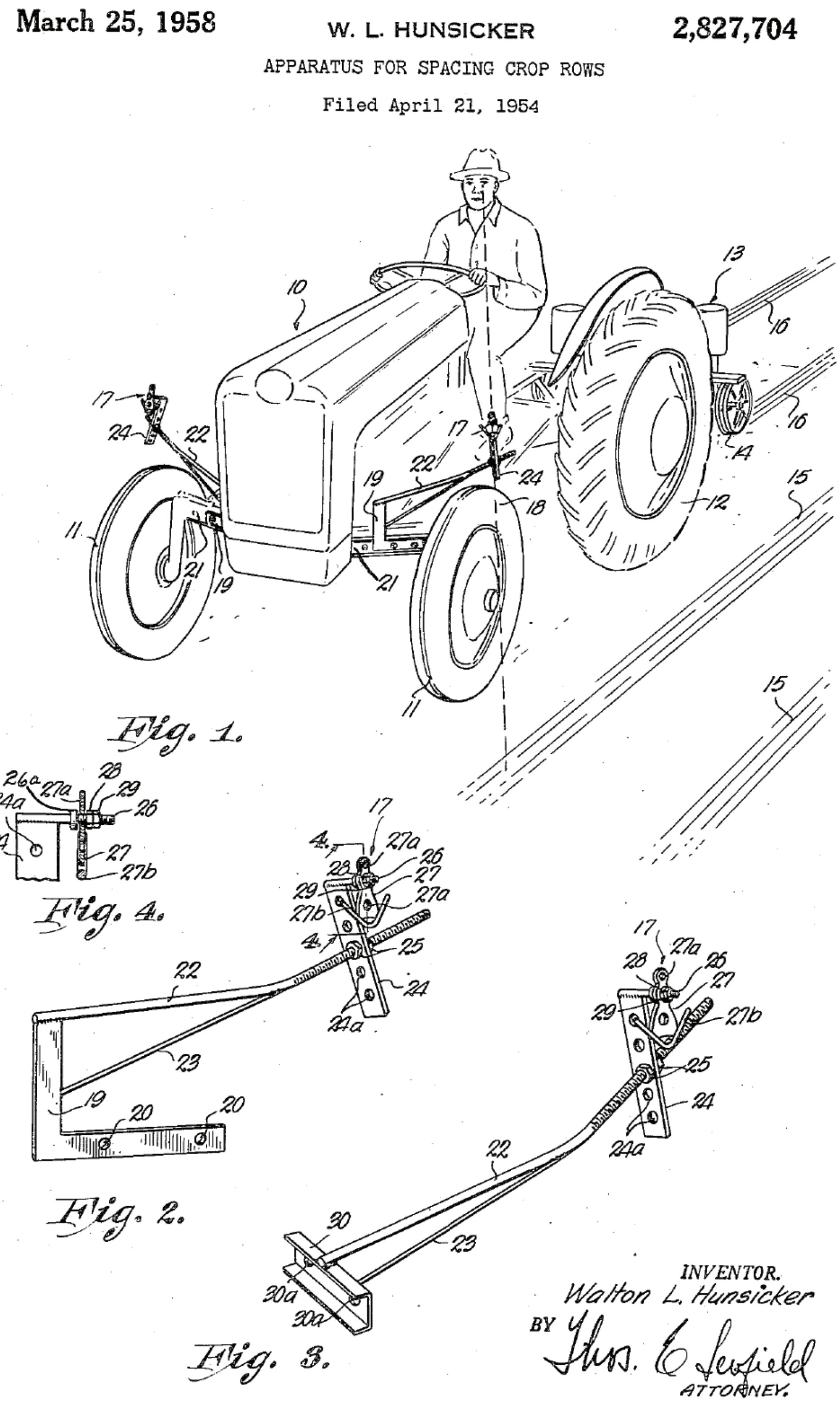

Figure A.14. Apparatus for spacing row crops.

In patent 3,932,028, Klingler (1976) disclosed a sighting device (item 47) and a mirror assembly (item 32) to allow the driver to observe the cultivator tools to facilitate guiding the tractor and trailing cultivator implement.

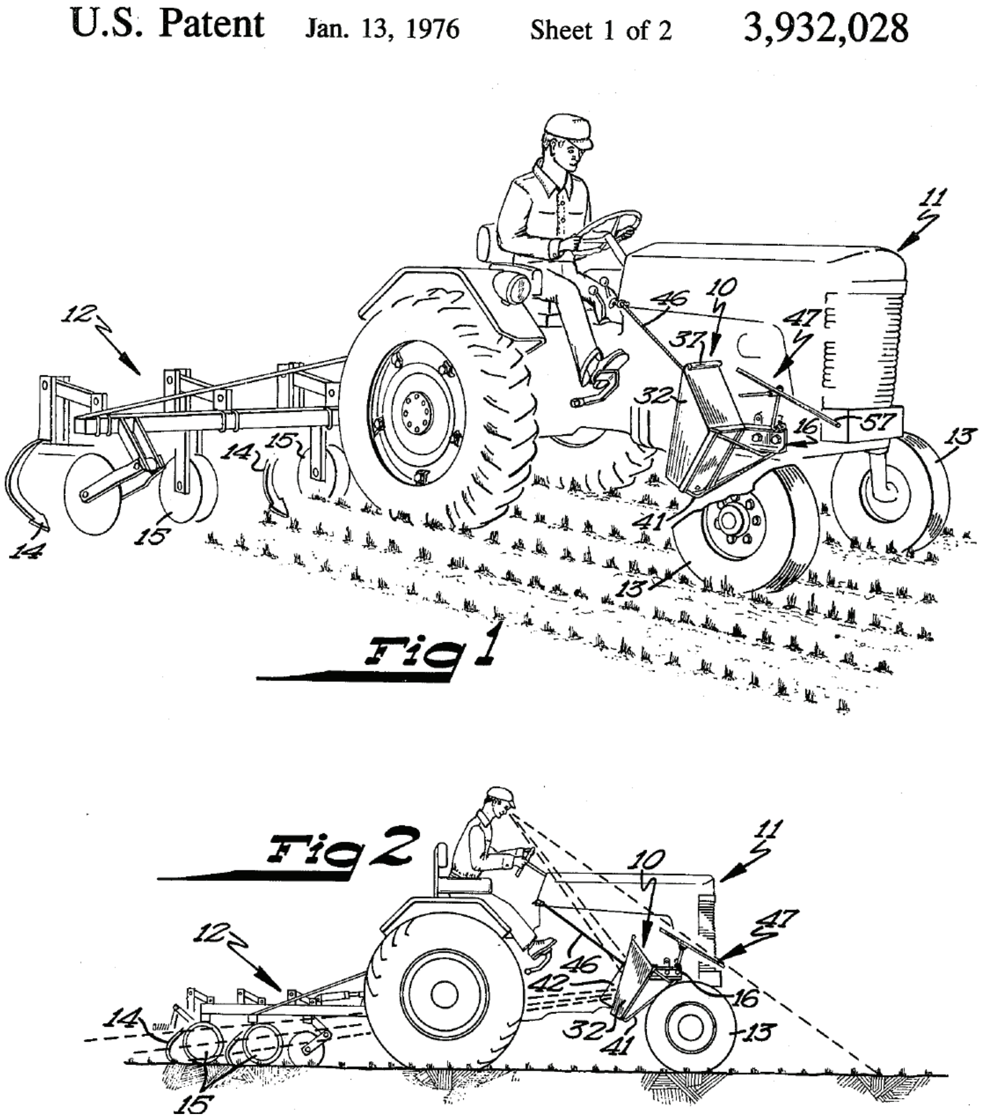

Figure A.15. Mirror and guide device for a tractor.

In patent 4,401,166, Brown (1983) disclosed a visual sighting device to enable a tractor operator to center the tractor over a guide furrow. To obtain consistent guess row spacing, it was necessary for the operator to sit in the same position continuously.

U.S. Patent **Aug. 30, 1983** **Sheet 2 of 2** **4,401,166**

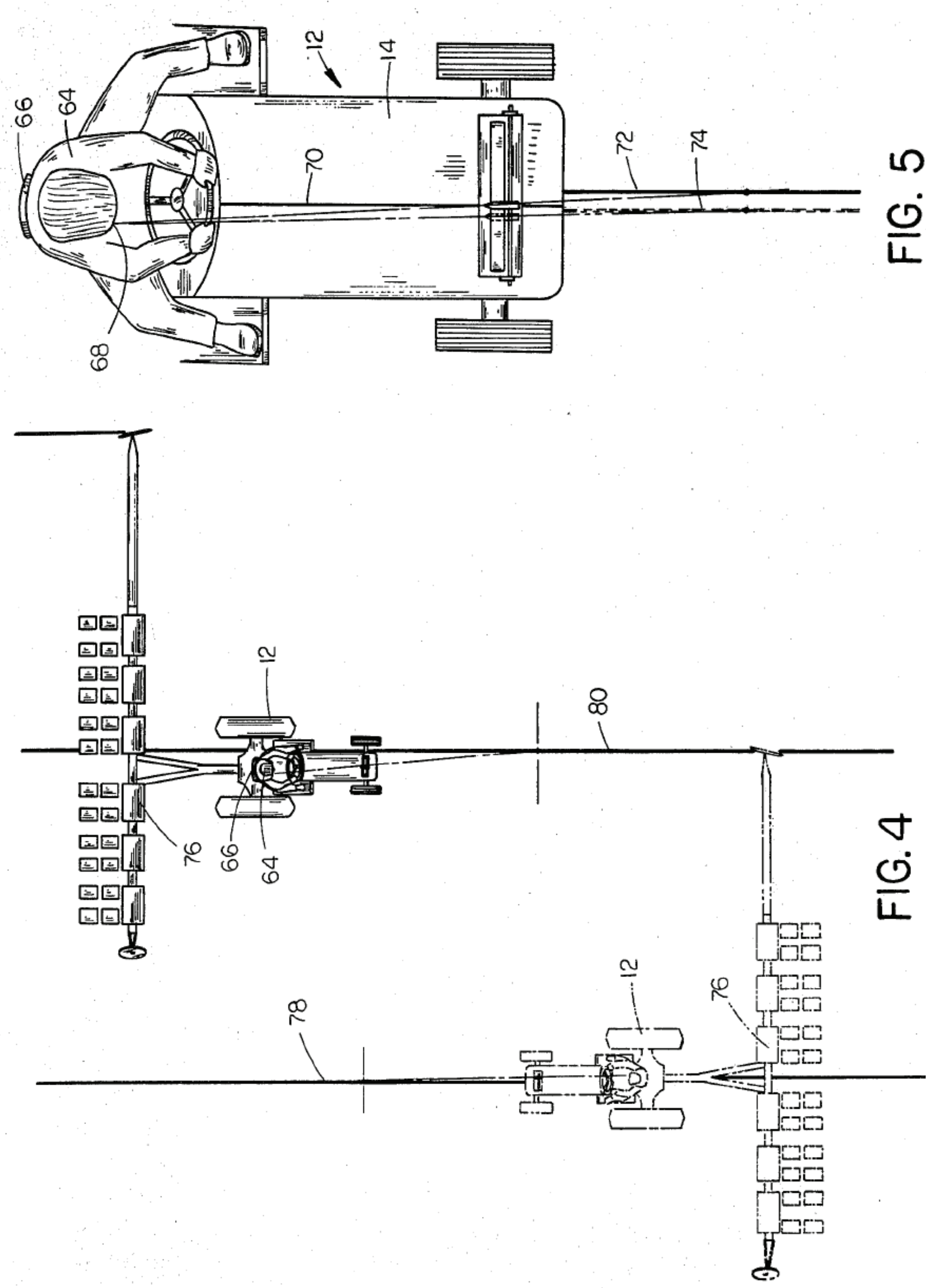

Figure A.16. Furrow follower vision correction system.

In patent 4,919,214, Brown (1990) disclosed an improved visual sighting system that would allow a driver to hold his head in a comfortable position. It used an electronically adjustable rear sight (item 70) mounted on the windshield and a front sight (item 26) mounted on the hood of the tractor.

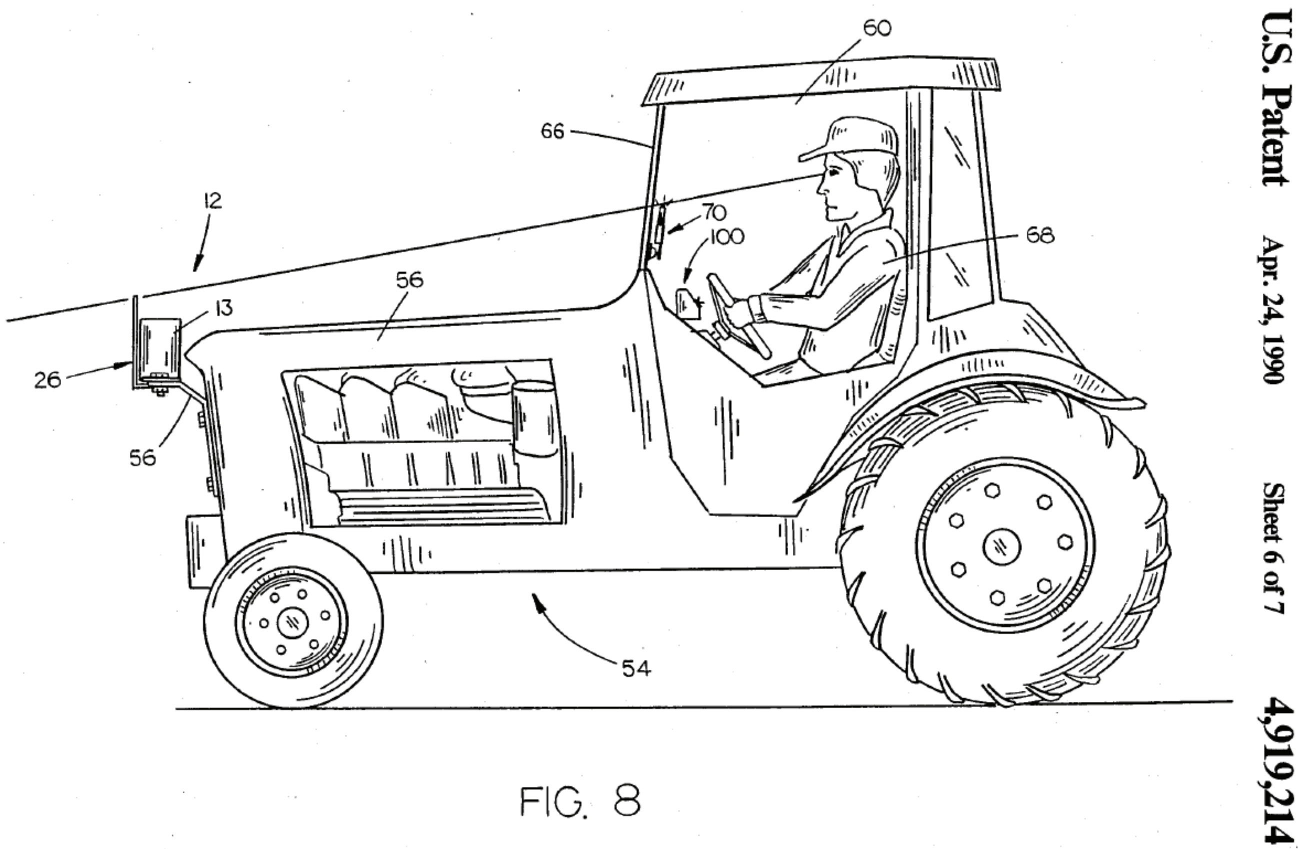

Figure A.17. Centerline sight.

Foam Marking

In patent 2,199,421, Stevens (1940) disclosed a liquid marking device for mounting on seed planters.

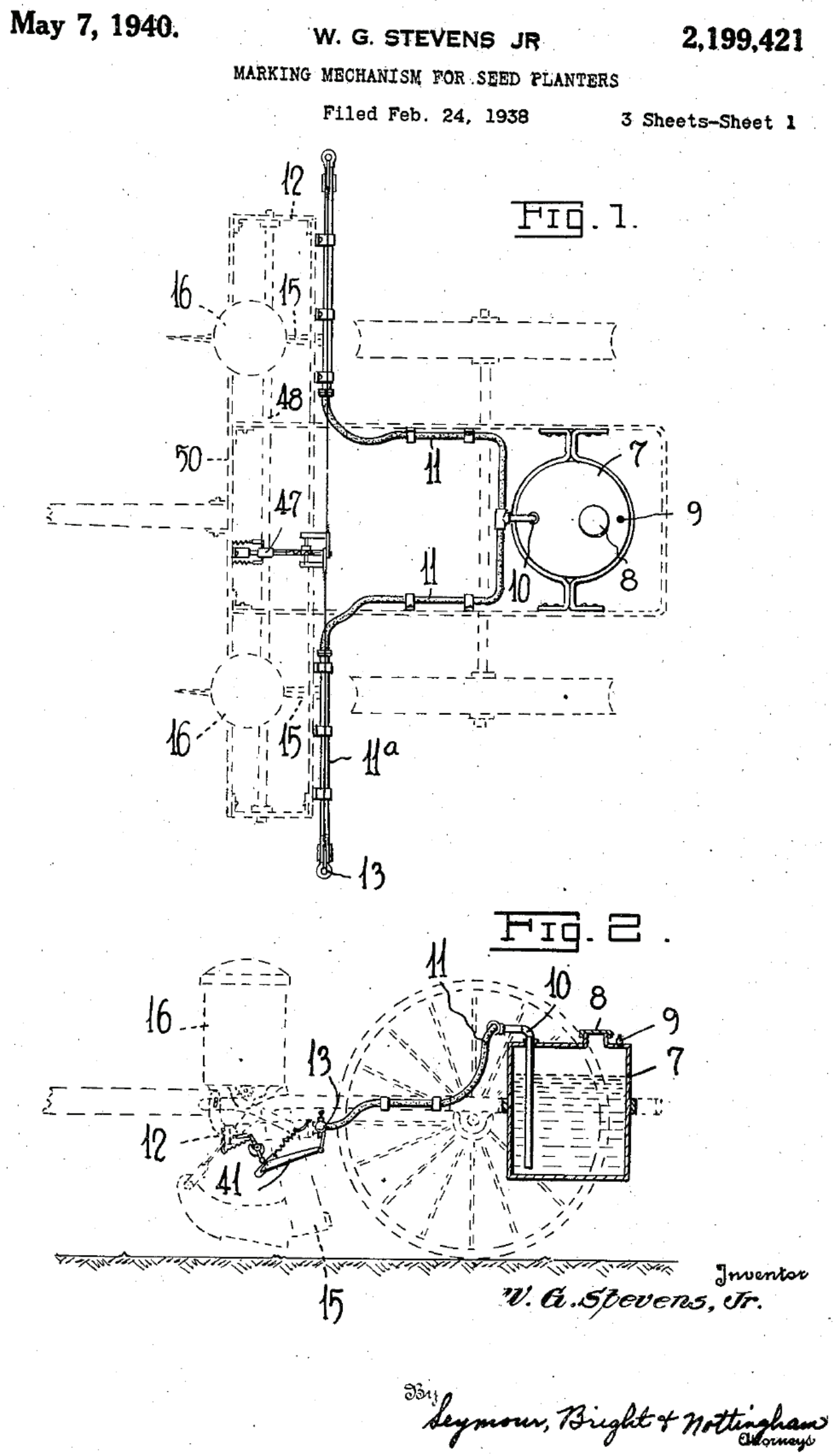

Figure A.18. Marking mechanism for seed planters.

In patent 3,481,545, Cooke (1969) disclosed a "method and apparatus for indicating the extent of land subjected to an agricultural operation."

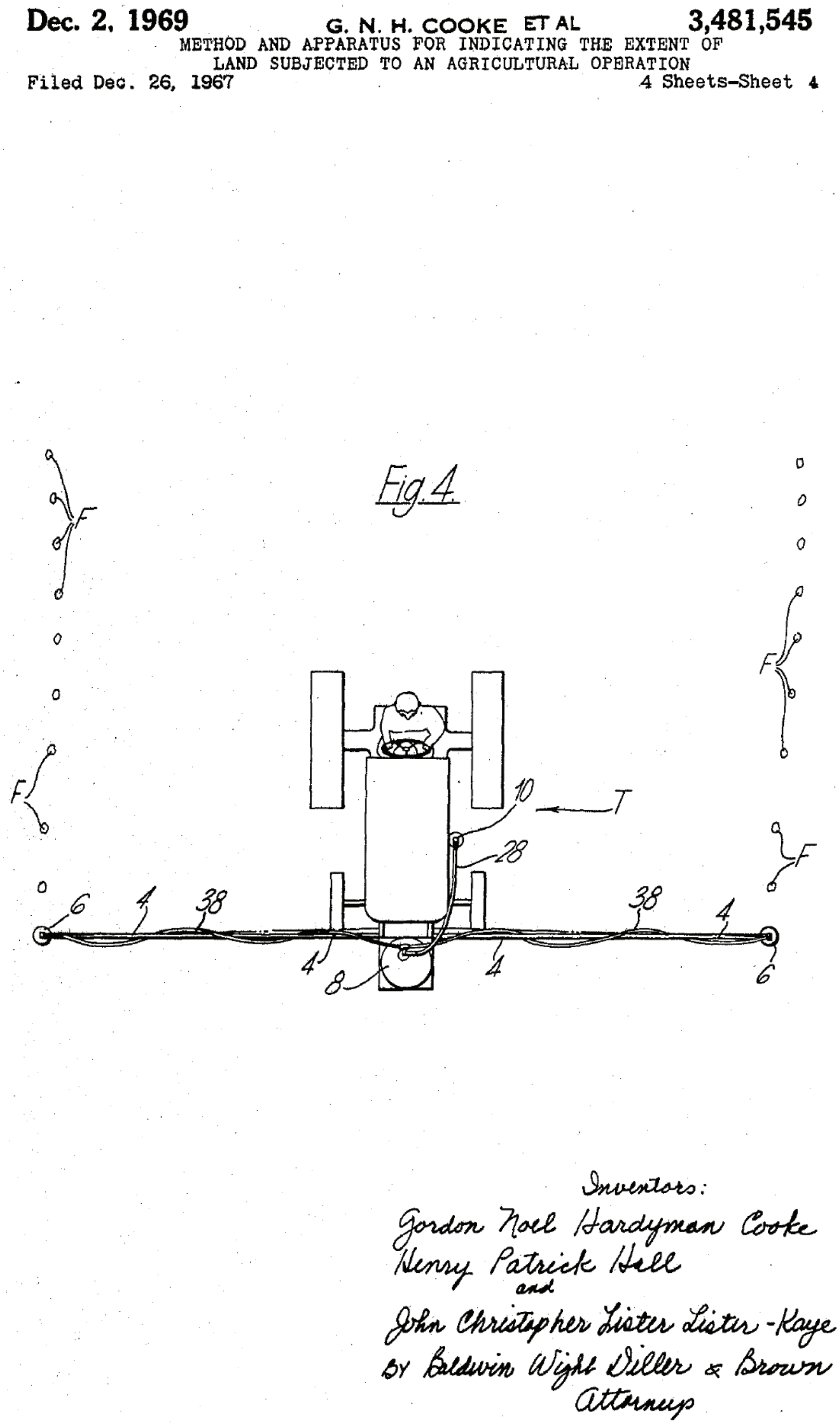

Figure A.19. Method and apparatus for indicating the extent of land subjected to an agricultural operation.

In patent 3,531,024, Rosselot (1970) disclosed an electrically operating foam system.

Sept. 29, 1970 C. L. ROSSELOT **3,531,024**

ELECTRICALLY OPERATED MEANS FOR MARKING THE EDGES
OF A STRIP IN AN OPEN FIELD OR COUNTRY

Filed May 16, 1968 2 Sheets-Sheet 2

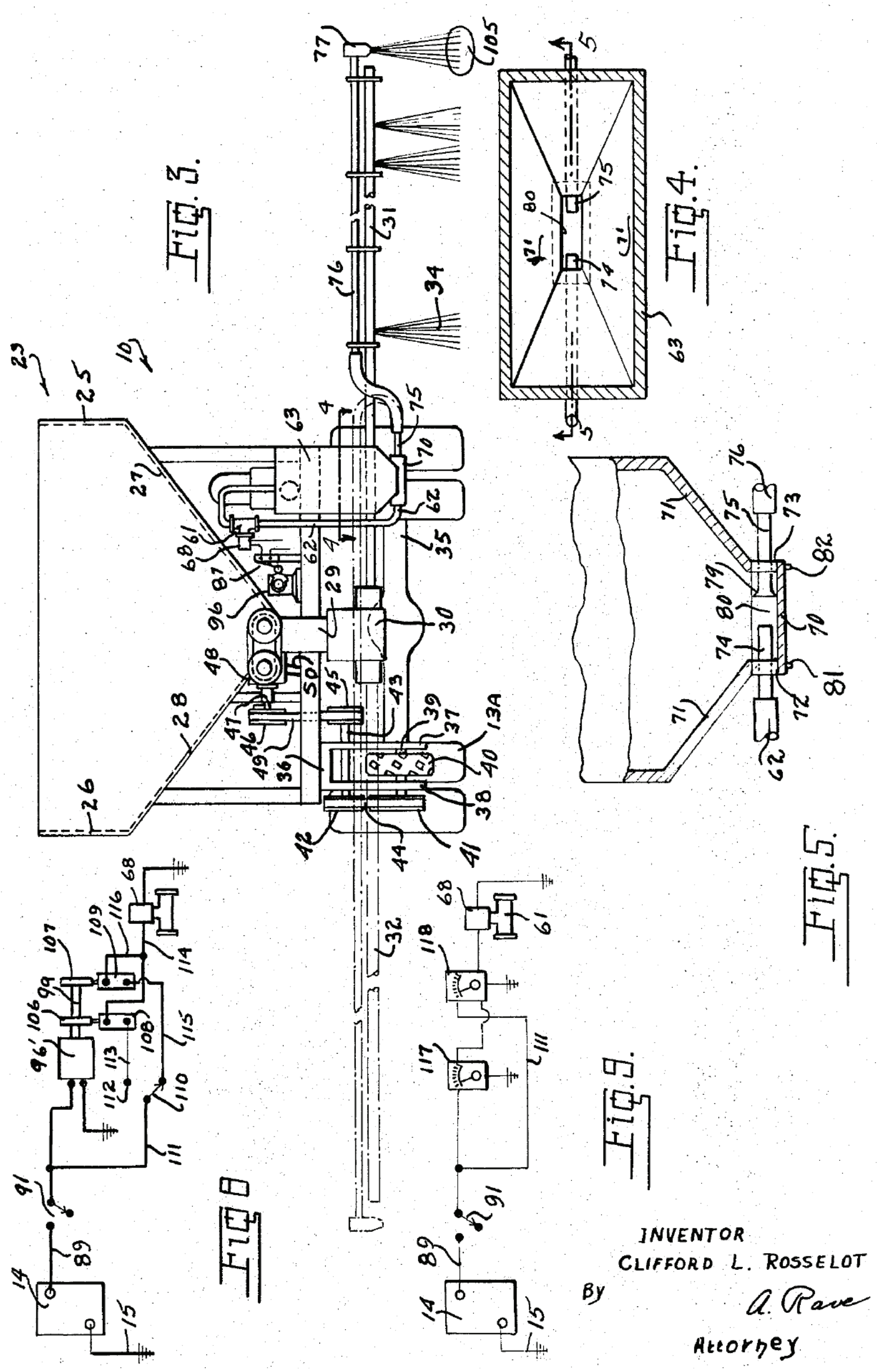

Figure A.20. Electrically operated means for marking the edges of a strip in an open field or country.

In patent 4,635,847, Jackson (1987) disclosed a method for marking a field that involved dropping pieces of tissue paper.

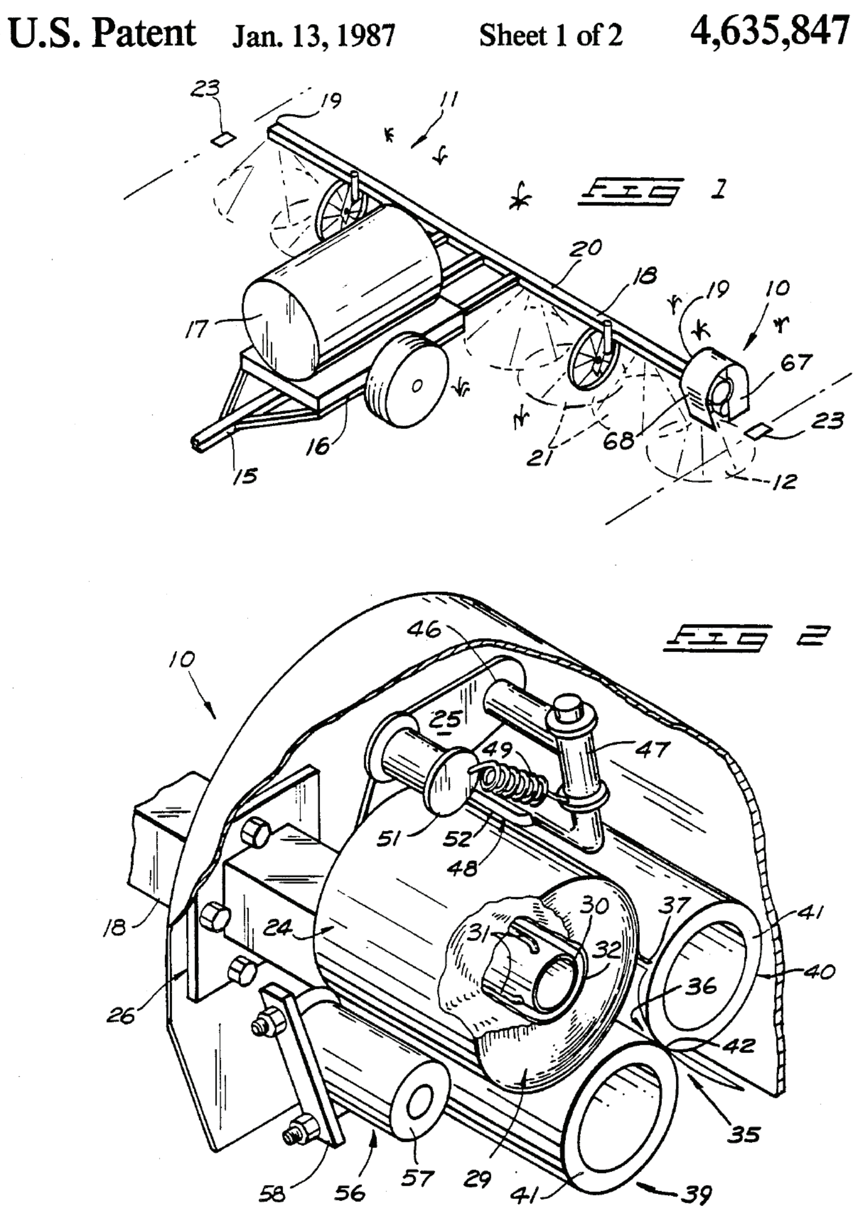

Figure A.21. Field marker and method.

Automatic Steering History

Manually steering a tractor was recognized as an extremely demanding task, and automatically steering a tractor has a long patent history. In patent 314,072, Snyder (1885) disclosed a "furrow pilot" for automatically steering a traction engine based on the last row.

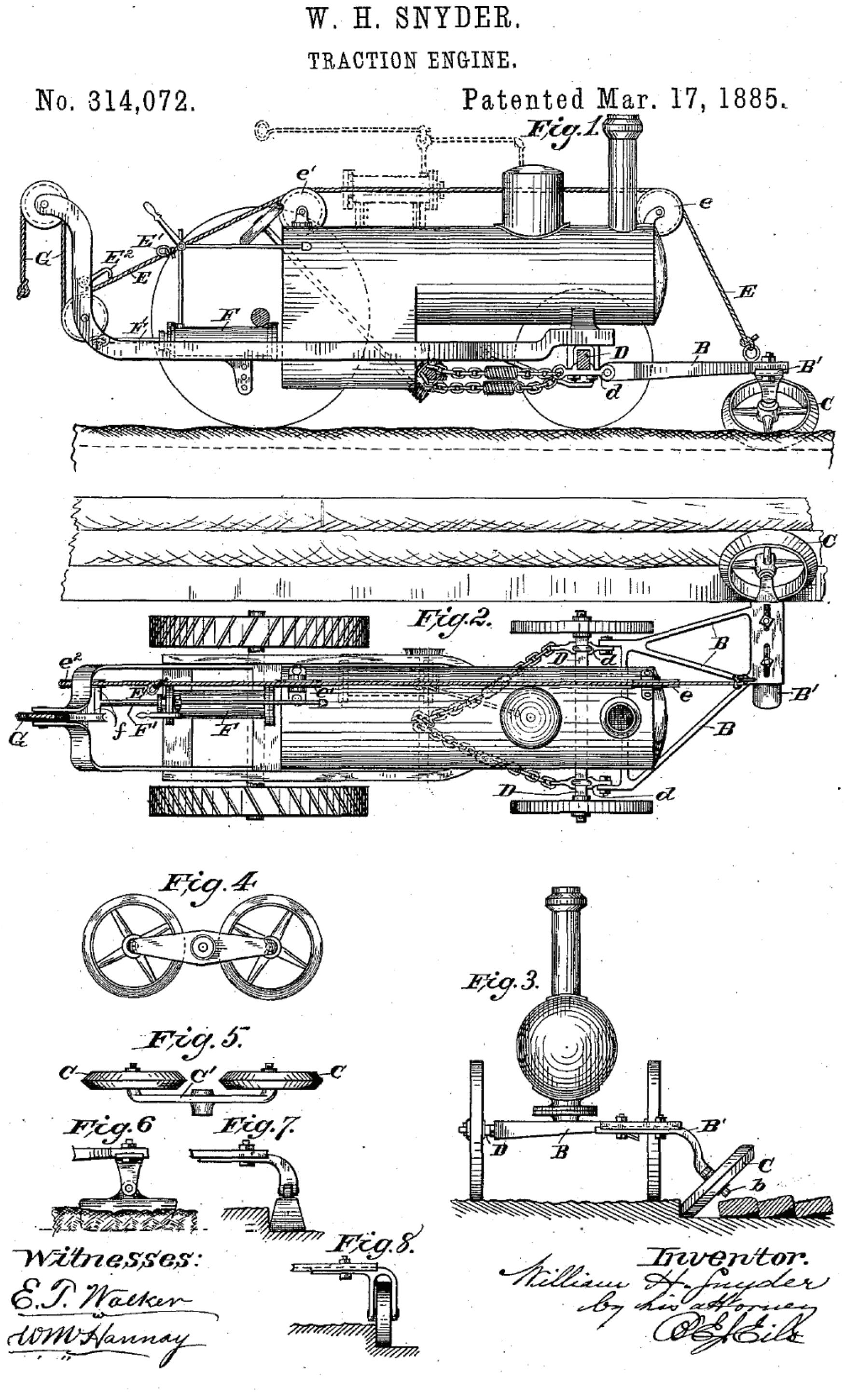

Figure A.22. Traction engine.

In patent 921,004, Rohan (1909) disclosed an improved furrow follower for a traction engine.

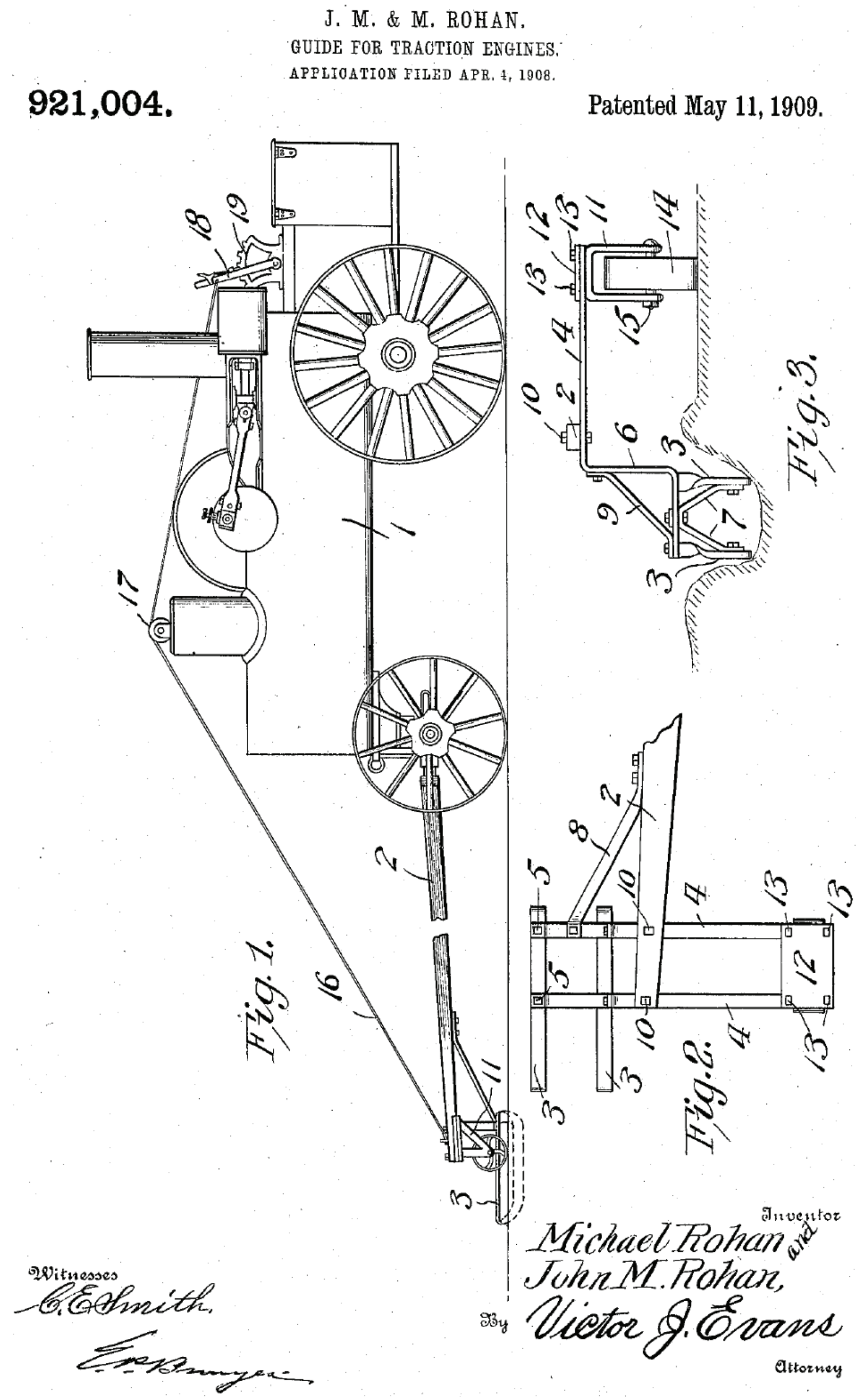

Figure A.23. Guide for traction engines.

In patent 1,114,586, Cuddy (1914) disclosed a steering device for a traction engine.

T. H. CUDDY.
STEERING DEVICE FOR TRACTION ENGINES.
APPLICATION FILED FEB. 8, 1913.

1,114,586. Patented Oct. 20, 1914.
3 SHEETS—SHEET 1.

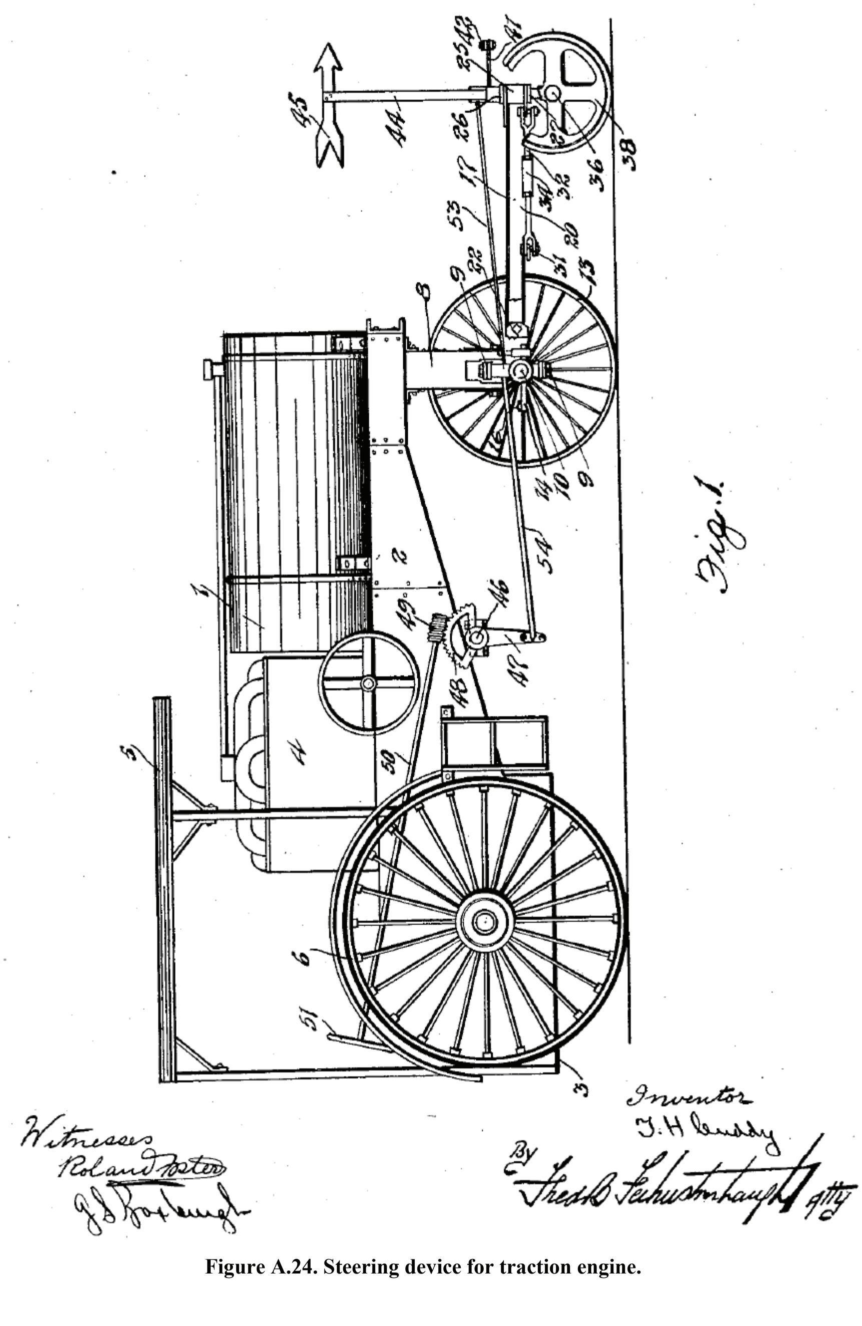

Figure A.24. Steering device for traction engine.

In patent 1,296,027, Whipple (1919) disclosed an automatic steering and control mechanism for a tractor using an internal combustion engine.

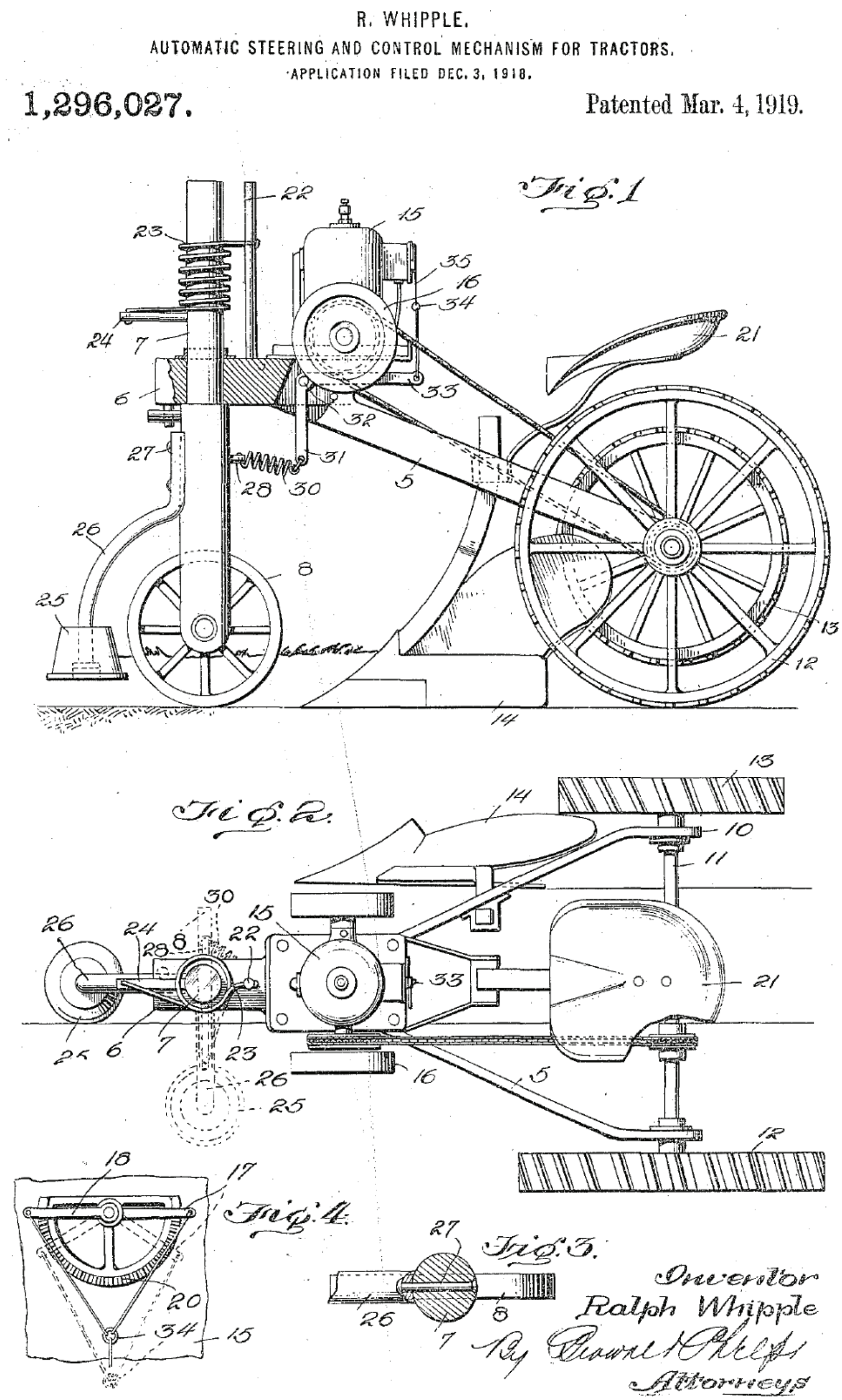

Figure A.25. Automatic steering and control mechanism for tractors.

In patent 1,868,360, Knight (1932) disclosed a furrow-following automatic steering apparatus that used an electric motor (item 55 in fig. 3) to turn the steering wheel of a vehicle with hydraulic steering cylinders.

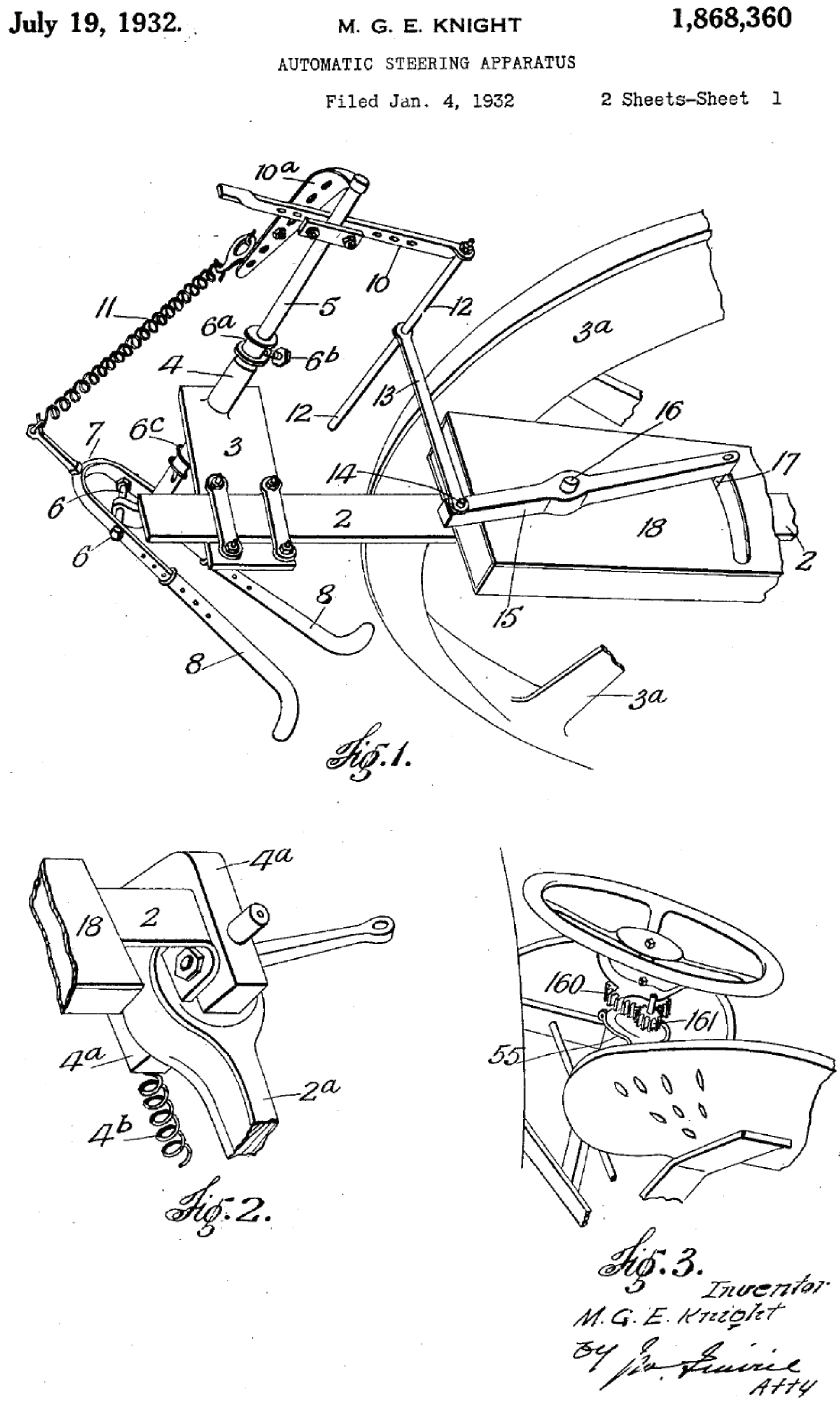

Figure A.26. Automatic steering apparatus.

In patent 2,259,193, Andrew (1941) disclosed an automatic guidance system that used a cable that wound around a drum in the center of the field.

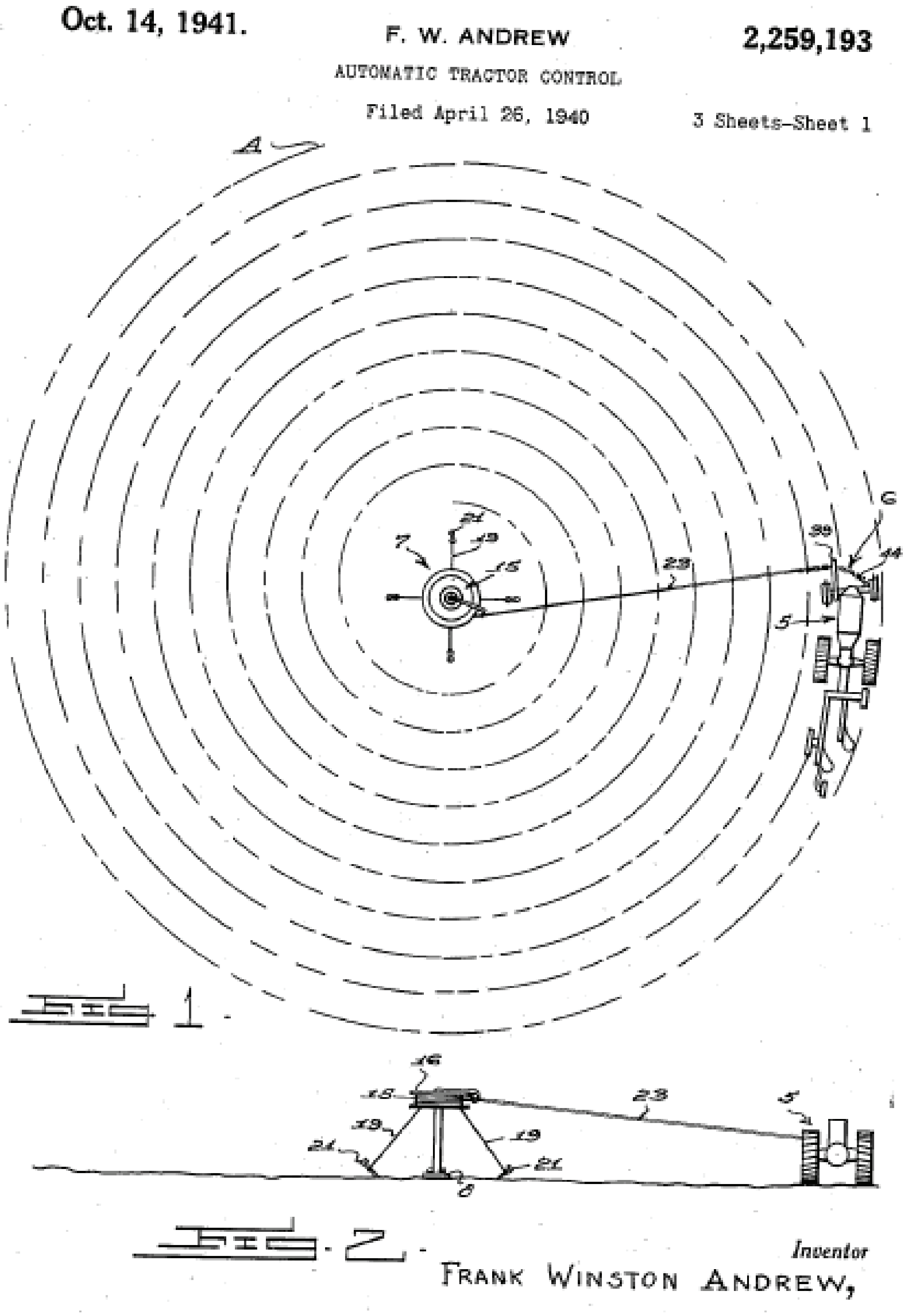

Figure 27. Automatic tractor control.

In patent 2,465,660, Phillips (1949) disclosed a furrow follower for autosteering a tractor that could be easily moved from one side to the other.

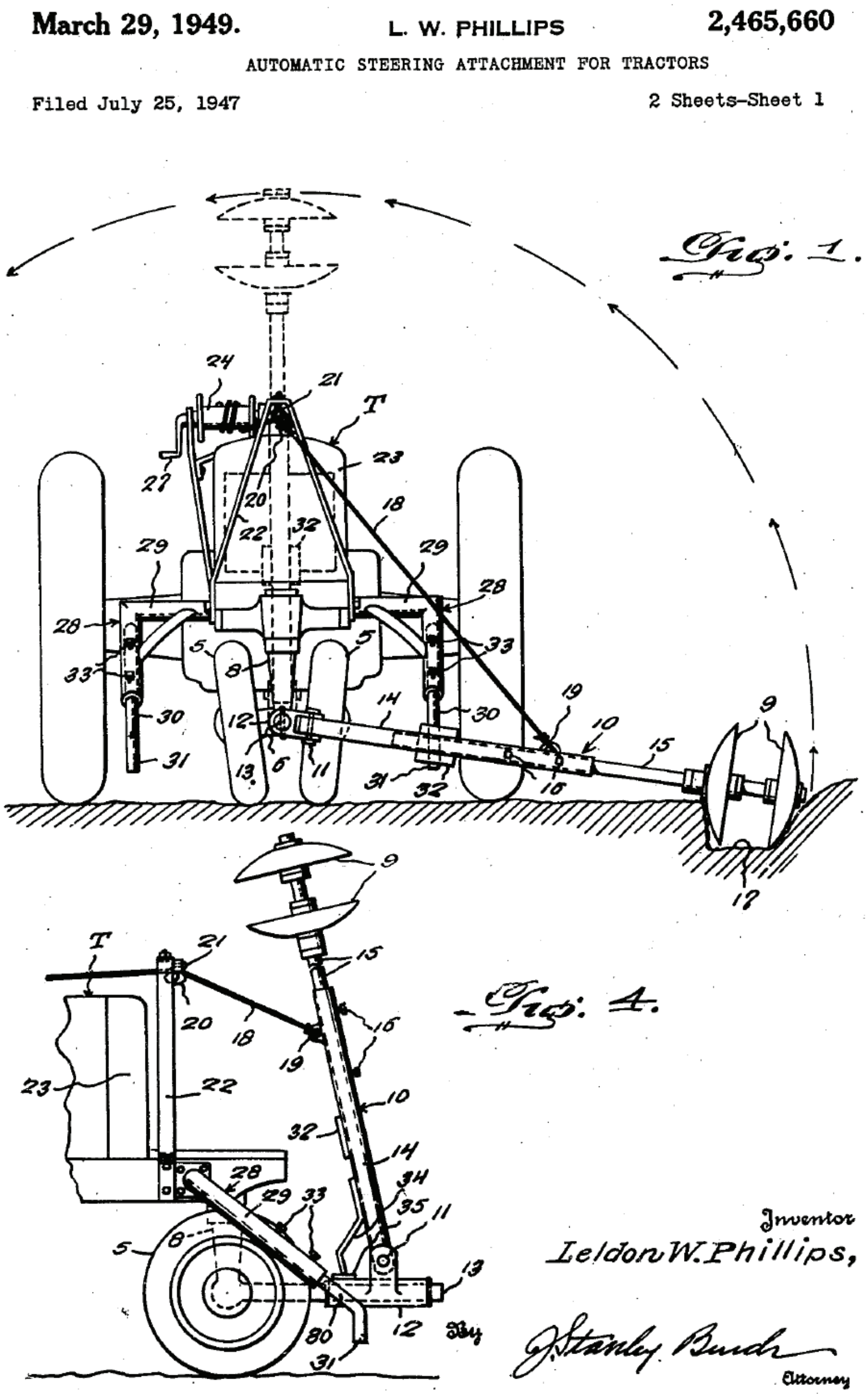

Figure A.28. Automatic steering attachment for tractors.

In patent 2,610,562, Ward (1952) disclosed an automatic steering device for a bean-picking machine that used crop feelers. This device used a hydraulic valve (item 37) attached to feeler rods (item 60 and 61) with a mechanical linkage.

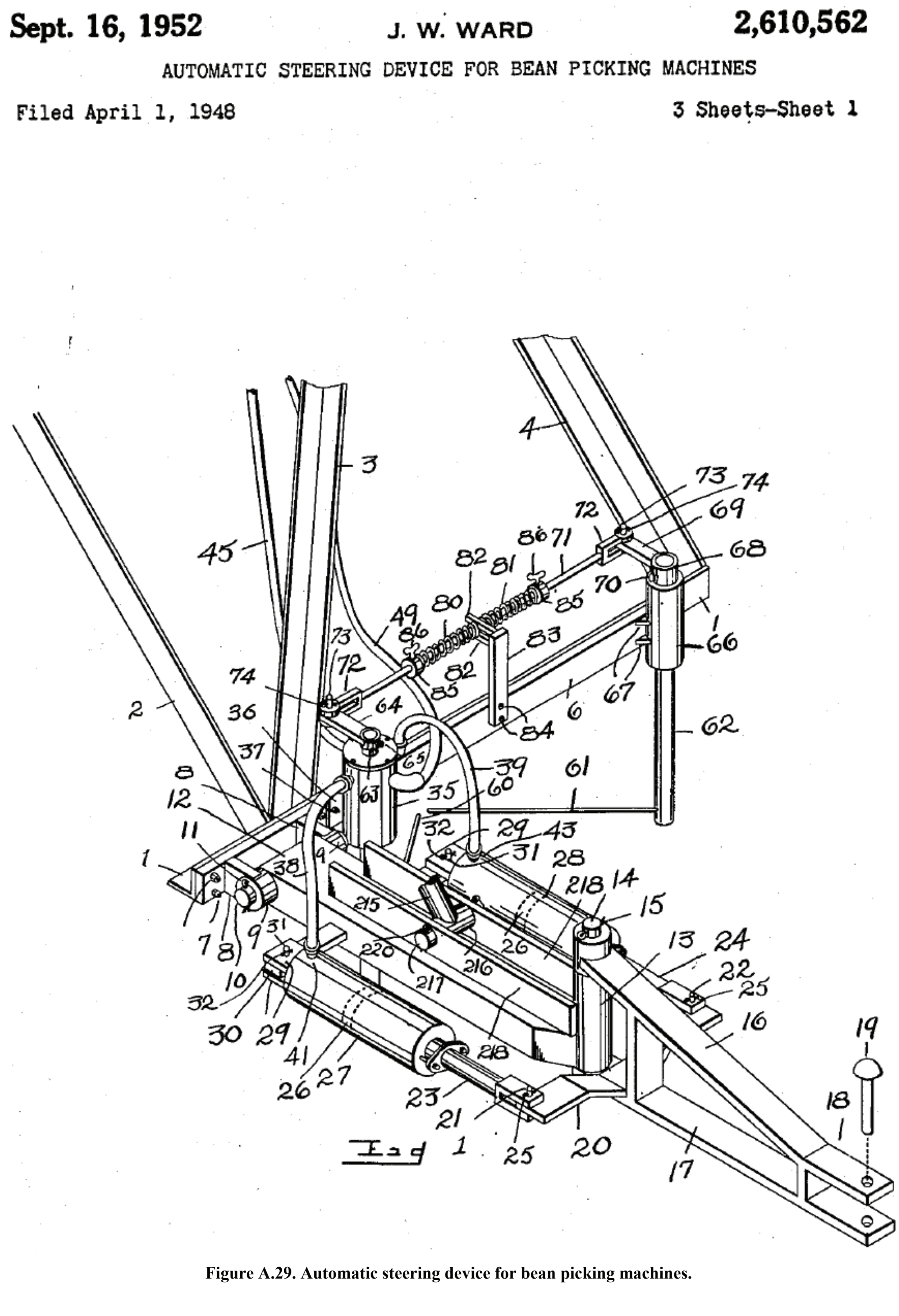

Figure A.29. Automatic steering device for bean picking machines.

In patent 2,847,077, Vaughan (1958) disclosed an automatic mowing machine guide that used differences in electric current flow through uncut and cut grass to guide the mower along the edge of the cut portion.

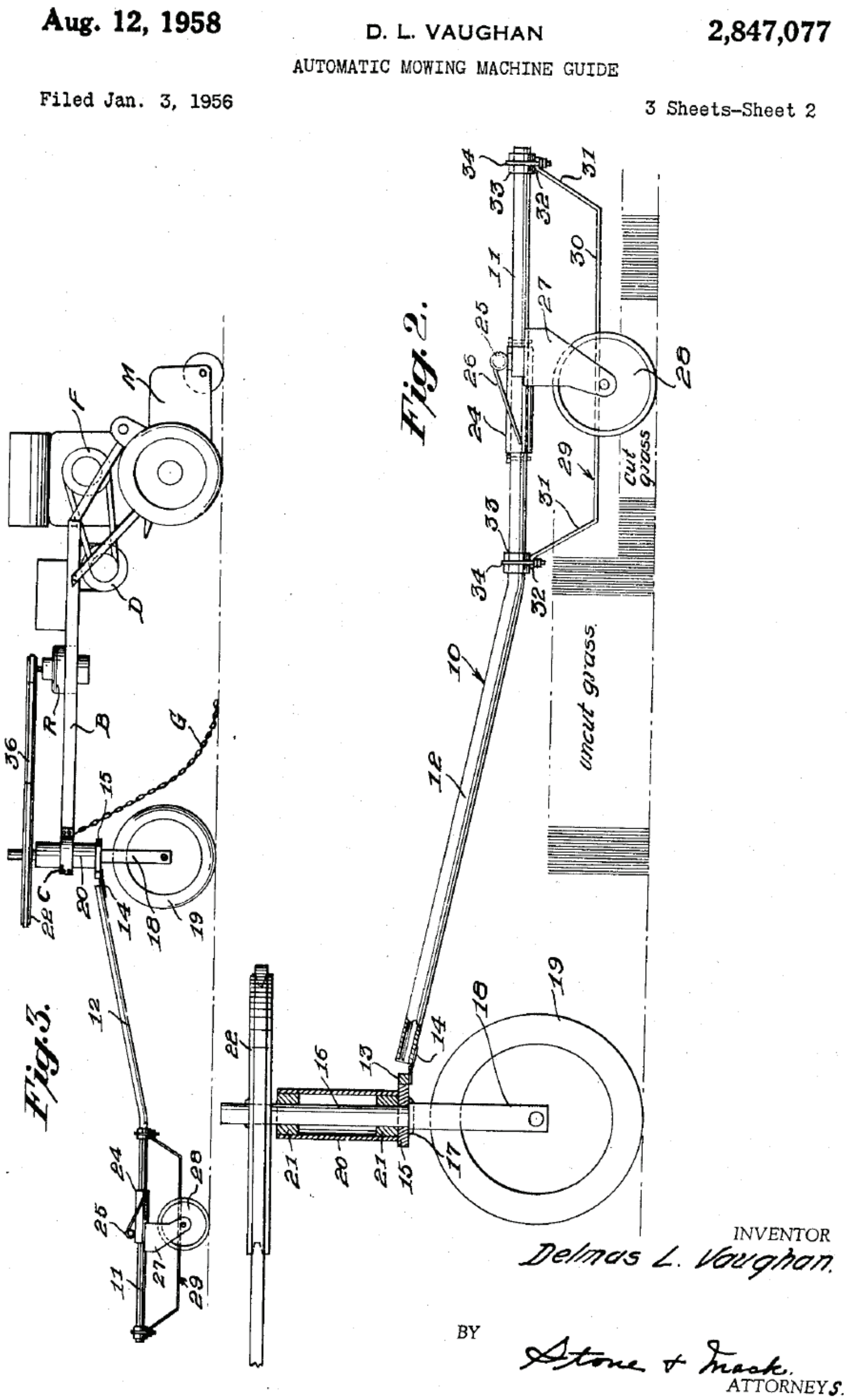

Figure A.30. Automatic mowing machine guide.

In patent 3,258,082, Amos et al. (1966) disclosed a control apparatus that used a wire guide (item 13) with a sensor (item 21) and a hydroelectric servo valve actuator to control a piston ram (item 17) for steering the front wheels.

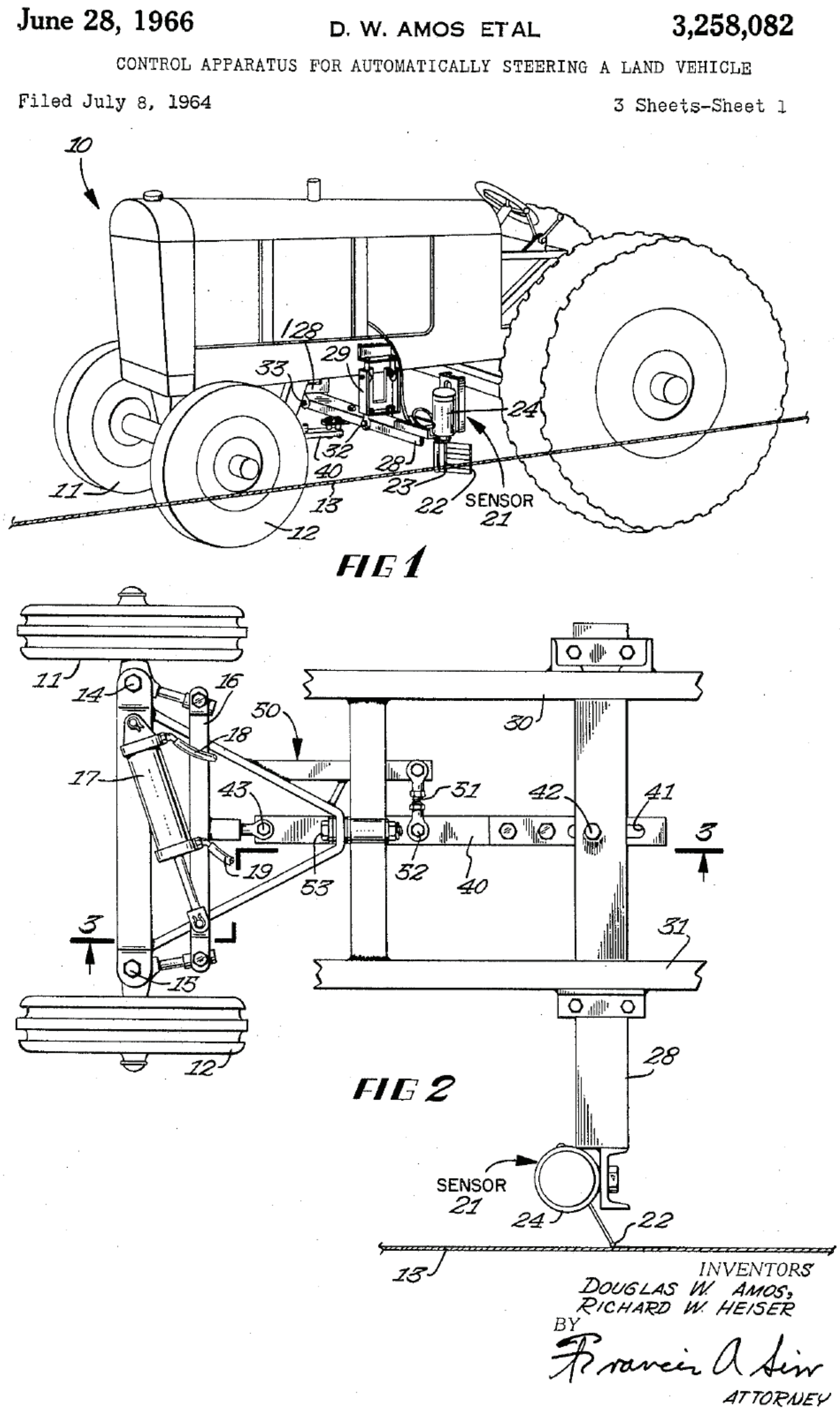

Figure A.31. Control apparatus for automatically steering a land vehicle.

In patent 3,548,966, Blacket (1970) disclosed an automatic device for steering an autonomous tractor in a spiral pattern. The operator can leave the tractor, which will continue, guided by the device, to plow the whole paddock on a spiral course. For safety, the tractor would stop if the feeler rods (items 64 and 65) struck an object.

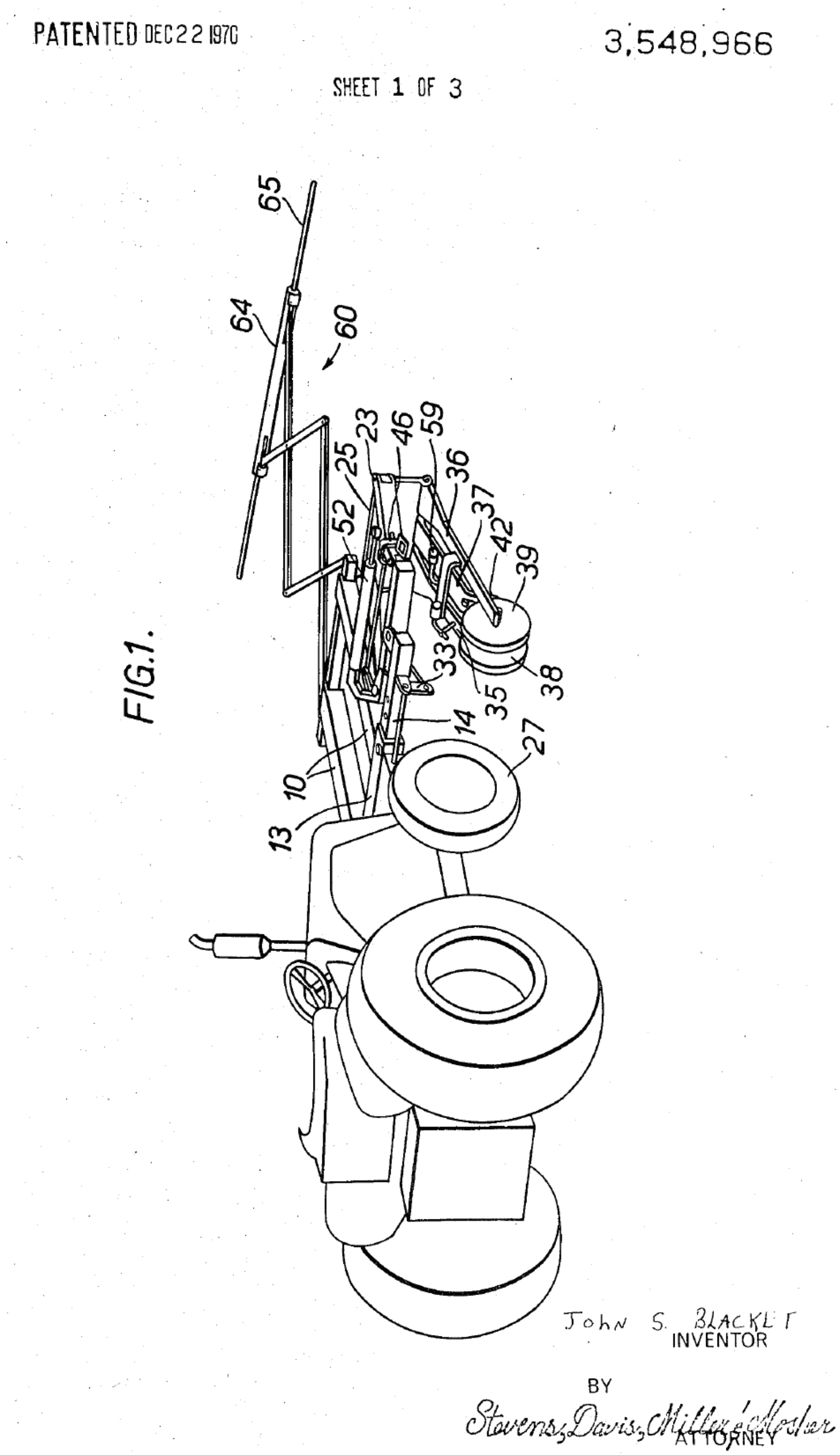

Figure A.32. Automatic steering means for an agricultural tractor.

In patent 3,946,825, Gail (1976) disclosed an apparatus for automatically steering a crop harvester along the edge of the previously cut swath in a standing crop.

U.S. Patent March 30, 1976 Sheet 2 of 5 3,946,825

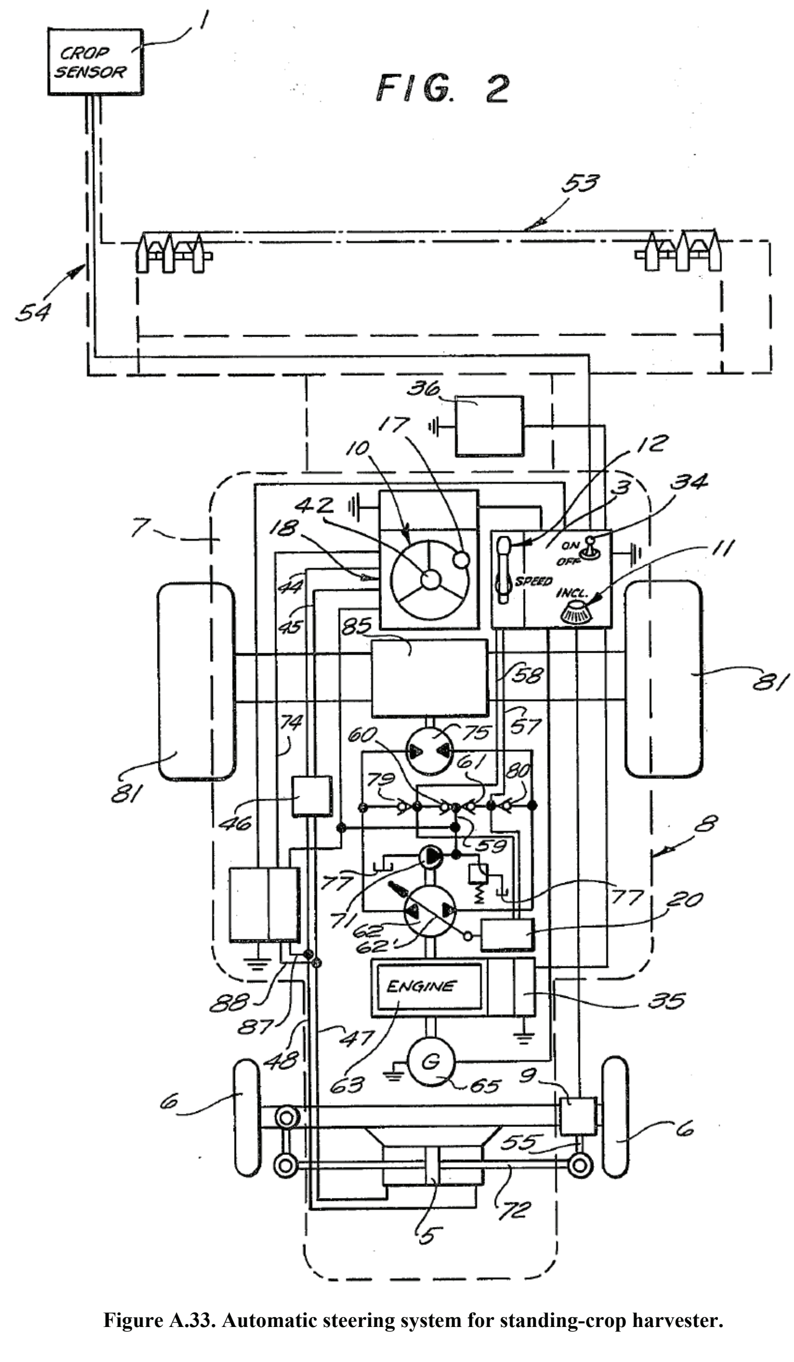

Figure A.33. Automatic steering system for standing-crop harvester.

The crop sensor feeler for patent 3,946,825 could be one of two alternatives: a crop feeler wand (figs. 4 and 5) or an optical sensor (figs. 6 and 7).

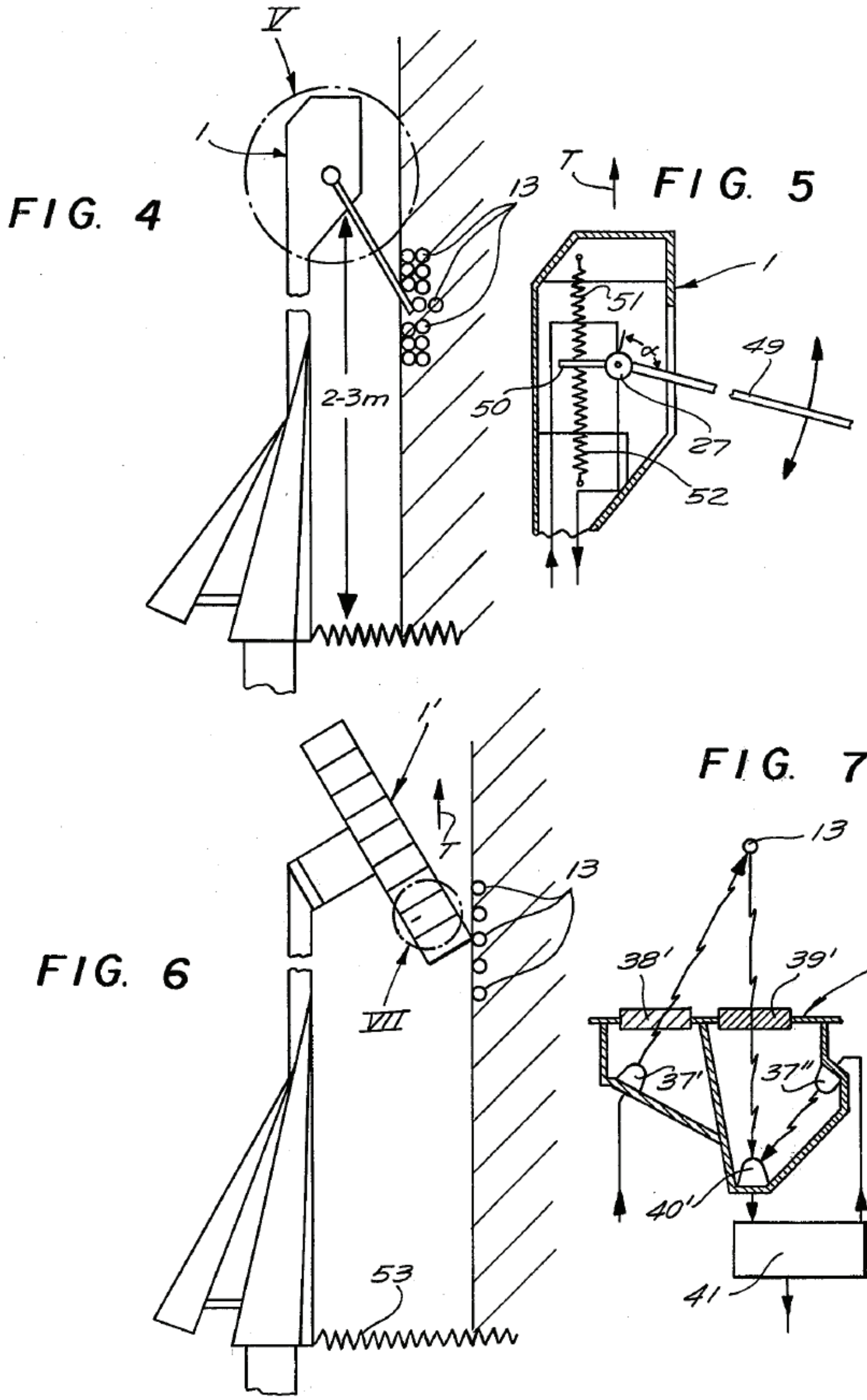

Figure A.34. Sensors for automatic steering apparatus.

In patent 3,991,618, Stampfer et al. (1976) disclosed a pair of row crop feeler wands that use strain gauges bonded to the rods adjacent to one end.

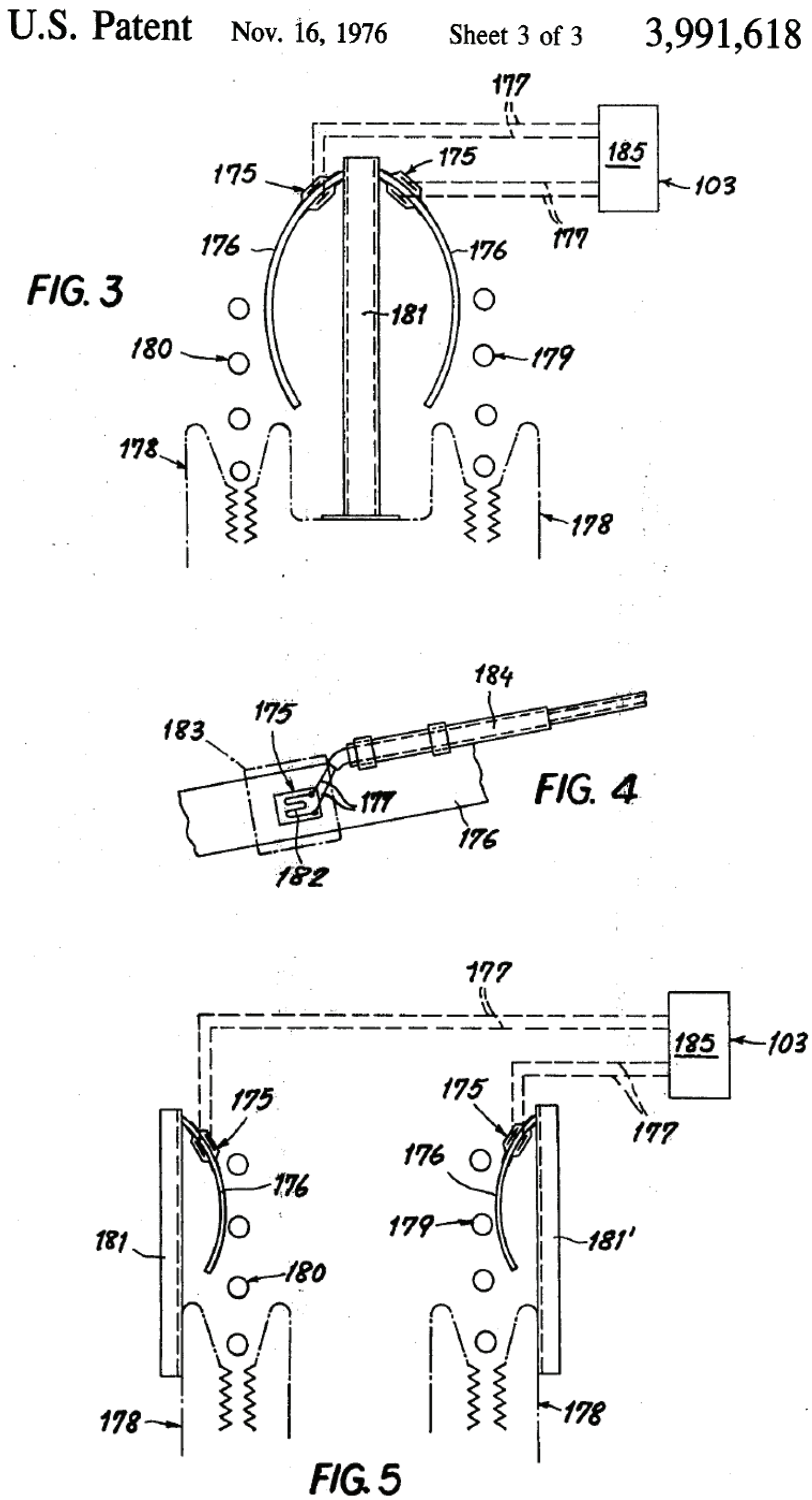

Figure A.35. Sensor for automatic steering system for row-crop harvester.

In patent 4,366,756, Brum (1983) disclosed an electronic tractor guidance system that used a furrow follower sensor and an electric motor connected to a steering wheel.

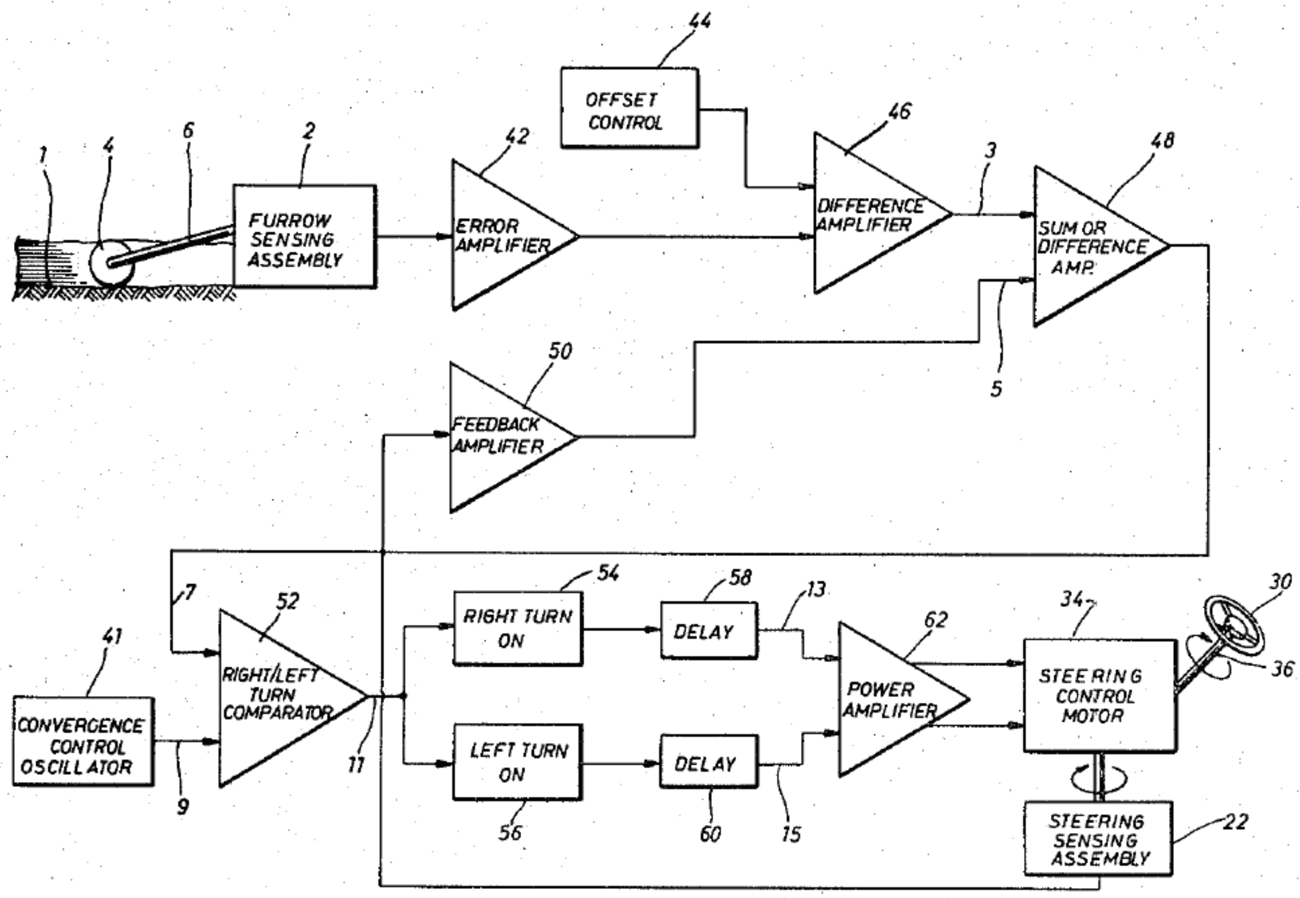

Figure A.36. Electronic tractor guidance system.

In patent 4,414,903, Fasse and Glesmann (1983) disclosed a furrow-following automatic steering system.

U.S. Patent Nov. 15, 1983 Sheet 1 of 6 4,414,903

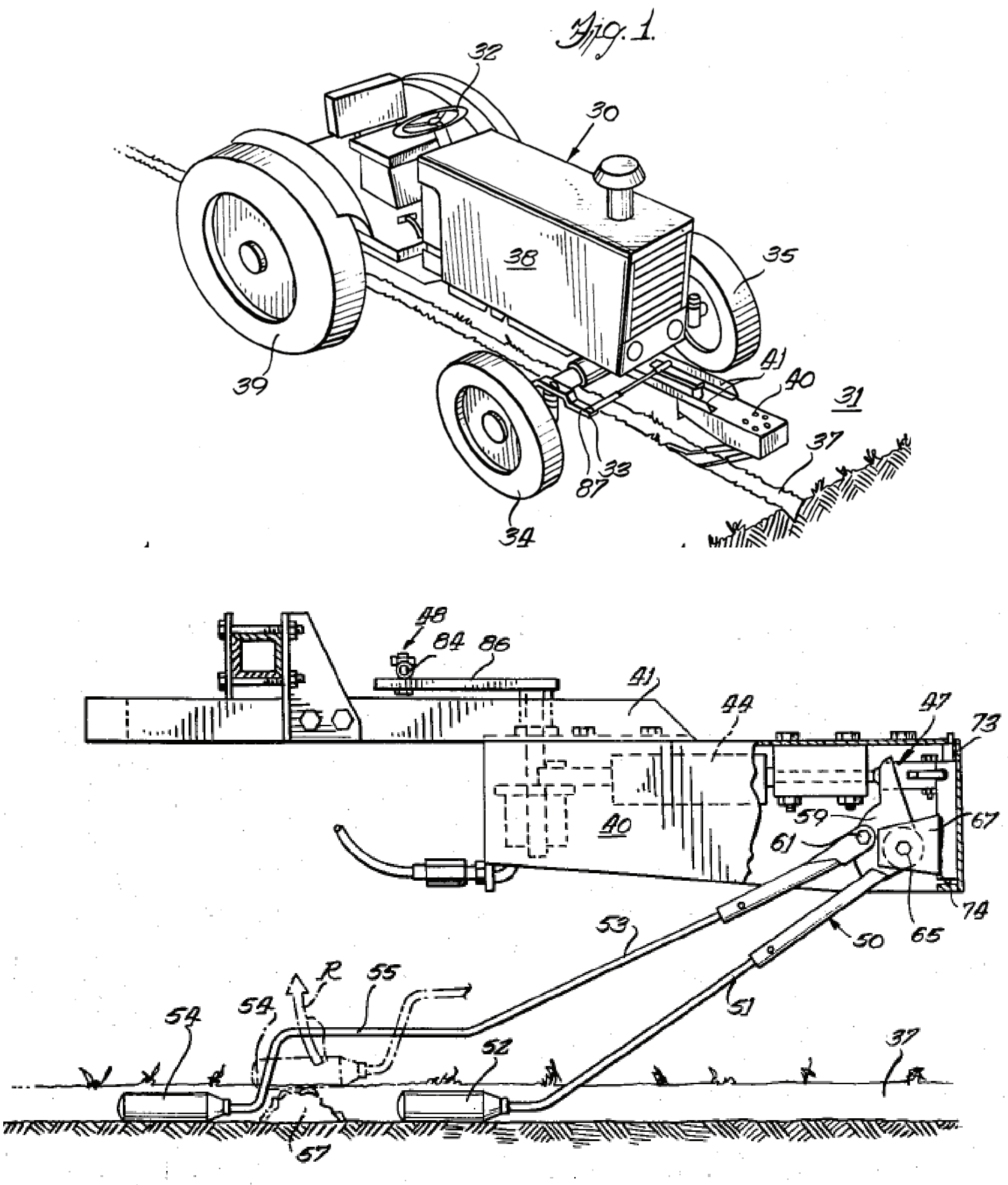

Figure A.37. Automatic guidance mechanism.

In patent 4,918,441, Bohman (1990) disclosed a non-contact row crop sensor comprising one or more transmitter/receptor pairs (items 40 and 42) mounted on two row separators (items 10 and 12) of a harvesting machine. A control signal is generated depending on the relative time of intercept of each beam.

U.S. Patent **Apr. 17, 1990** **Sheet 1 of 4** **4,918,441**

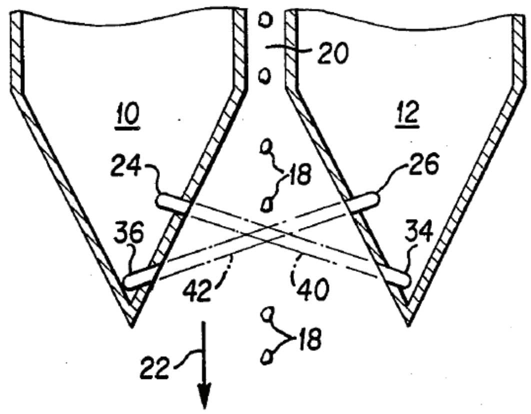

FIG. 1

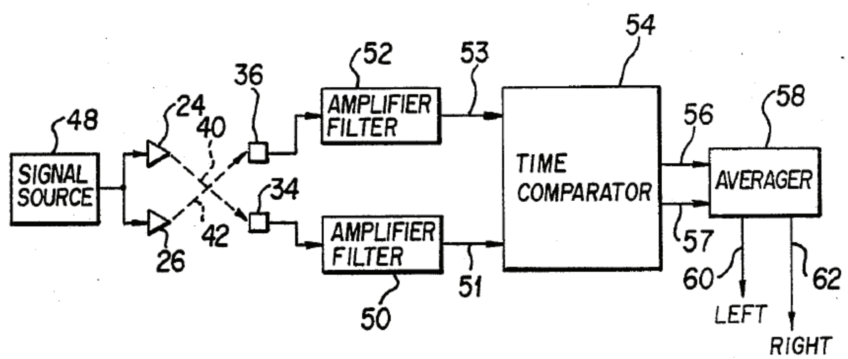

FIG. 2

Figure A.38. Non-contact sensing unit for row crop harvester guidance system.

In patent 5,279,068, Rees (1994) disclosed a crop row deviation sensing device that consisted of infrared sensor pairs (transmitter and receiver) operating in diffuse proximity mode with a definable range (variable power range) between two rows of plants, or above a single row of plants. When the rows deviate from equal distance from the sensor, a control signal is generated proportional to the difference in distance.

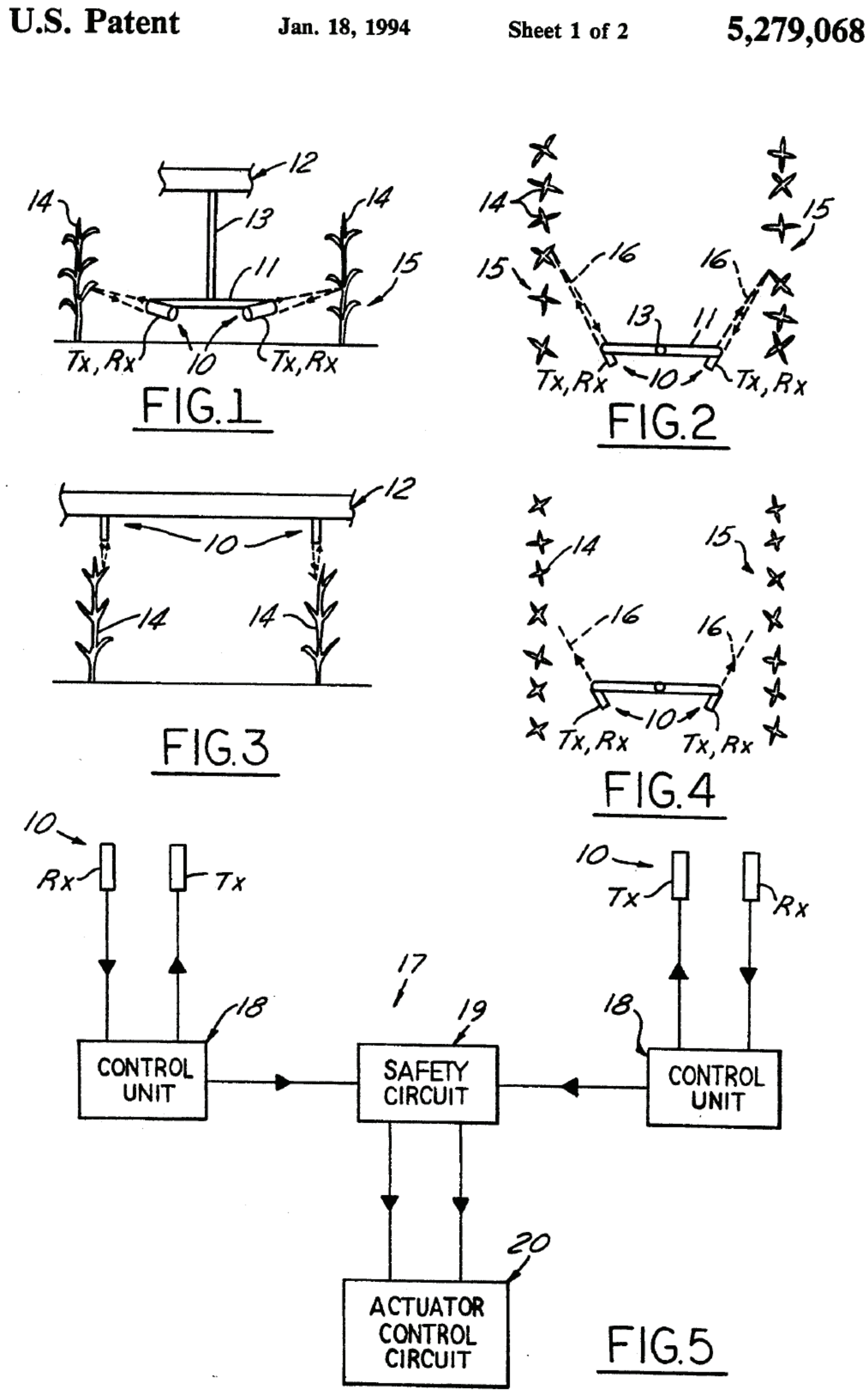

Figure A.39. Crop row deviation sensing device.

In patent 5,528,888, Miyamoto et al. (1996) disclosed an apparatus for detecting a cut boundary of a mowed field. This sensor consists of a plurality of rocking condition sensors, as shown in figure 5.

U.S. Patent **Jun. 25, 1996** **Sheet 5 of 21** **5,528,888**

FIG.5

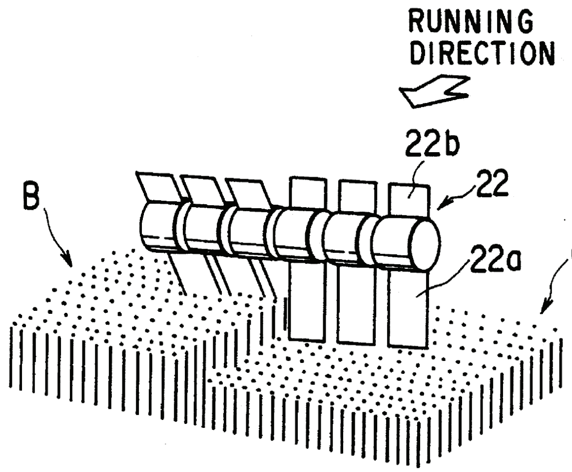

Figure A.40. Autonomous mowing vehicle and apparatus for detecting boundary of mowed field.

In patent 5,828,971, Diekhans et al. (1998) disclosed an automatic steering device that used a number of alternative locating device sensors. Figure A.41 below shows a locating device, ultrasonic or infrared, consisting of three components (OV1, OV2, and OV3). Another sensor for row crop use is the crop feeler wand shown in figure A.42 on the next page.

U.S. Patent **Oct. 27, 1998** **Sheet 5 of 5** **5,828,971**

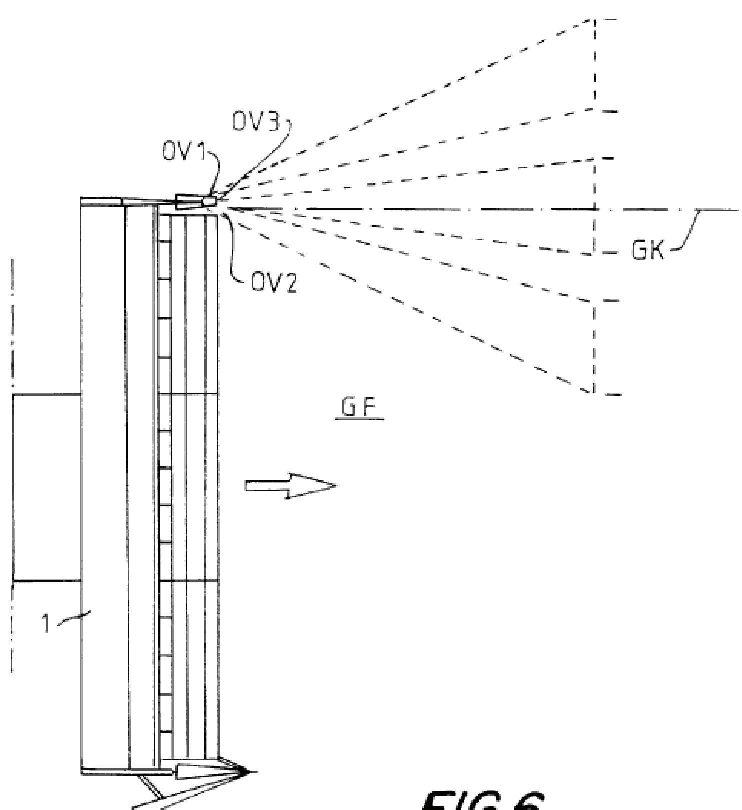

FIG.6

Figure A.41. Automatic steering device for an electrically controllable hydraulic steering system, especially for an agricultural vehicle.

U.S. Patent Oct. 27, 1998 Sheet 2 of 5 **5,828,971**

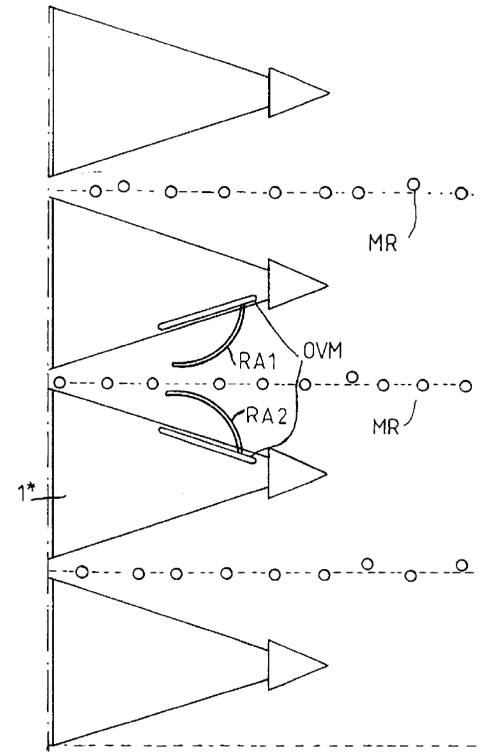

FIG.2

Figure A.42. Crop feeler sensors.

In patent 6,095,254, Homburg (2000) disclosed a device and method for detecting cut crop boundaries and other guide variables. Figure A.43 shows the location of the sensor (item 5), which is a laser ranging device.

U.S. Patent Aug. 1, 2000 Sheet 3 of 4 **6,095,254**

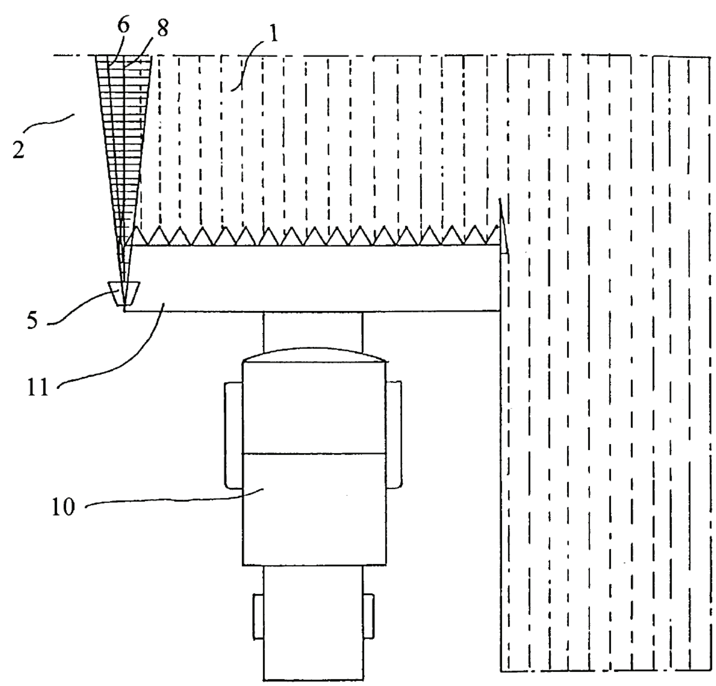

Fig. 4

Figure A.43. Device and method for detecting cultivation boundaries and other guide variables.

In patent 5,410,479, Coker (1995) disclosed an automated guidance apparatus that used ultrasonic sensors.

U.S. Patent **Apr. 25, 1995** **Sheet 1 of 5** **5,410,479**

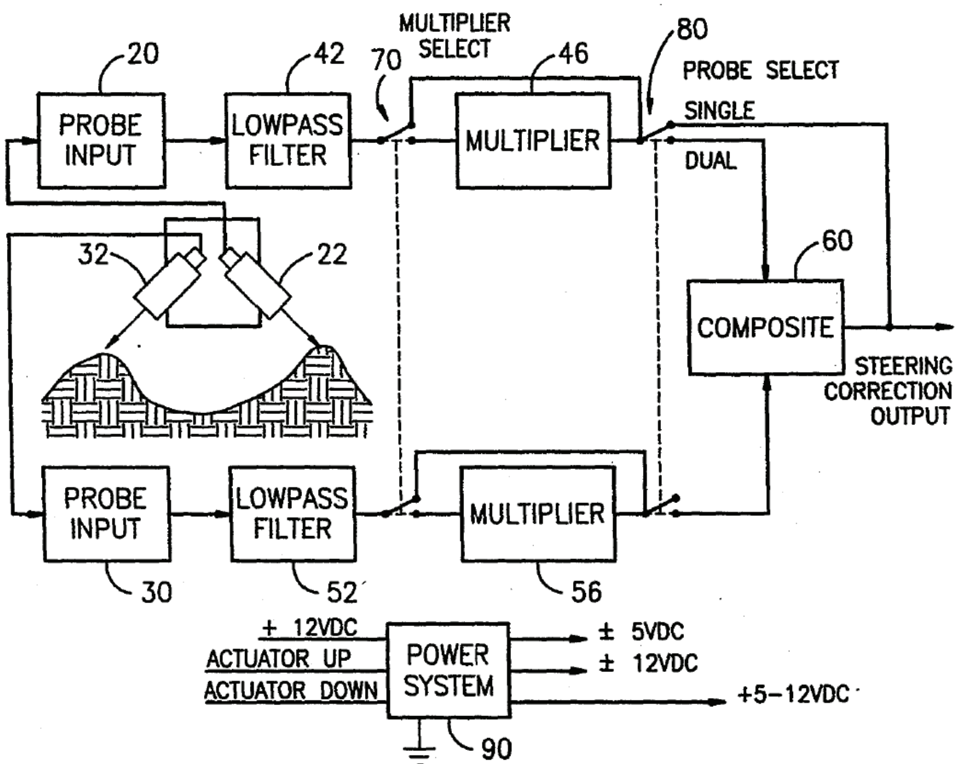

FIG. 1

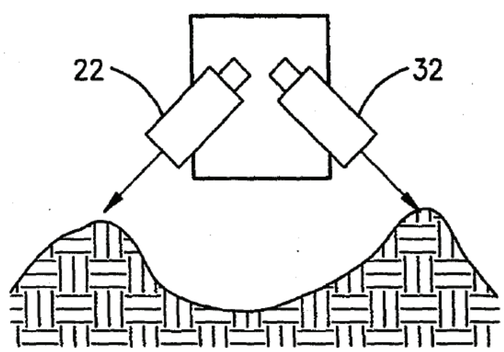

FIG. 2

Figure A.44. Ultrasonic furrow or crop row following sensor.