RESEARCH PROGRESS OF AGRICULTURAL IMPLEMENT GUIDANCE SYSTEMS. A REVIEW
/
农具自动导航技术的研究进展. 综述

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ABSTRACT
Automatic navigation system for agricultural vehicles have become a widely used technology in precision agriculture over the last few decades. More and more sophisticated tractor control systems, however, revealed that exact positioning of the actual implement is equally or even more important. Based on literature sources and patent databases, the aim of this review is to introduce implement guidance systems and describe its current application in agricultural implement. Agricultural implement guidance is an essential technology for autonomous vehicle operations. In addition, applications and new technologies associated with navigation sensors on passive and active implement guidance are analyzed. Finally, challenges and future perspectives of agricultural implement systems are summarized and forecasted. This study can enrich the application of automatic navigation sensors on agricultural implements and provide a reference for the application of automatic navigation on more field operations.

摘要
农业机械自动导航技术已经成为精准农业中广泛应用的技术之一。然而，田间地表情况复杂多变，及时、准确地农具的精准定位对提升机具作业质量具有重要的现实意义。在总结了目前作业农具研究现状的基础上，本文旨在重点介绍农具自动导航系统，并描述其目前在农业实施中的应用。农具自动导航技术是农业机械主动导航的一项重要技术。此外，还分析了导航传感器在被动和主动农具导航上的应用和新技术。最后，对自动导航技术在作业机具上的应用所面临的挑战和未来前景进行了总结和预测。本研究可以拓展自动导航技术在农具上的应用，为自动导航在更多田间作业上的应用提供参考。

INTRODUCTION
Agriculture is the foundation of human existence *(Ding et al., 2018)*. As the World's population continue to grow and will reach nearly 10 billion by 2050, the need for food and agricultural products is growing at the same time. However, the growing demand for food has resulted in a significant shortage of labor for agriculture. So, precision agriculture is considered to be one of the key technologies to ensure food security and reduced labor intensity *(Loures et al., 2020)*. Combined with an ever-declining rural labor force it causes the need for greater efficiencies and inevitably leads to increasing levels of in-field automation *(Mavridou et al., 2019)*. In addition, long hours and repetition easily result in operators' fatigue, which in turn causes safety issues and decrease operation efficiency (*Reid et al., 2004*). Therefore, the automatic navigation technology of agricultural machinery is the basis for the implementation of precision agriculture, which can effectively reduce the labor intensity of agricultural machinery operators, improve the operation accuracy and efficiency. *(Zhang et al., 2004; Li et al., 2009; Mousazadeh, 2013; Dong et al., 2017).*

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Tractor-mounted agricultural implements are rarely involved in navigation and positioning systems in the field. A recent expansion to the area of automatic vehicle guidance is the use of automatic implement guidance *(Werner, 2015)*. It is a natural extension because, after all, the implement is the actual device doing the fieldwork.

Agricultural implement guidance system controls tractor steering and position and sometimes implement steering to achieve accurate positioning of the implement rather than the tractor itself *(Oksanen et al., 2016)*. Agricultural Implement guidance continues to evolve, improving field performance, and providing capabilities beyond solely tractor guidance. The application to implement guidance systems to agriculture can yield significant productivity and efficiency benefits *(Balafoutis et al., 2017; Fue et al., 2020)*. Therefore, automatic control of agricultural implements such as cultivators and planters that are attached to the tractors is essential for automated or autonomous operations *(Han, et al., 2018)*.

There is a long history of creating automatic navigation guidance systems in agriculture. *Mousazadeh, (2013)* described a technical review on navigation systems of agricultural autonomous off-road vehicles. *Han et al., (2018)* gave a review of recent development in autonomous vehicles, including localization, navigation control, mission planning, perception and safeguarding, and implement control. But no summary of implement guidance system uses in agricultural applications has been reported. In this review, implement guidance systems are used mainly in agricultural applications such as soil cultivation implements, planting machines. These applications in implement guidance systems are presented. The challenges and future perspectives of implement guidance systems are discussed. Finally, the conclusions are drawn.

RESULTS OF THE STUDY

Agricultural implement guidance system

Currently, there are two types of implement guidance systems: passive and active (Fig. 1). Passive implement guidance does not require a steering mechanism on the implement, and the drift of the implement path is corrected by adjusting the tractor path. Active implement guidance system requires a localization sensor for the implement (e.g., GNSS or Machine Vision) and a steerable implement. Both the tractor and the implement follow the desired path.

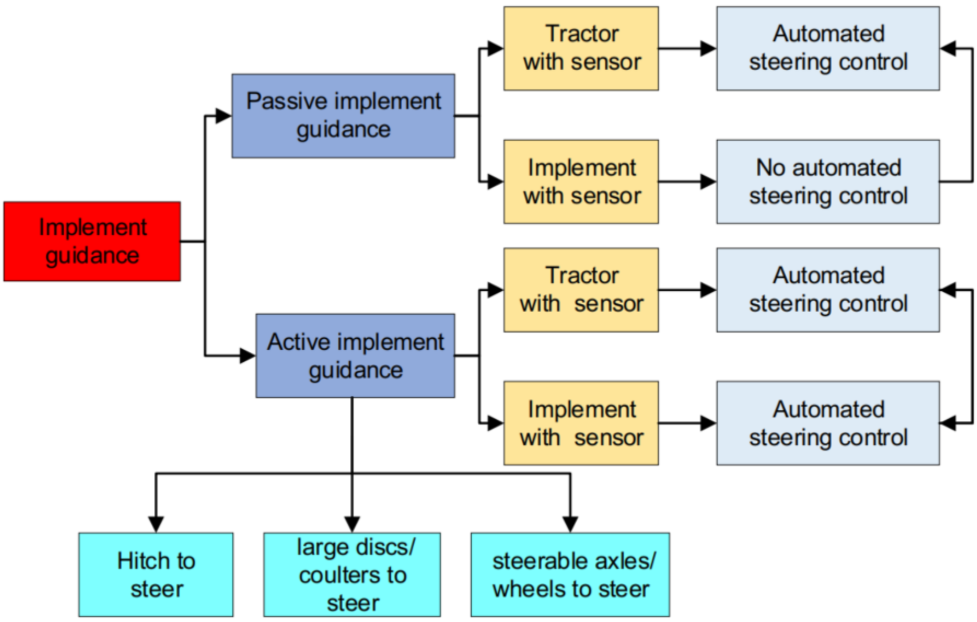

Fig. 1 - Agricultural implement guidance systems

Passive implement guidance systems

The most popular implement guidance solution is passive guidance *(Fontanelli, et al., 2015)*. Passive implement guidance system that monitors and corrects the position of the implement by moving the tractor (Fig. 2). However, 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 desired line.

Typically, two GNSS/Vision receivers are used, one mounted on the cab and one on the implement. The receiver will keep the implement on-track based on tractor heading and equipment geometry or dynamics.

This type of implement guidance solution is cheaper compared to its active counterpart. However, one disadvantage of passive implement guidance is that the tractor must steer the implement, which means that the tractor may be operating off of the guidance path.

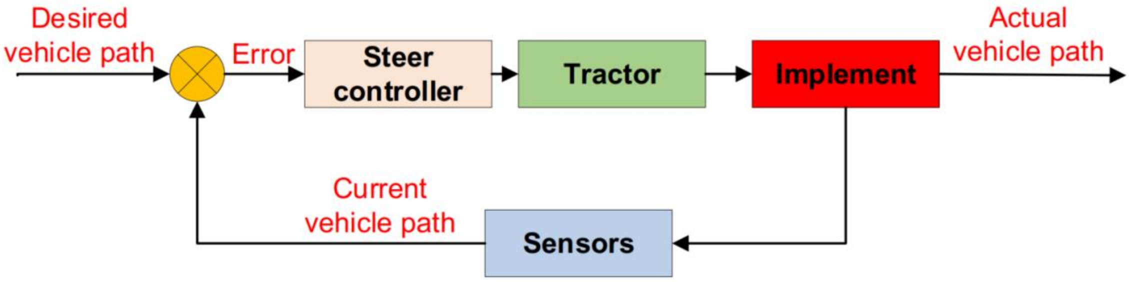

Fig. 2 - Control flow chart for passive implement guidance systems

Active implement guidance systems

Active implement guidance, in which the implement is steered independently of the tractor, may be particularly useful within an autonomous system, allowing implement guidance to operate somewhat independently of the vehicle guidance system *(Thomasson, et al., 2018)*. These systems guide the implement independently of the tractor. Active guidance describes when an implement is being guided independently of the tractor or prime mover (Fig. 3). A second GNSS/Vision receiver is mounted on the implement along with components depending upon the type of implement guidance system. The significant advantage of active over passive guidance is seen when operating in growing crops, ridges, or beds where both the tractor and implement will remain on the desired guidance path, preventing damage *(Feng, et al., 2005, Jessie, 2015)*. However, active guidance comes at a higher cost since it requires "active" technology to steer the implement independently of the tractor. Still, the extra accuracy may be warranted to improve cropping returns *(Jack, 2017)*.

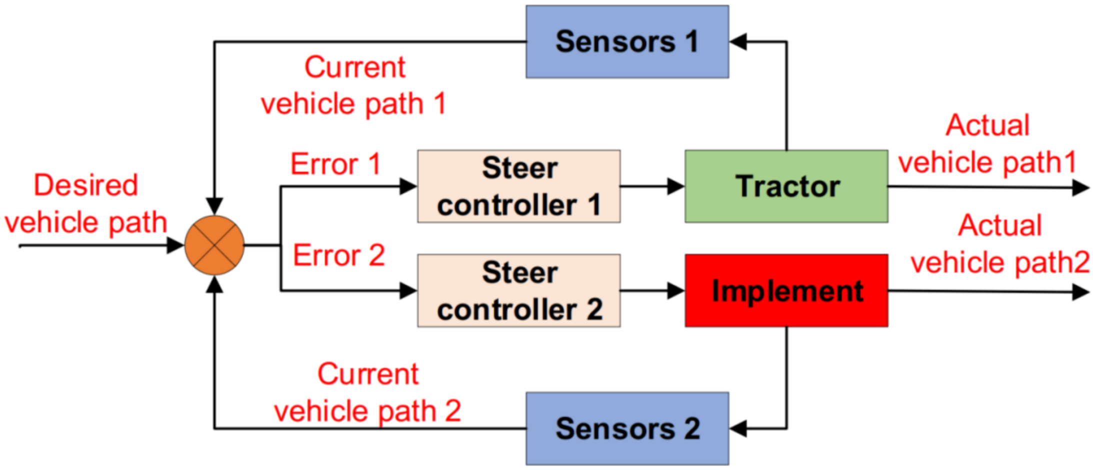

Fig. 3 - Control flow chart for active implement guidance

Application in agricultural implement systems

Automatic control of agricultural implements such as cultivators and planters that are attached to the tractors is essential for automated or autonomous operations *(Han, et al., 2018).* Agricultural implement guidance continues to evolve, improving field performance, and providing capabilities beyond solely tractor guidance. Due to the implement drift caused by varying soil conditions as well as gravity in sophisticated agricultural field applications, the implement path should be different from the tractor path. It is possible for the vehicle to follow the desired path but have the implement completely off its desired path *(Han et al., 2018)*. The cause for this is 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. Therefore, implement guidance systems can keep the implement on the desired path.

Application in passive implement guidance system

As shown in Fig. 4, the weight of pull-type implement will cause it to drift downhill in uneven terrain and on slopes. A shared-signal second StarFire Receiver installed on the implement communicates the implement's exact position to the tractor's AutoTrac system *(John Deere, 2020a)*. The tractor then changes its path to compensate for the implement drift and will get a perfect pass-to-pass result. Regardless of the terrain, AutoTrac Implement Guidance - Passive can now achieve the highest precision standards in all seeding, planting, and tillage operations.

Fig. 4 - Automatically compensate implement drift

As shown in Fig. 5, control the implement with the Trimble TrueGuide implement guidance system *(Trimble, 2020)*, a passive guidance system that monitors and corrects the position of the implement with compensation from the tractor. With TrueGuide, the implement's position is dependent on the tractor. When implement drifts, TrueGuide signals the tractor's Autopilot system to pull the implement on-line. TrueGuide provides passive implement guidance through integration with the tractor guidance system. The guided position of the tractor is adjusted to position the implement correctly. TrueGuide Implement Guidance System reduces uncontrolled drift of the implement by more than 50% over guiding the tractor alone, minimizes draft and results in more consistent guess rows, and increases precision with input placement.

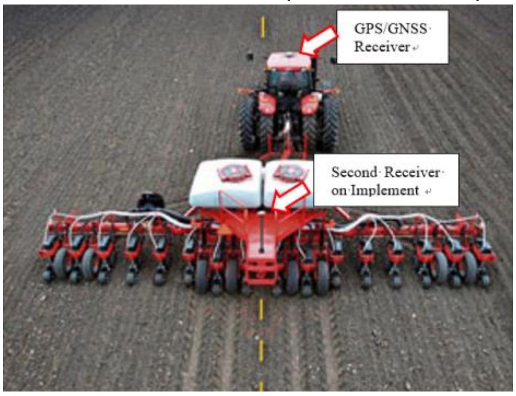

Fig. 5 - TrueGuide implement guidance system

Application in active implement guidance

Active implement guidance is based on dedicated 'auto-steering' systems for the implement, of which there are three main types.

Hitch correction

Hitch correction is where the tractor drawbar or the implement hitch tongue is hydraulically adjusted side-to-side to guide the implement *(Jack, 2017)*. Different compensation techniques are required, depending on whether the implement is mounted on a three-point hitch or towed behind the tractor *(Hou, 2010)*.

Implements are particularly susceptible to lateral drifts for various reasons. In this case, it is best if the implement is also controlled, not just the tractor. A system controller reacts to GNSS/Vision receiver position data from the implement itself or data from a stubble row or furrow/ridge tracking sensor fitted to the implement.

This approach adjusts the implement position up to a maximum offset but without correcting any skew angle *(Heraud et al., 2009; Rovira-Más, 2010)*. Therefore, typically, an implement controller is used in addition to a tractor controller. The advantage of implement control becomes immediately evident on rolling hills.

(1) Tongue Steer

As an implement tongue connection, tongue Steer (e.g., Laforge DynaTrac CLASSIC) is ideal for pulled implements to the left or right. The guided hitch allows a semi-mounted (2-point) planter and applicator to follow the GPS-RTK guidance line with a high level of accuracy in flat fields and on hillsides (Fig.6.a).

The hitch replaces the crossbar on planters, and adapters for other implements and nutrient applicators are available. The system gives users the same RTK repeatable sub-inch accuracy on tractors with the implement (Fig.6.b).

By automatically steering the planter, it compensates for planting side-hill drift and makes perfect end-rows to maximize yields. It also helps to prevent crop damage and improve efficiency in subsequent field operations (*Laforgegroup, 2020*).

Fig. 6 - Laforge Guided Hitch System (a) DynaTrac CLASSIC(b) The DynaTrac CLASSIC is used on towed tongue implements to allow lateral movement of the implements

(2) 3-point hitch system providing real-time lateral or side-shift adjustment

Perez-Ruiz et al. (2012) developed and evaluated an innovative machine for weed control in inter-row and intra-row areas, with a unique combination of inter-row cultivation tooling and intra-row band spraying and an electro-hydraulic side-shift frame (Fig. 7.a) controlled by an RTK-GPS system. Band spraying with mechanical weed control using RTK-GPS (Fig. 7.b) enabled the comparison between treatments from the perspective of cost savings and efficacy in weed control for a sugar beet crop. During one season, the herbicide application rate (112 $L \cdot ha^{-1}$) of band spraying with mechanical weed control using RTK-GPS was approximately 50% of the conventional method. Thus, a significant reduction in the operating costs of weed management was achieved.

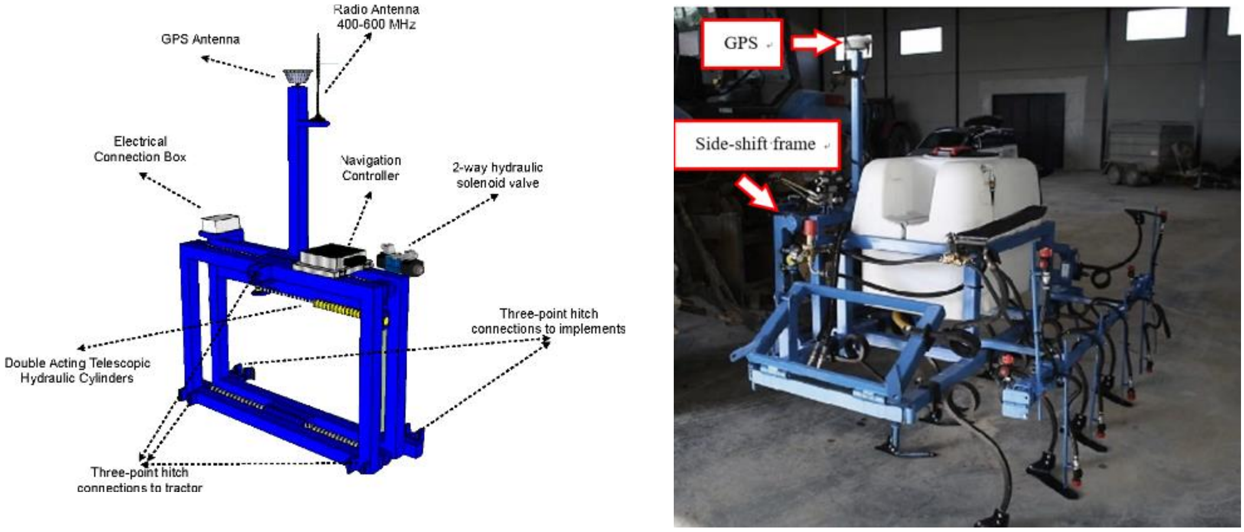

Fig. 7 - Combined cultivator and band sprayer with a Row-Centering RTK-GPS guidance system
(a) Schematic diagram of the side-shift frame system by an RTK-GPS geo-positioning system;
(b) The prototype of six-row mechanical weed control cultivator

Stehle et al. (2015) examines the work economic effects of a Garford camera system steering the hoeing tools attached to a hydraulic side shift frame (Fig. 8.a). The crop plant losses, type and number of weeds, and the standard deviation of the hoe were recorded. Based on the calculated standard deviation of the hoe, the proper settings for the distance between the hoeing tool and the plant row were calculated to minimize crop plant losses.

Contrary to expectations, the speed had no significant effect on the working accuracy of the camera control. Robocrop also has a crop imaging system which achieves excellent row following by viewing multiple crop rows over a large area. A stereo vision camera is mounted on the side shifting frame of Robocrop guided hoes (Fig. 8.b). Utilizing the Robocrop grid matching technique accurate row following is possible even on narrow row cereals and multi-line rows. Images are analyzed at a rate of 30 frames per second, and the direction of the hoe adjusted via a hydraulic side shift with anti-backlash action. The accuracy of the visual navigation system is typically 15 mm, and the machine can travel at speeds of up to 12 km/hr *(Garford Farm Machinery Ltd., 2020)*.

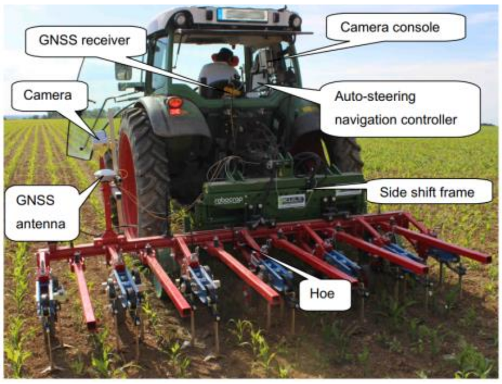

Fig. 8 - Robocrop Side Shift System. (a) GNSS guidance system. (b) Crop imaging system

(3) Portable hitch

Portable hitch attaches (e.g., Sunco Acura Trak) directly to the tractor and control all of the hitches mounted equipment with one portable solution (Fig. 9.a). The Sunco Hitch efficiently steers the implement from a leading position instead of a trailing position. In situations standard feedback options are not possible and implement accuracy is critical (such as strip-till, precision fertilizer placement, or drip tape installation), GPS implement guidance is a great option. The Sunco Implement Guidance Hitch, when used in conjunction with Sunco Stabilizers and John Deere's Active Implement Guidance System or Trimble's TrueTracker Implement Guidance System (Fig. 9.b), can solve many of the issues with current implement guidance products (*Sunco Farm Equipment, 2020*).

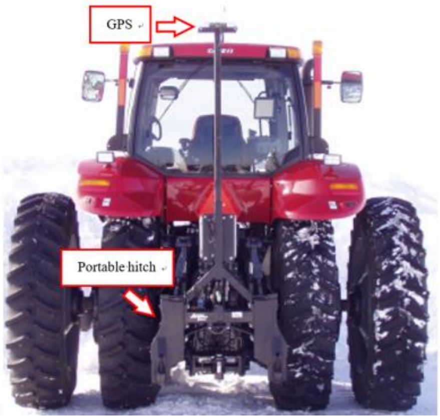

Fig. 9 - Acura Trak (a)Sunco AcuraTrak (b) Sunco AcuraTrak with an active implement guidance system

Using large discs/coulters to steer the implement

Using large discs/coulters to steer the implement develop to provide industry-leading precision guidance for drawn and 3-point mounted row crop units. For example, Orthman's Tracker IV system (Fig. 10) easily mounts onto the implement and is fully compatible with GNSS/Vision guidance systems. Available with ground-engaging steering blades, the system design features a single hydraulic cylinder that pivots all the blades simultaneously for consistent implement-tracking correction. Sub-inch implement guidance allows year-over-year repeatability of fertilizer and seeding operations, eliminates crop damage from implement drift, and reduces input cost by reducing seed and chemical overlap.

Implement guidance was shown to dramatically improve crop yields by precisely placing the seed and fertilizer closer to each other in separate field passes. Yields increased 13% when seed/fertilizer was placed with sub-inch accuracy compared to the crop planted at an 8-inch offset, and 5% higher when compared to the 4-inch offset *(Orthman Manufacturing, Inc. 2020)*.

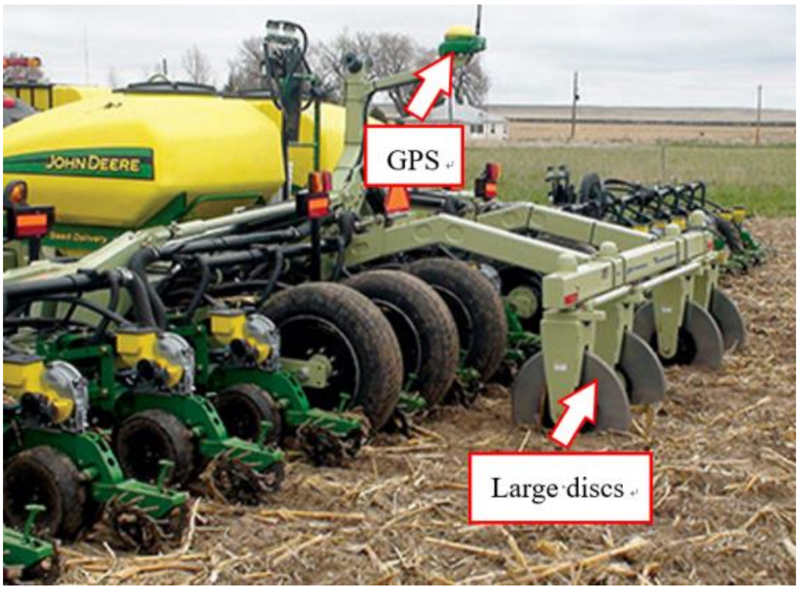

Fig. 10 - Orthman's Tracker IV system

Steerable axles or wheels on the implement

Load bearing wheel actively directs the implement frame over the guidance path using steerable wheels or disc blades to generate a corrective force (Fig. 11). Their action is controlled by GPS position data from both the implement and the tractor. Automatically steer implements with factory steering options for dramatic in-row precision. Active Implement Guidance helps optimize the use of inputs by increasing accuracy at the implement and facilitating seamless, repeatable passes throughout the growing season. Active Implement Guidance can help to reduce input costs in a variety of applications. Potato producers and other specialty crop producers that make frequent passes through the field have seen the value of active Implement Guidance as they precisely plant and care for their crops. Additionally, producers employing strip-till practices are better able to align their seed placement with their fertilizer placement, maximizing the uptake of their valuable nutrients *(John Deere, 2020b).*

Fig. 11 - Load bearing wheel with active implement guidance

Challenges and future perspectives

Agricultural automatic navigation technology has become increasingly mature after years of development. Navigation sensor technology based on vision and GNSS has become the leading technology of automatic navigation system of agricultural vehicles *(Hu et al., 2015; Dong et al., 2017)*.

Automatic navigation sensors of agricultural implements have been widely used in agricultural production practice *(Han et al., 2018)*. However, there are still many challenges in the automatic navigation technology of agricultural implements that need further research.

The sole control of the path of the tractor without controlling the path of the agricultural implements cannot meet the needs of today's precision operations. Passive and active implement guidance systems can deliver additional accuracy and cost-effective guided agricultural machinery practices in challenging conditions. Although implement guidance system has been explored extensively for weed removal, field spraying, and seeding in cultivated soils, no-till seeding in restricted rows has not yet been addressed *(Chen, 2018).* Therefore, the application of implement guidance systems in the mechanization of the agricultural process needs to be further explored.

The steering controller is a compulsory module for implement guidance systems. The steering controller is the actuator that converts a control signal from a feedback controller to an appropriate mechanical adjustment in the steering angle *(Reid et al., 2000)*. Steering controller design needs for agriculture differ from that of on-highway vehicles due to operating conditions of the vehicle in the field. Agricultural equipment often operates on unprepared, changing, and unpredictable terrain, ranging from asphalt to spongy topsoil in the field *(Han et al., 2018).* In the case of automatic or autonomous operation, steering controllers should be able to provide appropriate steering actions in response to the variations in equipment operation states, traveling speed, tire cornering stiffness, ground conditions, and many other parameters influencing steering dynamics *(Zhang et al., 1998).* Therefore, a steering controller suitable for problematic agricultural practices is essential for implement guidance systems.

In addition, the cost of agricultural navigation sensors, as well as the cost and safety of using and maintaining the implement guidance systems *(Mousazadeh et al., 2013)*, still need to be further addressed in future research.

CONCLUSIONS

This review has briefly discussed the current development of automatic navigation system and its application in agricultural implements. Despite many reviews of automatic navigation sensors and their development in an automatic guidance system, no summary of implement guidance systems uses in agricultural applications has been reported.

In this article, we have roughly described that implement guidance systems is an essential technology for autonomous vehicle operations. In addition, applications and new technologies associated with navigation sensors on passive and active implement guidance are analyzed. Finally, challenges and future perspectives of navigation sensor use on agricultural implement are summarized and forecasted.

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