JARQ 59 (1), 9-15 (2025) https://www.jircas.go.jp

REVIEW

Advanced Operation and Social Acceptability of Robotic Agricultural Machinery for Ultra-Labor-Saving Smart Production

Mitsuru HACHIYA*

Division of Intelligent Agricultural Machinery Research, Institute of Agricultural Machinery, National Agriculture and Food Research Organization, Saitama, Japan

Abstract

For tremendous labor saving of land-use type agriculture, development research on remote monitoring-type uncrewed autonomous traveling systems, which enable uncrewed work in multiple fields, including movement between them, was conducted. In this system, position estimation for inter-field movement, detection of obstacles around the vehicle, and detection and recognition technology of operable farm road areas were developed as robotic implementations. An application for condition monitoring and operation of multiple robots was designed through a mobile terminal. In addition, a farm in virtual space was constructed based on a drone's survey data of the robot operation area, and a tool simulating robot movement was developed. This paper outlines the technology constituting the system and the technical problems to be solved, as well as the social issues for a practical operation of the system. In particular, given the characteristics of this system, in which an uncrewed robotic agricultural machinery autonomously travels on a road after finishing work in a field, comprehensive consultation, such as examination of the system design and social acceptability to enable the uncrewed operation, is required based on a system-operation situation under the current legal system.

Discipline: Agricultural Engineering
Additional key words: institutional design, moving between farm fields, smart farming, social implementation, vehicle-based robotic agricultural machinery

Introduction

Smart farming machines, which are currently implemented in various farming fields, can reduce fuel and material input by following the optimum route based on data with high accuracy and applying the optimal amount of material to optimal locations. Smart farming will promote the "The Strategy for Sustainable Food System, MIDORI," a comprehensive initiative developed by the Ministry of Agriculture, Forestry and Fisheries (MAFF) in Japan due to the ripple effect. In addition, it is an effective technology for overcoming a big problem that threatens the survival and sustainability of individual agricultural management and, in turn, Japanese agriculture, due to the decrease in the number of farmers and aging. The following are symbols of smart agricultural technology: robotic tractors, rice transplanters, combine harvesters, agricultural machines with automatic steering functions, yield monitoring combine harvesters, drones, and automatic water management systems.

Figure 1 shows the advancement of travel progress control technology for agricultural machinery, and an outline of the agricultural machinery in each step is presented below. "Step 0" refers to a conventional agricultural machine or an agricultural machine equipped with Global Navigation Satellite System (GNSS) guidance. "Step 1" includes an automatic steering system based on GNSS or agricultural machines such as tractors and rice transplanters equipped with such function. Moreover, an on-board operator is a major premise of this

*Corresponding author: mhachiya@affrc.go.jp
Received 4 December 2023; accepted 19 April 2024.

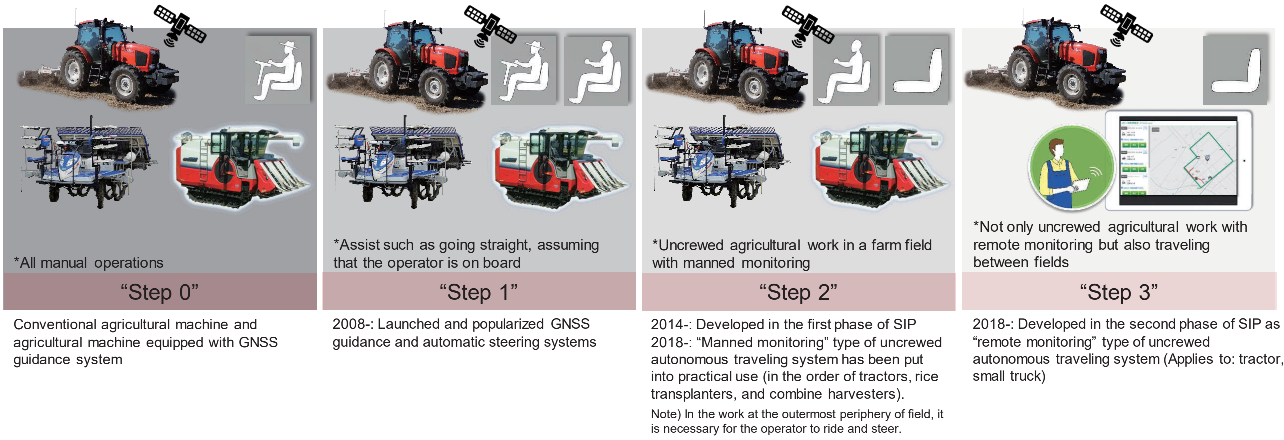


Fig. 1. Advancement of travel control technology for agricultural machinery

step. The introduction of the system in Japan commenced approximately 15 years ago, initially mainly in Hokkaido, but has since expanded to Honshu and nationwide in recent years. As an example of the application of this system, it is particularly effective for operations such as land leveling, fertilization, and pest control, where seeing the tire tracks or visual confirmation during tractor operation is challenging.

"Step 2" involves uncrewed robotic agricultural machines limited to in-field operations, requiring operators to monitor robot operations near fields. However, for work at the outermost periphery of the field, an operator must operate onboard the robot and memorize the position information and shape of the field. Tractors categorized in Step 2 entered the market between 2017 and 2018, followed by rice transplanters and combine harvesters. Compliance with the "Safety Assurance Guidelines for Automatic Operation of Agricultural Machines" stipulated by MAFF is essential for introducing such machinery to the market.

"Step 3" represents the technology concept that further advances Step 2, referred to as a remote monitoring type of uncrewed automatic traveling system. In this system, a robot vehicle automatically travels and moves on a road from a field where the uncrewed work is completed to the subsequent work field. An operator monitors the robot vehicle via a screen on a communication device as required. However, the constraint of constant monitoring is less than that in Step 2. As a result, Step 3 posits the prospect of operating multiple robots.

Development and initiatives for robotic agricultural machinery in SIP

In the first (2014-2018) and second (2018-2022) phases of the Cross-ministerial Strategic Innovation Promotion Program (SIP), i.e., "Technologies for Smart Bio-industry and Agriculture" (funding agency: Bio-oriented Technology Research Advancement Institution), research consortiums such as NARO advanced the development of robotic agricultural machinery and promoted solutions to labor shortages and food insecurity problems in Japan. The SIP is a national project established by the Cabinet Office of the Japanese government, specifically the Council for Science, Technology and Innovation, for realizing science, technology, and innovation through the control tower functions and by management beyond the framework of the Ministry and the old field. In this process, we achieved two governmental objectives: the "commercialization of uncrewed autonomous traveling system in the farm field under manned monitoring by 2018" and the "realization of uncrewed autonomous traveling system by remote monitoring including moving between farm fields by 2020," which were stated in the Japan Revitalization Strategy, 2016 (Fig. 2). The concept of the technology stated in this governmental objective is presented in Figure 2.

In the first phase of SIP, NARO developed a tractor and rice transplanter with the functions of Step 2. Based on the results, a "Step 2" robot tractor was placed on the market by a domestic agricultural machinery manufacturer at the end of 2018, following the governmental objective of the former. The following year, the "Step 2" robot tractor was introduced to production sites in Japan through the Smart Agriculture Demonstration Project of MAFF, which started in 2019, and the demonstration is currently ongoing. In addition, a "Step 2" robotic rice transplanter was placed on the market by an agricultural machine manufacturer in 2022 and is currently under proliferation.

In the second phase of the SIP, the research

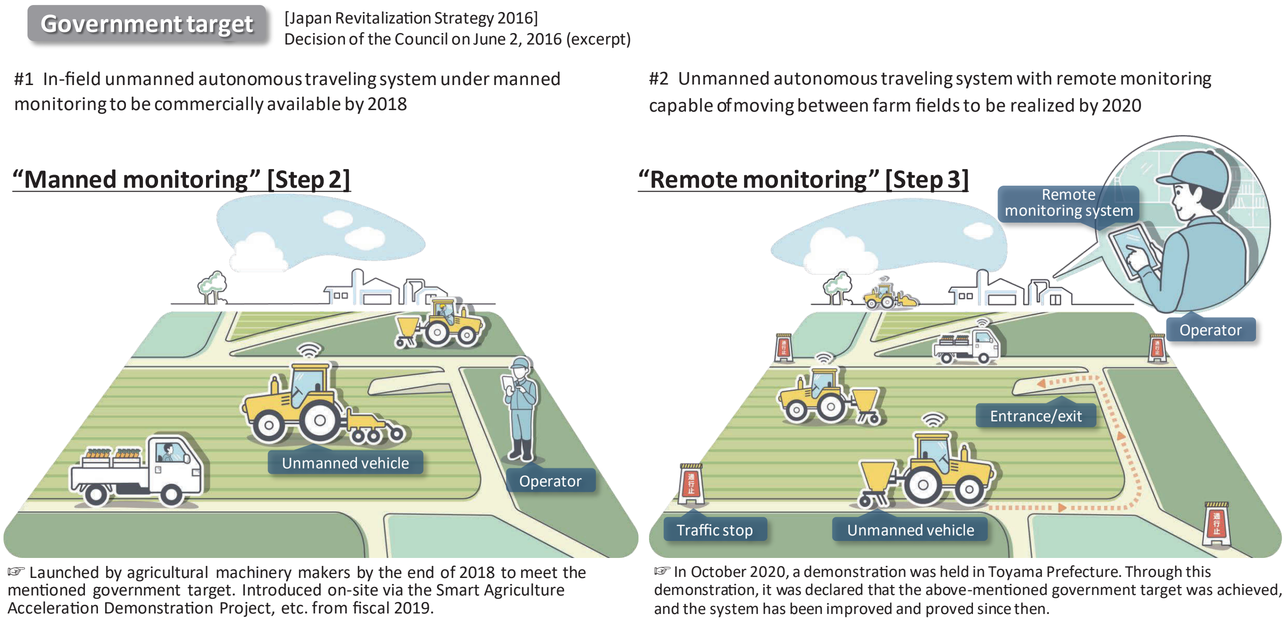


Fig. 2. Concept of uncrewed autonomous traveling system for agricultural use in Japan Revitalization Strategy 2016

consortium focused on developing Step 3. The development results were presented at a demonstration held at the agriculture production corporation site in Toyama Prefecture in October 2020, and the latter government objective was declared to be achieved. After that, the research consortium continued improving robustness and convenience while improving safety and reducing costs through developing, improving, and demonstrating the "Step 3" system described below.

Technical overview of "Step 3" system

The remote monitoring type of autonomous traveling system, referred to as "Step 3" and shown on the right-hand side of Figure 2, is composed of remote monitoring technology, robot technology (Cho et al. 2022, Kurashiki et al. 2022), and robot operation support tools such as traveling simulators and digital maps (Matsushima et al. 2022). An outline of each technology that constitutes the system development thus far is presented below.

1. Remote monitoring technology

A remote monitoring application was constructed to confirm the status and operation of multiple robot vehicles through a mobile terminal. Specifically, real-time notifications of control and request messages with functions such as "start traveling," "pause," "emergency stop," and "download digital map data" were implemented for two types of robot vehicles from a single tablet screen. It was confirmed that information such as vehicle traveling speed and vehicle status can be collected, reported, and displayed from the robot vehicle to the communication device without delay. Based on these results, the following functionalities have been considered for future social implementation of remote monitoring technology.

- Clear delineation of responsibility boundary between the robot vehicle side and remote monitoring technology as a platform.
- Provision of extensibility for practical use by defining optional specifications.
- Capability to handle multi-vendor machines.
- Assurance of functional and practical robustness, making it commercially usable.

2. Robot technology

Methods for self-localization, path planning (for farm roads between fields), obstacle detection around vehicles, and drivable farm road detection areas were developed, enabling uncrewed vehicles to navigate between farm fields. For example, as a safety measure while traversing farm roads, deep-learning-based AI technology detects obstacles in images captured by cameras mounted on robot vehicles, automatically halting the vehicle when obstacles are within a hazardous range. These individual functions were combined to construct an integrated operational control system. This system was implemented on a vehicle equipped with various sensors (GNSS, inertial measurement unit (IMU), infrared (IR) camera, red, green, and blue (RGB) camera, three-dimensional (3D)-LiDAR), and a performance evaluation was carried out in several agricultural fields. Field demonstration tests indicated that the lateral deviation between the actual vehicle path and the target path remained within 5 cm. Moreover, it successfully detected people and obstacles within the hazardous range of its path, initiating an emergency stop at a distance of 4 meters from the vehicle to the detected objects. Additionally, stable autonomous operation, especially in areas where GNSS signals are unreliable due to windbreaks common in hilly terrain, must be ensured. Therefore, besides the self-localization method with the detection of landmarks such as poles installed on the side of agricultural roads and road surfaces, localization methods utilizing GNSS-only, camera-only, LiDAR-only, and camera-LiDAR fusion were also developed. Then, a function for evaluating the reliability of each method and switching between them was introduced and tested, enabling stable autonomous travel on approximately 1.2 km of farm roads, including GNSS-denied areas.

The following challenges are required for the social implementation of the traveling control technology related to the movement between fields in “Step 3”:

- Development of dynamic path generation technology to detour and avoid collisions with obstacles on the travel path.
- A method contributing to robustness improvement and cost reduction of GNSS-independent self-localization technique.
- A traveling control technique in cooperation with traffic infrastructure, such as integrating with traffic signals for traveling on public roads.

3. Robot operation support tool

Autonomous driving requires enhancing in-vehicle sensors and AI while establishing an information infrastructure for accurate localization and predictive driving based on traffic conditions. This is where the three-dimensional high-definition (HD) map plays a pivotal role. The HD map contains lane-specific road information, surrounding structures, signs, and signals with high precision. More accurate localization can be achieved by comparing the vehicle-mounted sensor data to the map data in real-time. Constructing the HD map involves utilizing a Mobile Mapping System (MMS) comprising cameras, laser scanners, and satellite-based positioning devices installed on a vehicle to gather three-dimensional data of road shape, lane information, and surrounding environments such as signs.

Similarly, a comprehensive map of the operational area is essential for efficient vehicle navigation in a wider area of agricultural environments. However, due to unique conditions such as sparse feature points in farm fields and roads, constructing a digital map for agricultural machinery requires a suitable approach balancing cost reduction and safety. A map (FarmMap) was created for an entire farming area by acquiring three-dimensional high-precision point cloud data through photogrammetry using a drone instead of MMS. This FarmMap was then converted into a format usable in a remote monitoring system. Field tests confirmed the usability and coordinate accuracy of path data generated by FarmMap for autonomous travel via remote monitoring. In addition, a simulator was developed utilizing the three-dimensional point cloud data to reconstruct a virtual farm, enabling the driving of robot vehicles in cyberspace. This simulation can identify unsafe travel points, ensuring safe navigation by rectifying detected hazards at the field entrance in physical spaces. In the future, there’s a need to facilitate discussions to establish common specifications for FarmMap, ensuring its usability across various agricultural machinery platforms.

Institutional design and social acceptability for social implementation

When a robot vehicle moves between fields without a human operator, issues with current regulations arise when it passes and crosses a road, governed by road traffic laws. Autonomous traveling without a human operator cannot occur unless general traffic is prohibited and restricted at the location of the passages. However, in the agricultural fields in Asian regions such as Japan, where fields are smaller than those in Europe and America, it is crucial for the robot to be able to move between multiple fields. If robot vehicles do not have a function to move between fields autonomously, the improvement of work efficiency is reduced.

In contrast, concerning autonomous driving of the automobile, in the Public-Private ITS Initiative and Roadmap, 2020, it has been assumed that the commencement of autonomous driving mobile services by remote monitoring will occur approximately in 2022. The revision of the road traffic law, including the Autonomous driving level 4 permission system, was passed in April 2022 and enforced in April 2023. Autonomous driving of the automobile, categorized as “Level 4,” indicates fully automatic operation under specific conditions, such as limiting an area. With the enforcement of the revised Road Traffic Law, it is assumed that autonomous mobile services on public roads will commence gradually. In particular, mobile

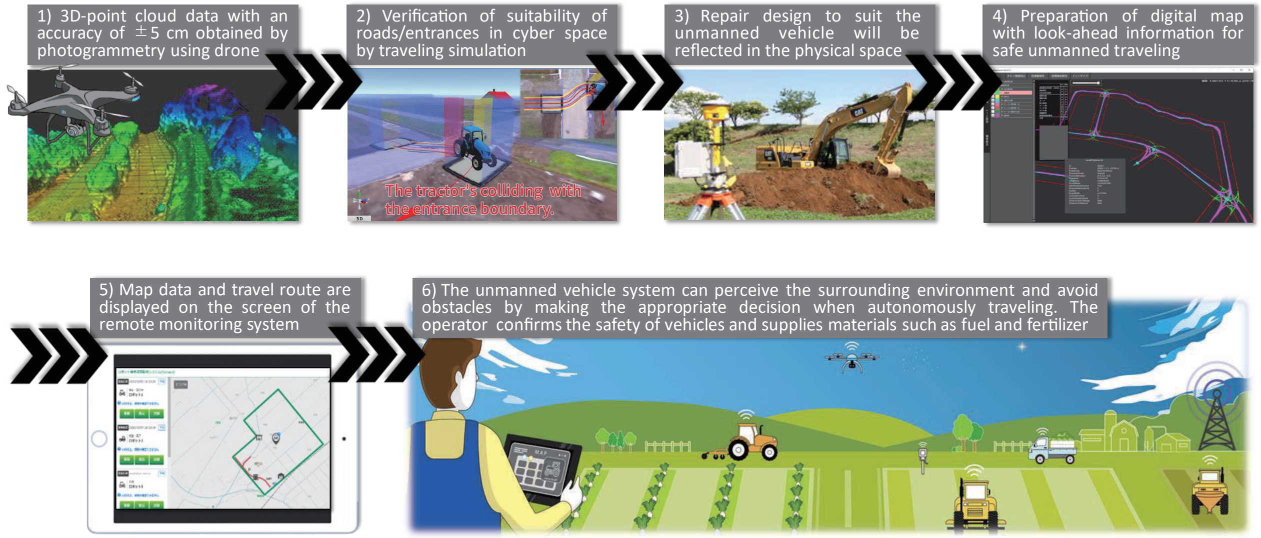


Fig. 3. Overview of "Step 3" (Remote Monitoring Type Uncrewed Autonomous Traveling System for Cyber-Physical Fusion)

services that reduce labor costs can be provided, and autonomous buses will be expected to spread mainly in areas where transportation is inconvenient.

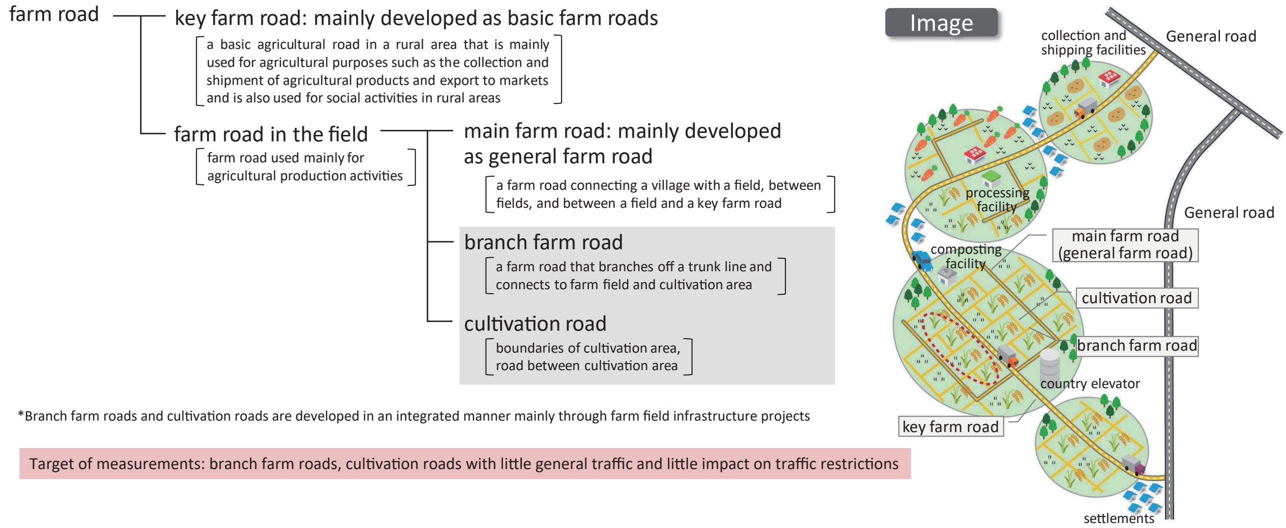
In the case of an uncrewed vehicle, it is similar to the operational concept of the route bus in the abovementioned "Level 4" category, in that it is operated in a defined limited area, i.e., the operational design domain (ODD) mainly on farmland owned by the farmer. Moreover, it is common with respect to the operation of robot farm machines, in that remote monitoring technology is critical and indispensable for emergency responses and efficient operation. In addition, there are geographical conditions in the ODD, and factors such as road type and traveling speed are included. The traveling route around farmland can be specified almost uniquely, even when passing and crossing the road; the abovementioned challenge, which is equivalent to the deregulation of mobile services, can serve as a reference in the discussion of the system design.

When it is determined that a robot vehicle cannot continue autonomous operation in the ODD, the machine system must guide itself to minimal risk conditions, e.g., to stop the vehicle safely. At the same time, if a robotic system, i.e., an edge-side decision, cannot operate autonomously, the system must alert a remote person (operator or assistant) of the event. Thereby, an operator or assistant with remote monitoring and operation authority will quickly assist the system, and if necessary, a human will ride and maneuver the robotic vehicle instead of the system controlling the vehicle.

The remote operator does not need to constantly monitor the vehicle on the tablet screen during the robot vehicle's operation. In the effective operation of "Step 3," it is believed that constant monitoring is not reasonable. In other words, if constant monitoring becomes a rule, it will not be possible to operate multiple robots and will not lead to drastic efficiency improvement in agricultural work. However, when the robot exits the field to the road or enters the field from the road, it stops once, and the operator must check the vehicle's surroundings through the tablet screen when the robot generates an alert to the remote monitoring system. In our development group, it is a rule that an operator always monitors through a tablet screen while a robot travels on the road. In the future, ensuring the safety of "Step 3" will be the main point of discussion in defining operation rules.

In 2019, the administrative communication "Measures on traffic of vehicles on farm roads" was issued by the National Police Agency and MAFF. Moreover, the procedural theory related to the road closure of farm roads, assuming the traveling of robot vehicles, is shown in Figure 4 (MAFF 2019). Based on this notification, when traffic control is carried out for the operation of robot vehicles on farm roads subject to the Road Traffic Law based on the decision of the farm road manager as to whether or not the robot vehicles are to be used in general traffic, it may be carried out after consultation and coordination in advance with relevant organizations such as prefectural public safety committees and after implementing appropriate measures such as the prohibition and restriction of traffic.

In the field demonstration of the SIP, per the measures implemented, appropriate procedures have been conducted concerning municipalities, land improvement districts, and police stations, which are



Source: Adapted from "Measures for the passage of vehicles on farm roads-image of the scope" (MAFF 2019)

Fig. 4. Measures for the passage of vehicles on farm roads – image of the scope

farm road managers. Moreover, prior notifications and traffic restrictions were implemented concerning local residents, and tests were conducted. However, it is unclear to what extent the current measures can be implemented for actual operations at the production site, given that the demonstration test exhibits a closed period due to traffic restrictions and farmland in the closed area is significantly limited. In the case of actual operation, the lender of the farmland may refuse to use the farmland in the closed area, as it is more difficult for non-bearers to use the farmland, and an agreement may not be reached. In such a case, it is necessary to undergo a complex process such as (1) consolidating the land of the farmland owner (lender) who demonstrates the plan of the "closed period" and accepts, and (2) ensuring merit for the farmland owner who accepts the "closed period."

In the actual operation of this system, a wide area can be assumed to increase the operation rate of the machine, considering the characteristics of the vehicle and the management scale of the introducing entity. It is necessary to carry out field demonstrations with a sense of scale that can be used for actual operation by utilizing the current measures. Moreover, it is necessary to discuss the problems related to the current system through the cooperation of related organizations based on the social acceptability of uncrewed vehicles in the area and to share it with the related ministries and agencies, to ensure a more drastic system design.

Conclusion and scope of future research

In the second phase of the SIP, developing and demonstrating "Step 3" systems, a core technology of super labor-saving land use type agriculture, has undergone advancements. In summary, this study describes the outline and technical problems of environmental recognition and traveling control technology capable of uncrewed movement between multiple farm fields for tractors and small trucks; vehicle operation support technology such as simulation and digital maps based on farmland base information; and remote monitoring platforms enabling monitoring and traveling operations by remote connection with robot vehicles. Beyond addressing technical challenges, the practical deployment of "Step 3" robot vehicles over wider areas requires the establishment of deregulation measures for travel on both farm roads and public roads. Collaboration with regional authorities, local governments, and administrative bodies is crucial for this endeavor.

In particular, concerning robot operations wherein the agricultural road traffic closing measure under the current law is required, the object is limited to farm roads, and the procedural theory and period of the measure are considered less appropriate in practical operations. It is necessary to promote a discussion focusing on more concrete system design while expanding the scope of ODD with the evolution of technology and accumulating the operational performance of the system, in addition to considering its social acceptability.

Acknowledgements

This work was supported by the Cross-ministerial Strategic Innovation Promotion Program (SIP), "Technologies for Smart Bio-industry and Agriculture" (funding agency: Bio-oriented Technology Research Advancement Institution).

References

Cho, W. et al. (2022) Autonomous tractor navigation system for agricultural work in plural paddy fields. *The XX CIGR World Congress 2022*, OS-20-01.

Kurashiki, K. et al. (2022) Autonomous driving of a small truck on agricultural roads including GNSS denied area. *The XX CIGR World Congress 2022*, OS-20-02.

Matsushima, K. et al. (2022) Designing of the farm roads/entrances to suit for a vehicle-based robotic agricultural machinery capable unmanned moving between farm fields by traveling simulation technology. *The XX CIGR World Congress 2022*, OS-20-03.

The Ministry of Agriculture, Forestry and Fisheries (2019) Measures for the passage of vehicles on farm roads. https://www.maff.go.jp/j/nousin/seibi/sogo/s_seibi/attach/pdf/noudou2-1.pdf. Accessed on 30 October 2023.