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REVIEW

Risk Analysis, Safety Assurance Requirements, and Safety Evaluation Test for Robotic Agricultural Machinery

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Abstract

The advancement of robotic technology in the agricultural industry is continually progressing with research, development, and practical applications in agricultural machinery. However, a crucial factor for the widespread acceptance of these machines is ensuring their safety. To date, risk analysis has been conducted on the basis of unmanned work in the agricultural field and troublesome cases using vehicle-style robotic agricultural machinery. Moreover, necessary safety requirements have been identified for both hardware (Machine) and software (Operation & management) components. Furthermore, safety standards, guidelines, and evaluation methods have been established to guarantee the safety of robotic agricultural machinery.

Discipline: Agricultural Engineering
Additional key words: agricultural vehicle, inspection, robot, safety standard, tractor

Introduction

Technological advancements in the automotive industry have led to increased research and development in the robotics field for agricultural machinery. The full-scale commercial use of manned–supervised robot tractors began in 2018. Ensuring the safety of these machines is essential for their acceptance in the agricultural industry and society. This report highlights research that determined safety requirements for hardware (Machine) and software (Operation & management) components and the risk analysis based on unmanned work in the agricultural field and troublesome cases using vehicle-style robotic agricultural machinery. Moreover, this report summarizes safety standards and guidelines for robots in agriculture and other fields and the safety evaluation test for robotic agricultural machinery performed by the National Agriculture and Food Research Organization (NARO).

Development of risk analysis and safety requirements for robotic agricultural machinery

1. Level of automation of agricultural machinery

The Ministry of Agriculture, Forestry and Fisheries (MAFF) classifies the level of automation for agricultural machinery (Fig. 1). Level 0 involves manual operation of all tasks such as driving, work, and emergency procedures. Level 1 is partially automated with technology such as a global navigation satellite system (GNSS), allowing for straight-line driving with an onboard user. Level 2 is unmanned but supervised, with the user monitoring the machinery's progress from the field or a nearby location and taking control in emergencies. Level 3 is unmanned and remotely supervised, with the machinery self-assessing risks and stopping autonomously (Kikuchi 2020). Currently, level 2 machinery, such as tractors and rice transplanters, is commercially available, whereas level 3 machinery is still in the research and development phase. This report focuses on level 2 robotic agricultural machinery.

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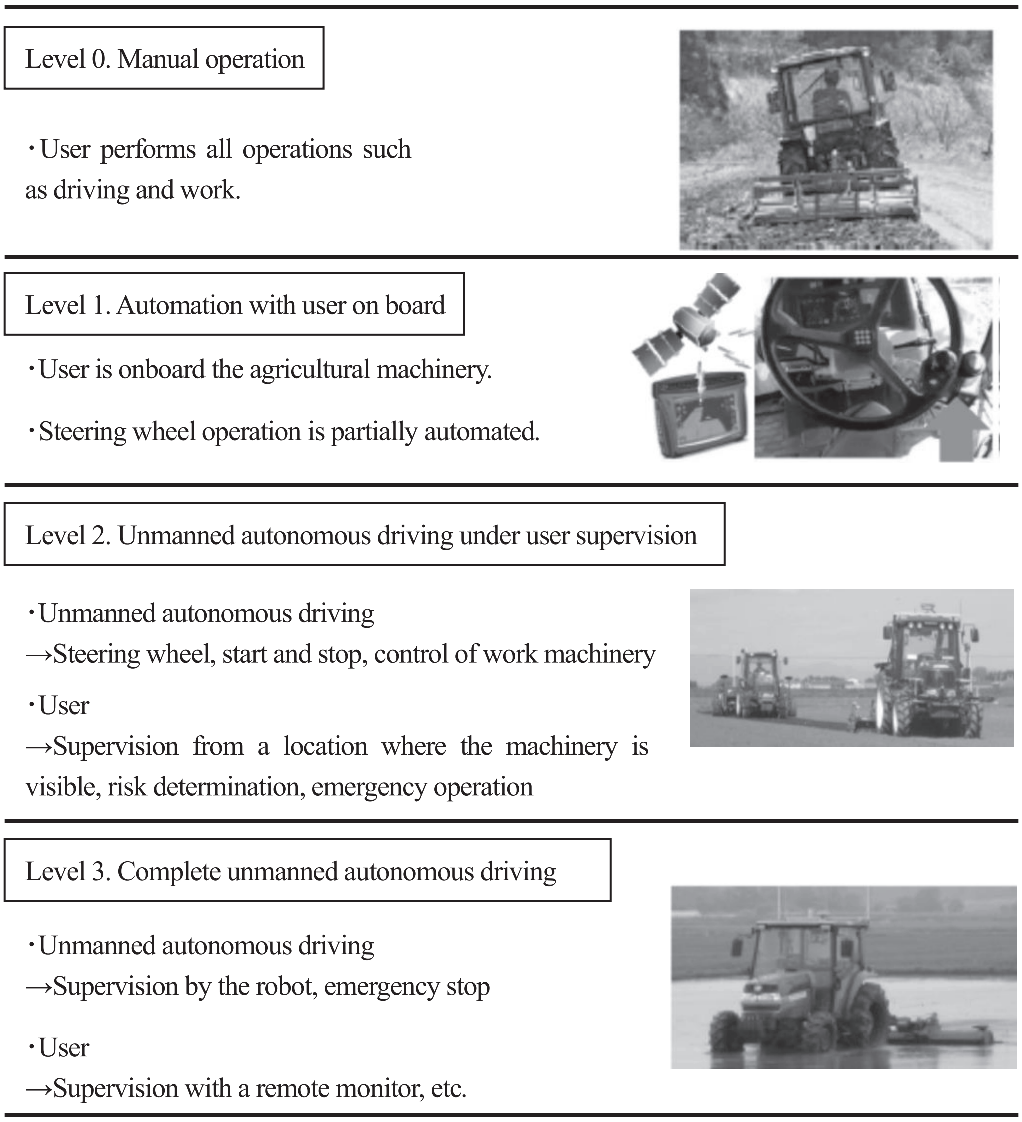

Fig. 1. The levels of automation for agricultural machinery

2. Summary of the robotic agricultural machinery

Risk analysis of robotic agricultural machinery typically focuses on vehicle-based machines, such as riding tractors (58.8 kW (80 PS) class), rice transplanters (eight-row planting), and head-feeding combine harvesters (four-row harvesting). These machines are equipped with components such as GNSS antennas, inertial measurement units, controllers, and actuators, and they perform agricultural tasks through autonomous driving while receiving positional information from artificial satellites. The basic operation involves setting the work area, speed, and width using a controller or inputting preset data. Then, the operator switches the machine to the automatic drive mode and starts the task by pressing the start button. The machine performs the prescribed work without human intervention, with the operator either on board or supervising nearby (Kikuchi et al. 2015).

3. Risk analysis based on the specifications of the robotic agricultural machinery

Hazardous scenarios in robotic agricultural machinery were identified on the basis of models, sizes, and operating methods (Fig. 2): (1) if there are persons around the machinery, poor checking of surroundings and signing at the start of unmanned driving can result in collisions with persons; (2) a user who gets on the machinery for initial setting tries to get off autonomously during the drive and falls from it; (3) because of input errors and failures, the machinery deviates from the planned route and collides with surrounding persons, it leaves the work area and collides with third parties, and

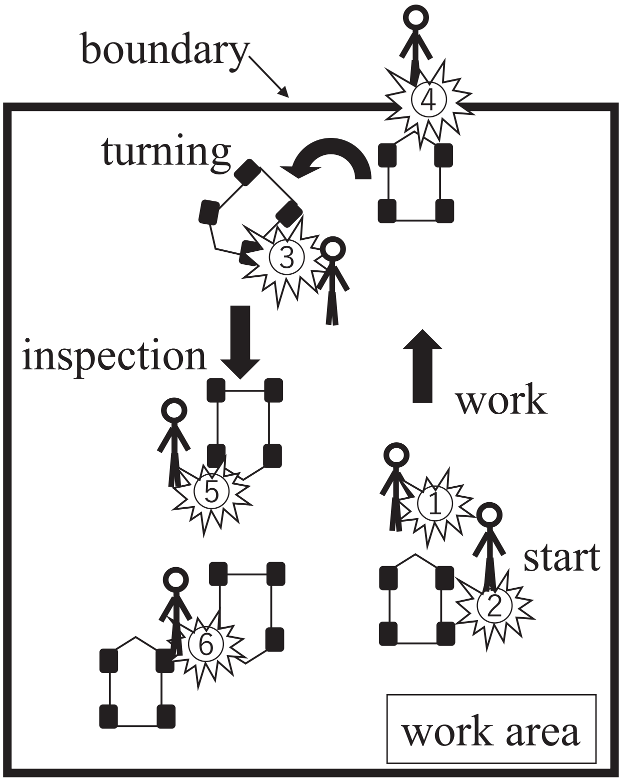

Fig. 2. Possible hazardous events on robotic agricultural machinery

Fig. 3. A robot tractor doing farm work

Fig. 4. A robot rice transplanter doing farm work

machines collide with each other or entrap persons if present; and (4) collisions or entrapment can occur from inspecting without confirming the machinery has stopped or third parties carelessly entering the work area (Kikuchi et al. 2015, 2016).

4. Risk analysis in field verification tests

In the developmental stage of robotic agricultural machinery, field verification tests were conducted to observe tasks performed by the robot tractor, robot rice transplanter, and robot combine harvester (head-feeding). These tests identified any hazardous events that could pose a risk. In testing the robot tractors during tillage, two machines were used to work on different agricultural fields (six adjacent fields, ranging 3,000 m^2-11,600 m^2), while a user supervised the machines from the edge of the agricultural fields (Fig. 3). Testing the robot rice transplanters involved using one machine to plant rice in one agricultural field (7,000 m^2), with the user supervising the task from the edge of the field, including the preparation and supply of seedlings (Fig. 4). Meanwhile, the robot combine harvesters were tested by having two machines run parallel, approximately 10 m apart, in a single agricultural field (5,000 m^2), harvesting the crops counterclockwise, while the user supervised the task from the edge of the field (Fig. 5).

We identified the following risks in testing robot tractors: (1) a steering malfunction resulting in the tractor moving to the next step with the rotary tiller; (2) difficulty in deciphering the driving state of the robot tractor due to the limited indication of unmanned driving, represented only by blue light; and (3) persons walking on farm roads near the agricultural field, presenting a third-party risk.

In testing robot rice transplanters, we determined the following risks: (1) risks associated with sudden thunderstorms and lightning strikes; (2) risks of physical contact or falls while supplying the seedlings or adjusting the machine, although the risk of contact with third parties in paddy fields was low; (3) difficulty in understanding the state of the robot rice transplanter from the edge of the agricultural field due to a lack of indicators; and (4) persons walking on farm roads near the agricultural field, presenting a third-party risk.

We observed the following risks in testing robot

Fig. 5. A robot combine harvester doing farm work

combine harvesters: (1) the following vehicle, which should wait until the preceding vehicle stabilizes, started autonomous driving too quickly; (2) the battery voltage of the GNSS base station dropped, and the vehicle stopped automatically; (3) changes in task speed caused vehicles to approach each other; (4) occasional removal was necessary to prevent clogging from wet or lodged rice, and weeds had to be separated from the rice before task completion; (5) the indicator was not visible from the left side because it was at the center of the right side; and (6) persons walking on farm roads near the agricultural field presented a third-party risk (Kikuchi et al. 2015, 2016, 2017).

5. Examination of the safety assurance requirements

For the analyzed hazardous incidents, protective measures, such as "inherently safe design measures," "machine-side safeguarding," "additional machine-side complementary protective measures," "machine-side usage information," and "user measures," were investigated on the basis of the International Organization for Standardization (ISO) ISO12100:2010 (2010) risk-reduction process. Table 1 shows a sample review sheet for protective measures. Table 2 and Figure 6 illustrate comprehensive safety measures, including "machinery," "environment," "human," and "methods" (Kikuchi et al. 2015, 2016, 2017; Kikuchi 2019, 2020).

Safety measures for robotic agricultural machinery

1. Differences from robot safety measures in conventional agricultural fields

Conventional agricultural fields have implemented various types of robots and unmanned machines, such as unmanned monorails, robot sprayers, milking robots, unmanned speed sprayers, and radio-controlled helicopters, which are already in practical use (Okazaki et al. 1996, Hachiya et al. 2001, Tozaki et al. 1996). These

Table 1. A review sheet for protective measures against hazardous events (excerpt)

Hazardous events	Potential accidents	Protective measures	Details
The front wheel steering was inadequate due to a program error, etc., and it almost deviated from the field when turning the headland.	While turning at the headland, the machinery deviates outside of the field and collides with a third party.	[Inherently safe design] ・none	
		[Safeguarding on the machinery side] ・Function to stop deviation from the route	・Robot automatically stops if the predetermined deviation is exceeded.
		・Function to stop deviation from the work area	・Robot automatically stops if the robot deviates out of the predetermined work area.
		・Function to stop the machinery when there is an abnormality	・Each part is sequentially monitored, and if any abnormalities are detected, the robot automatically stops.
		[Complementary protective measures on the machinery side] ・Emergency stop device	・User continuously supervises and stops the robot immediately if a risk is detected.
		[Usage information on the machinery side] ・Indicator for operating status	・Operating status is indicated with visual and auditory means so that users and so on can detect risky situations with ease.
		[User measures] ・User training	・Training on dangerous events, supervision criteria, and stopping of operation
		・Warning signs	・Risks and warnings are displayed around agricultural fields to alert third parties.

Table 2. An example of safety measures for hazardous events and work elements for robotic agricultural machinery

Hazardous events	Machinery	Environment	Human	Methods
All	improved reliability, positional information confirmation function, automatic-manual switch, indicator, alarm, human error countermeasures, emergency stop, remote operation device, emergency notifications, supervision support device stopping due to deviation from the route	warning signs, protective fences, passage maintenance, obstacle removal	user training, limited users, manuals	risk assessment, manuals, risk avoidance routes, supervision, reduced supervision load, maintenance and inspection, insurance
Contact with person and obstacles	obstacle detection device, proximity stop function	protective fences, obstacle removal	↑	supervision, risk avoidance routes
Driving outside of the area	work area setting function, stopping due to deviation from the route, speed restraint function	warning signs, protective fences	↑	supervision, perimeter manual operation
Runaway due to erroneous operation	safety confirmation circuits, measures against dirty sensors, waterproofing, dust-proofing, electromagnetic wave countermeasures, abnormality diagnostic function stopping due to deviation from the route, stopping due to excess speed, easy-to-understand interface	↑	↑	proper battery management, supervision
Machine rolling	tilt alarm, speed restraint function	gentler slope, step elimination	↑	risk avoidance routes, supervision

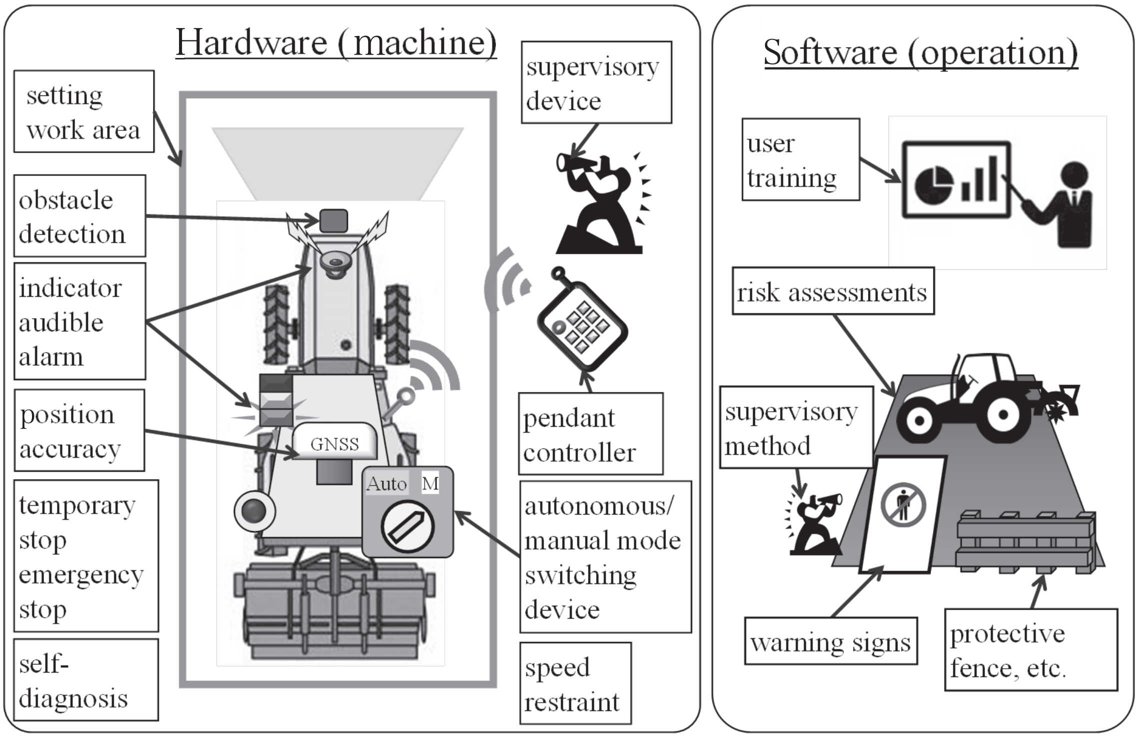

Fig. 6. Examples of measures to ensure the safety of robotic agricultural machinery

machines (1) are operated only along designated routes, such as rails or induction wires; (2) are used in enclosed spaces, such as greenhouses or barns; (3) have small size; and (4) have a qualification system for their usage. Various safety measures have been implemented to ensure the safety of these machines, including securing routes, automatic stoppage when deviating from these routes, automatic runaway brakes, protective fences, and automatic stoppage during radio wave outages.

Moreover, this study highlights the following differences: (1) unlike traditional machinery with predetermined routes, these machines drive autonomously using satellite positional information and route data; (2) these machines are used in open outdoor fields; (3) their weight exceeds 1,000 kg and the engine output surpasses 10 kW, which is unique and unseen previously; (4) no established qualification system for usage exists; and (5) lack of familiarity with such machinery makes it challenging to predict potential dangers, making advanced safety measures crucial (Kikuchi 2019).

2. Trends in safety standards and guidelines in agriculture and other fields

The overall machinery safety standards of ISO, International Electrotechnical Commission (IEC), and Japanese Industrial Standards (JIS) have a three-layer system consisting of "basic," "group," and "product" safety standards. Machinery without "product safety standards" is required to reference similar machinery or higher-level "basic" or "group" safety standards (ISO/IEC Guide 51:2014 (2014)). In Japan, the Industrial Safety and Health Act and related regulations by the Ministry of Health, Labour and Welfare (MHLW) were set traditionally for each type of machinery, but these regulations are gradually being revised to incorporate ISO standards.

In Japan, the safety standards for agricultural machinery include JIS B 9220:1993 (1993) (Agricultural Machinery – General Requirement for Safety) and the safety evaluation test conducted by the Institute of Agricultural Machinery (IAM) of NARO, which evaluates the safety of agricultural machinery. The safety evaluation test is based on ISO and European and American safety standards, etc., which are necessary to ensure the safety of agricultural machinery.

The international standards for robotic agricultural machinery include ISO 18497:2018 (2018) and ISO 10975:2023 (2023).

In Japan, the Ministry of Economy, Trade and Industry (2007) established the "Safety Assurance Guidelines for Next-generation Robots" for robotic agricultural machinery, including care, communication, and agricultural support robots. The guidelines promote the implementation of safety measures and risk assessments by manufacturers and managers. In 2017, the MAFF introduced the "Safety Assurance Guidelines for Autonomous Driving of Agricultural Machinery," emphasizing the importance of risk assessment and the roles of manufacturers, sellers, and users. In response, the Japan Agricultural Machinery Manufacturers Association (2018) developed various guidelines, including "Guidelines for Visual and Auditory Devices for Robotic Agricultural Machinery;" "Instructor Training and User Training Guidelines for Safety Assurance of Robotic Agricultural Machinery;" "Specific Items of the Training Curriculum for Robotic Agricultural Machinery Using GNSS;" "Guidelines for Recording and Managing User Training for Robotic Agricultural Machinery;" and "Guidelines for the Creation and Installation of Warning Signs, etc., for the Safety Characteristics of Robotic Agricultural Machinery" (Fig. 7).

The MHLW (2007) established "The Guidelines for Comprehensive Safety Standards of Machinery" to ensure safe machinery usage. The guidelines are based on ISO 12100:2010 (2010), a basic concept of machine safety, and emphasize the importance of minimizing risks through risk assessments and protective measures by manufacturers and users (Fig. 8). Moreover, the MAFF (2018) has published "The Guidelines for Agricultural Work Safety," which outline considerations for farmers when using unmanned machinery.

3. Outline of the safety evaluation test for robotic agricultural machinery

In 2018, the IAM of NARO began inspecting robotic agricultural machinery to promote and advance its practical usage (Konya 2019a, 2019b). As of 2022, the target models for the evaluation test were riding-type agricultural tractors and rice transplanters, which can be operated without a driver while the user oversees the machinery from within or near agricultural fields.

The implementation methods and criteria of the safety evaluation test for robotic agricultural machinery were established by examining the minimum requirements that these machines must meet following current technical standards. The standards are primarily based on two guidelines:

- The "Safety Assurance Guidelines for Autonomous Driving of Agricultural Machinery," which outline the responsibilities of manufacturers and users to ensure the safety of robotic agricultural machinery (MAFF 2023), which was established first in 2017 and with several revisions.
- ISO 18497:2018, "Agricultural Machinery and Tractors – Safety of Highly Automated Agricultural Machinery – Principles for Design."

The test items and objectives for robotic agricultural machinery are outlined as follows, with the specific criteria for each item shown in Table 3.

(1) Structural inspection verifies the presence of essential equipment for autonomous operation, including an autonomous or manual mode switching device, an indicator displaying the operating status, systems

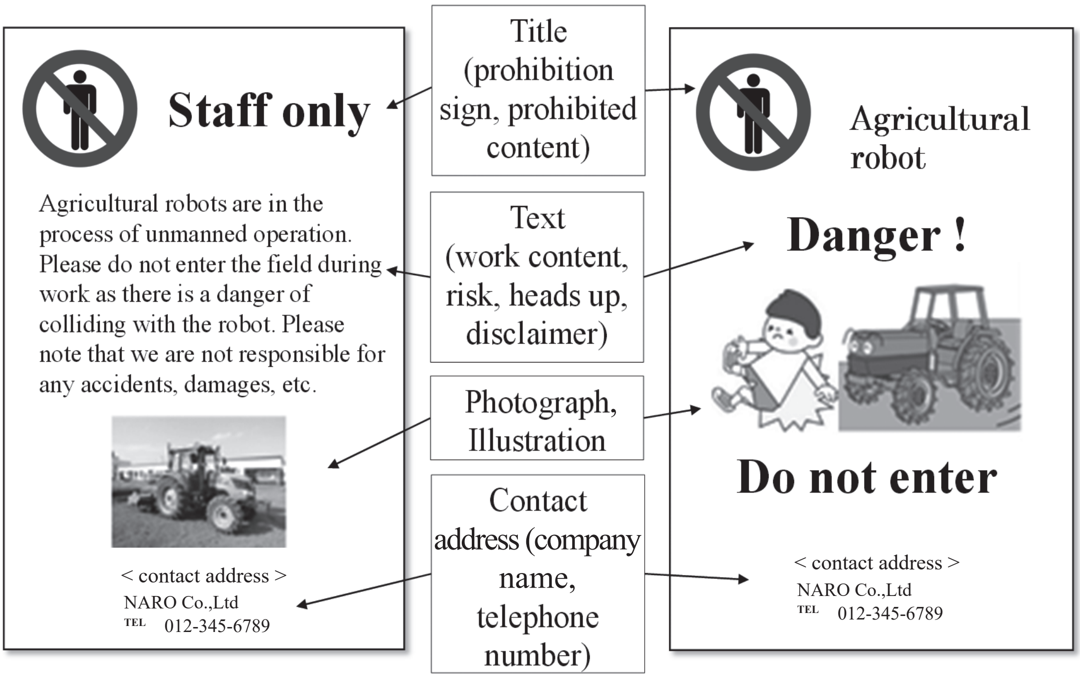

Fig. 7. An example of a warning sign

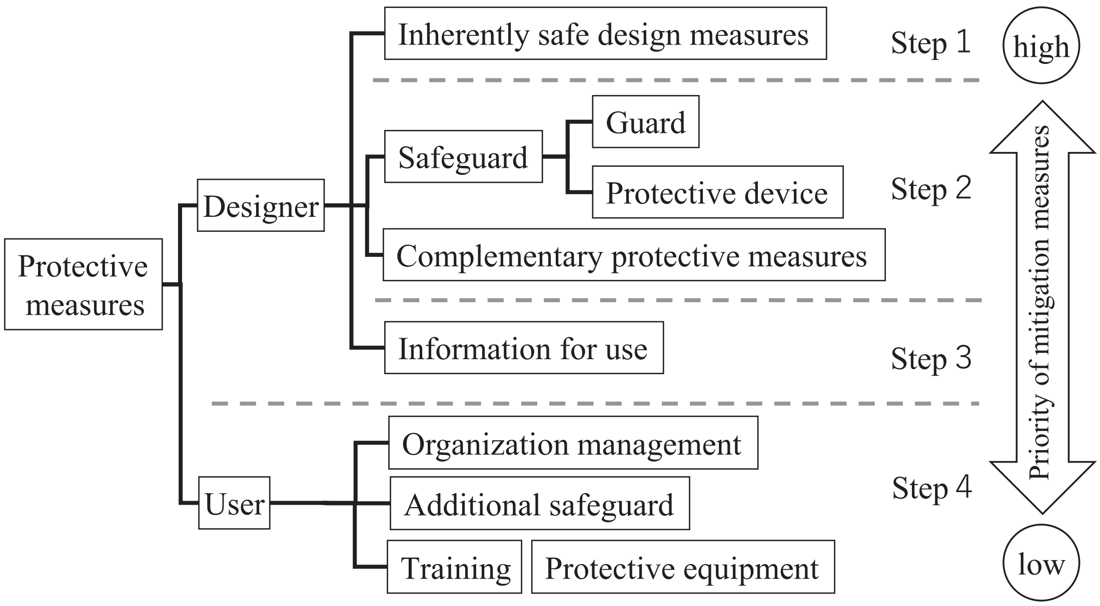

Fig. 8. Steps of protective measures

required for autonomous operation, a function to prevent deviation from the work zone, and other necessary equipment.

(2) The manual mode function test confirms the ability to disable the autonomous operation of a tractor.

(3) The operation status indication function test validates that the operating status can be checked using an indicator.

(4) The person and obstacle detection function test reinforces the contactless detection function for persons and obstacles approaching the tractor during operation, which triggers an alarm and automatically stops the tractor if detected. This test is required for tractors and optional for rice transplanters (Fig. 9).

Table 3. Criteria of the safety evaluation test for robotic agricultural machinery (excerpt for tractors)

Test items	Criteria
(1) Structural inspection	Equipment necessary for the autonomous operation is installed, and the equipment that requires operator's inputs for operation is positioned so that it can be safely and easily handled by the operator in the normal working position. In addition, the functions and operation methods of the equipment are clearly indicated. Furthermore, the tractor shall have a function to prevent from going outside the work zone during the autonomous operation.
(2) Manual mode function test	The autonomous operation cannot be started in the manual mode.
(3) Operation status indication function test	The state of the tractor is indicated properly, and the operator can easily recognize the state of the tractor.
(4) Person/obstacle detection function test	A warning signal is issued in the warning zone. The tractor and its implement do not contact with a test obstacle. Also, the tractor and its implement stop in the hazard zone.
(6) Other necessary safety function test	The pendant control device has a function to prevent erroneous handling. The tractor and its implement stop when the operator, using the pendant control device, instructs the machine to stop. The tractor stops autonomously when a malfunction happens such as communication interruption between the tractor and the pendant control device. There are no defects in the functions required for safety. In addition, at starting, the autonomous operation cannot be started when there is a failure in the system required for autonomous operation.
(7) Operability test	The tractor and its implement shall not deviate from the work zone established. In addition, there shall be no significant defects in operability and safety.
(8) Person/obstacle detection function test (on starting)	The tractor and its implement stop when a test obstacle exists in the hazard zone.

(5) The prevention of running out the paddy field function test affirms the function that prevents deviation of rice transplanters from the cropland. This test only applies to rice transplanters (Fig. 10).
(6) Other necessary safety function tests demonstrate the safety functions in case of malfunctions in the remote control device and communications.
(7) The operability test guarantees the capability for appropriate autonomous driving without deviation from the designated work area.
(8) The person and obstacle detection function test (on starting) verifies that when a tractor is set to an autonomous mode, persons and obstacles are detected, and the tractor is stopped. This test is optional only for tractors.

Future trends in robotic agricultural machinery

Despite using the latest robotics technology, current robotic agricultural machinery has limitations and is restricted to specific conditions. Accidents resulting from falls or rolls with high rates of fatalities are not being effectively managed. There are distinct risks associated with this machinery, and many challenges remain. To address these concerns, the MAFF initiated the "Smart Agriculture Verification Project" in 2019, aiming to introduce innovative and technologically advanced agriculture practices such as robots, Artificial Intelligence (AI), and Internet of Things (IoT) to society by developing a robust system from production to shipment and conducting thorough verification studies. Through these efforts, they identify the optimal technology system that prioritizes safety and supports data-driven decision-making to determine and resolve issues promptly.

Significant advancements in the development and distribution of various types of robotic agricultural machinery are expected in the future, including level 2 vehicle-type machinery supervised on-site, remotely supervised level 3 vehicle-type machinery, tomato harvesting robots, small vehicle-type robots such as lawn mowers, flying robots such as drones, wearable robots such as power assist suits, and stationary robots such as milking robots. For remotely supervised level 3 vehicle-type machinery, it is crucial that it can independently assess work accuracy, detect failures and risks, replenish materials automatically, and navigate autonomously on farm roads while prioritizing safety. While technological advancements and shared regulations for vehicles and roads are ongoing, high technology and economic hurdles remain to be overcome, as farm roads and agricultural fields lack the infrastructure of public roads. Research, development, and verification of infrastructures, as well as the establishment of laws, standards, guidelines, and test methods related to safety, are underway to support the development of robotic agricultural machinery.

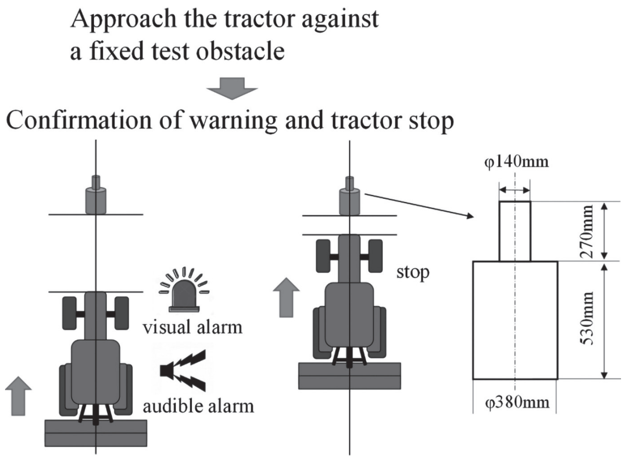

Fig. 9. The person and obstacle detection function test and test obstacle

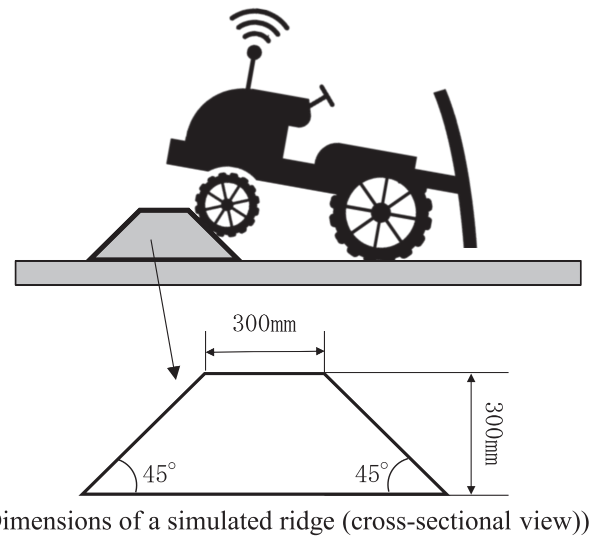

Fig. 10. A function check of deviation prevention from the cropland

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