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RESEARCH ARTICLE

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Spiral model development of retrofitted robot for tele-operation of conventional hydraulic excavator

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Abstract

This paper describes the effect of applying spiral model to the development process of robot system for a new entrant company. The robot system was developed to remotely control a conventional hydraulic excavator in order to improve the safety of operators in disaster emergency restoration. The issues of development are the definition of requirements and integration for a practical system in a real environment by a new entrant company. The constraints to the new entry of smaller companies are the following three points. (1) Lack of industry knowledge and data to define requirements (2) Lack of on-site environment and machinery for investigation and testing (3) Lack of experience in robot development To solve the problems under these constraints, the spiral model divides the development based on the prototype into 4-steps, and repeats this series of processes. This method was applied to clarify the necessary functions and performance of the robot step by step, and to construct a system with robustness in a real environment. As a result, this robot system has been successfully utilized in emergency disaster recovery tasks due to landslides, and removing debris in the Fukushima Daiichi Nuclear Power Plant, reducing the mental and physical burden on the operators.

Keywords Spiral type development, Tele-operated robot, Pneumatic rubber artificial muscles, Construction machinery

Introduction

In recent years, the frequency of natural disasters such as earthquakes, typhoons, and volcanic eruptions has increased in Japan, and emergency recovery system has become more important [1]. At the site of a disaster, it is necessary to ensure the safety of workers from secondary disasters such as landslides, while requiring faster restoration work. The technologies for tele-operation of construction machinery, which began to be developed due to the volcanic disasters of Fugendake of Mount Unzen in the 1990s, have been used in disaster response systems [2, 3, 5].

There are three methods of modifying construction machinery to remote control. The first method is a hydraulic control method in which the hydraulic system of the construction machinery is bypassed to additional hydraulic valves [4]. The second method is an electronic control method with CAN communication for electronically controlled construction machinery [5]. The third method is the retrofit method with a robot driving the control lever mechanically. Hydraulic and electronic control systems to directly modify construction machinery have advantages in responsiveness and reliability. On the other hand, these specialized machines have not been widely used because of the prior modifications. Therefore, it is necessary to transport them to the disaster site in an emergency by large

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trailer. Furthermore, it is difficult to use these methods because the information for modifying construction machinery is not disclosed by the construction machinery manufacturer. However, the retrofit method can be applied to conventional machines because the retrofitted robot mechanically drives the control lever.

The preceding machines based on the retrofit method are Robo Q developed by both the Kyushu Technical Office of the Ministry of Land, Infrastructure, Transport and Tourism and Fujita Corporation in 1998 [6], and the robot developed by Kawashima et al [7]. The issue is the mountability of the robot. It was necessary to mount a large generator and electric compressor on the roof of the construction machine and to remove the driver's seat to retrofit the robot. Therefore, Kowatech, to which the author belongs, began the development of a retrofit robot for hydraulic excavators in 2013. The retrofitted robot was commercialized as "Active Robo SAM" in 2015 after repeated system improvements through field demonstration tests. The robot features a compact and energy-saving system with pneumatic rubber artificial muscles and can be easily mounted on construction machinery of various models and manufacturers. SAM has successfully reduced the mental and physical burden on operators for the work of construction machinery in inaccessible areas. For example, it performed emergency restoration work after a landslide, forestry work with a high incidence of falls, work in a steel mill in a dirty environment, debris removal work at the Fukushima Daiichi Nuclear Power Plant, and work at a volume reduction facility in Fukushima Prefecture, as shown in Fig. 1.

The issues in this development are the definition of requirements and integration for a new system that functions in a real environment. There are some well-known development models, such as waterfall model, spiral model and agile model in the software development field.

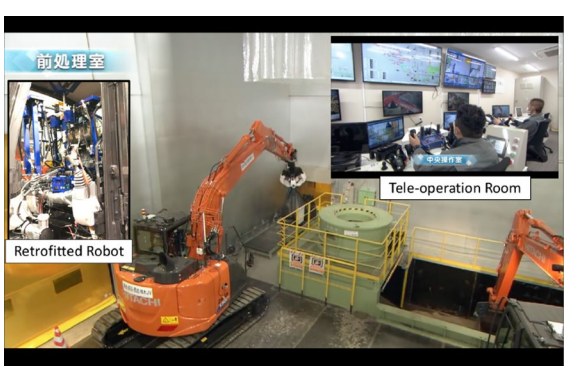

Fig. 1 Retrofitted robot for hydraulic excavator installed in volume reduction plant

Waterfall development [8] is commonly adopted by large companies in Japan due to its straightforward approach to development planning and management. Waterfall development is a methodology where a series of stages, including requirement definition, architectural design, detailed design, development, testing, and operation, are carried out sequentially from the initial stages. However, applying this method to our current project poses challenges, mainly because defining robot requirements is essential early in the development process.

Because Kowatech is a small manufacturer of special vehicles, it lacks the basic knowledge and data on construction machinery and work methods needed to define the requirements for a teleoperated system. Thus, it is difficult for such a small company to apply the Waterfall development.

Therefore, a system development process for smaller companies is required. A representative concept is the PDCA cycle [9], which is used to solve problems and continuously improve things. This concept entails the cyclic rotation of the four stages-Plan, Do, Check, and Action-as a single entity. It involves implementing processes and measures to bring outcomes closer to the intended goal. Nonetheless, this concept lacks the requisite specificity for the system development process.

On the other hand, agile and spiral development are methodologies involving iterative requirement definition. Agile development has gained prominence globally in recent years [10]. Emphasizing velocity and adaptability, agile development aims to rapidly cycle through and release each function in short intervals. Given the nature of our current development, which necessitates the integration of not only software but also hardware into a cohesive system, relying solely on agile development poses challenges. Spiral development, a quality-centric approach, enhances system comprehensiveness through a series of iterative development phases. This method involves a continuous loop where requirement definitions are refined iteratively, addressing gaps in development knowledge and enabling system integration. Therefore, this method seems to be suitable for this development.

In this research, based on such a spiral model, a spiral development process that can be implemented by small and medium-sized companies is proposed. The feature of this method is the structure that contains both small spirals, such as design, development, testing, and improvement, within a large spiral, in order to develop a robot system consisting of both hardware and software.

This paper describes the effect of applying spiral development to a retrofit robot to teleoperate a conventional hydraulic excavator. The purpose of this development is

to integrate a practical robot for a new entrant company in a real environment. The paper is organized as follows. Section 2 describes the spiral development flow, and section 3 explains a case study of a robot developed with spiral development. Next, section 4 discusses the development process, and finally, section 5 summarizes the entire process.

Spiral development process for construction robot systems

This section provides an overview of the conventional spiral development and a new spiral development with modifications for construction robot systems.

Overview of conventional spiral development

Spiral development is an iterative and incremental development method to construct a system while minimizing development risks through the development of prototypes. It consists mainly of the following 4 steps.

- Determine objectives, alternatives, constraints
- Evaluate alternatives, identify/resolve risks
- Develop, verify next-level product
- Plan next phases

A feature of this method is the ability to feed back user requests obtained from prototypes to the development process. In addition, by sharing specific features of the product, it is possible to detect any differences in perception with the user and errors in design and requirements definition at an early stage, thereby preventing the occurrence of rework. The disadvantage is the increased amount of development by repeated specification changes. This method is suitable for the development of small- and medium-scale systems because costs are incurred for each iteration of prototype development.

A new spiral development for construction robot systems

Spiral development for construction robot systems based on the conventional method is proposed. In order to develop an effective robotic system for a construction site, it is important to define the requirements appropriate to the site conditions and integrate the system to satisfy those requirements. Therefore, the requirements of the system are extracted by verifying and improving the system in the field environment. And, the reliability of the system is enhanced by solving the issues obtained.

The process of this development is divided into the following 4 steps in a series of spirals as shown in Fig. 2. This spiral is repeated several times to construct the system through the phases shown in Table 1. In this method, each prototype separates a series of spirals, and next-level products are planned and verified in the next spiral.

(I) Requirements analysis
(II) Development
(III) Test
(IV) Improvement

Step(I) is to investigate conventional technology and the conditions of the robot's operation and environment and to interview prospective users for this system such as operators in construction companies and developers in construction machinery manufacturers. The method of setting development specifications based on requirements analysis greatly affects the degree of difficulty and

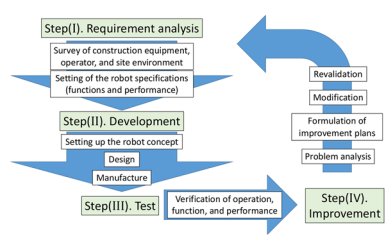

Fig. 2 Spiral model for robot development process

Table 1 Phase guidelines for building construction robot systems

	Phase	Requirements and verification guidelines	Scope of investigation
6	Industrialization	Economic efficiency, and expandability	Data measurements and interviews with operators at multiple operation sites
5	Commercialization	Safety, reliability,and service and maintainability	Data measurements and interviews with operators at a few operation sites
4	Implementation	Construction capability and usability	Data measurement of multiple machines environments and interviews with multiple operators
3	Late development	Performance	Multiple machines, environments,and interviews with operators
2	Mid-term development	Basic function	Data measurement of a few machines, environments,and interviews with a few operators
1	Early development	Concept	Literature, a few machines, environments and interviews with operators

required development time for subsequent development. Therefore, the requirement items are the minimum functions and performance required for the robot to achieve the desired tasks in the initial phase, and items are added and redefined according to the phase as the spiral progresses. In addition to basic functions and performance, requirement items include construction capability, usability, safety, reliability, service and maintainability, economic efficiency, and expandability.

Step(II) is to determine the robot concept based on the defined requirements. In setting up the concept, the robot's characteristics are determined. System configuration is designed from concepts and requirements, and hardware and software are designed and manufactured.

Step(III) is to test whether the prototype developed satisfies the requirements defined in Step(I). The key is to verify not only the robot alone, but also the system as a whole, including the hydraulic excavator and the retrofitted robot. This method provides a way to identify unclear elements of development in the early stages.

In the early phase of development, the feasibility and effectiveness of the concept are verified. In the mid-term phase, the feasibility of basic functions is confirmed under limited conditions, such as a single type of construction machinery and a standard environment. In the later phase, performance is verified under limited conditions. In the implementation phase, the construction capability and usability of the system are verified. Construction capability is the work performance of a teleoperated hydraulic excavator. The usability is the transportability of the robot, the quickness of the detachment operation, and the site applicability to multiple models of construction machinery. In the commercialization phase, safety, reliability, and service and maintainability are verified. Because smaller companies entering the market do not own construction machinery and the environment, it is difficult to verify a robot with them. Therefore, there are ways to utilize prefectural and national subsidized support, and to request cooperation from interviewed construction companies and potential future users.

Step(IV) is to improve the problematic parts and reverify them to satisfy the requirements. Problems that cannot be solved in the current spiral are reflected in the design of the next spiral and verified at that stage. The final step in each spiral is to verify the validity of the requirements. At this point, the lack of requirement items and the appropriateness of the set performance values are checked.

Retrofitted robot with spiral development

This section shows a method of applying spiral development to the development process of a robotic system for tele-operation of a conventional hydraulic excavator.

The flow of the development process with spiral development

This development spiraled 4 times before the robot was commercialized.

In Spiral-1, prototype 1 was developed as a feasibility study to verify the feasibility and effectiveness of the concept. From the results of the requirements analysis, the requirement items were defined as function, performance, safety, and reliability. First, the operation of the robot alone on the platform was verified. Next, the prototype was mounted on a hydraulic excavator to verify its limited functionality.

In Spiral-2, prototype 2 was developed to improve the functions and usability, which were issues for Spiral-1, in order to achieve the target functions. The scope of the survey was expanded, and it was confirmed that there was no change in the configured functions. The target performance value of communication distance was changed from the test of Spiral-1. The feasibility of the basic functions of the system was verified in the experimental field. The mechanism and software were improved due to control performance issues.

In Spiral-3, prototype 3 was developed to improve the performance, mountability, and safety for practical application. The set values for the lever stroke, response time, and communication distance were changed due to the increase in the number of types of construction machinery surveyed. The prototype was tested in a demonstration test sponsored by the Ministry of Land, Infrastructure, Transport and Tourism. Issues in the actual environment were identified and improved.

In Spiral-4, a mass-production prototype with improved basic functions and performance, as well as improved operability, was developed for practical application and commercialization. The developed robot was commercialized and its functions were further enhanced through field operation.

Specific methods of spiral development

Spiral 1(Feasibility study)

Step(I): Requirements analysis The first spiral is explained in detail. The functions and performance requirements of a robot to teleoperate a hydraulic excavator are established. The basic characteristics, operating method, and operating environment of construction machinery (1 model) were confirmed, and the operator and engineer (2 persons) from the construction machinery manufacturer were interviewed. As a result, the functions required for tele-operation of a hydraulic excavator were the ability to control the engine key, the safety lever, and the 4 control levers that drive each axis of the machine (boom, arm, bucket, and vehicle body swing). In addition, this development was designed to be able to

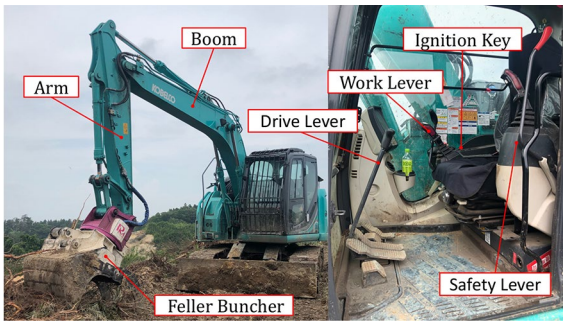

Fig. 3 Operation interface of the hydraulic excavator

operate a forestry attachment (ferrabuncha) with a view to the tele-operation of a hydraulic excavator in forestry work, where many accidents involving tipping over occur due to uneven terrain. Each control unit of the hydraulic excavator and forestry attachments is shown in Fig. 3.

Next, Table 2 shows the environmental conditions and target performance of the robot, which were established based on information from previous surveys and literature information on prior machines and similar technologies. The values set for each spiral in this development are shown. In Spiral-1, the ambient temperature and relative humidity are assumed to be in the operation room. A construction machinery battery (12/24 [VDC]) was used as the power source to enable long hours of operation (8 [hours/day]). Impact resistance was set based on literature information, and vibration resistance was not set as a requirement item at this stage. The stroke amount and positional accuracy of the control lever were set based on the lever movement range and amount of play measured during the machine survey. The response time (time from activation of the joystick on a remote controller to activation of the excavator's lever) was set to within 500 [ms], based on human operation behavior.

Step(II): Development In Step (II), the robot concept is set. It is designed and manufactured to satisfy the concept and the functions and performance set forth in Step (I). 4 concepts were established for this robot, and their items are listed in Table 3.

Section A is the functional requirements. The aim of the system is to realize the set basic functions remotely with wireless communication for a hydraulic excavator.

Section B is the reliability requirement. The objective is to ensure that the robot is not easily broken and can be operated without any problems in remote control, even in an environment where hydraulic excavators are subjected to vibrations and shocks during operation.

Section C is the requirement for usability. The goal is to be able to install the system on existing construction machinery with simple modifications without the need to remove the seat and with the possibility of restoring it.

Table 2 Operating conditions and target performance of hydraulic excavators

	Specification item	Spiral-1	Spiral-2	Spiral-3	Spiral-4	Products
Conditions	Operational temperature	0–50 [°C]	←	←	←	0–50 [°C]
	Operational humidity	Less than 90 [%]	←	←	←	Less than 90 [%]
		(No condensation)	←	←	←	(No condensation)
	Supply voltage	DC12/24 [V]	←	←	←	DC24 [V]
	Impact strength	Max. 10 [G]	←	←	←	Max. 10 [G]
	Vibration resistance	-	←	←	JIS1601D3B	JIS1601D3B
Specification	Working lever range	±100 [mm]	←	±110 [mm]	←	±110 [mm]
	Driving lever range	±150 [mm]	←	←	←	±150 [mm]
	Positional accuracy	±25 [mm]	←	±5 [mm]	←	±2 [mm]
	Response time	500 [ms]	200 [ms]	100 [ms]	←	100 [ms]
	Wireless distance	50 [m]	100 [m]	1 [km]	200 [m]	200 [m]

Table 3 Concept of robot system

A	Capability of basic operation for hydraulic excavator with radio control.
B	Robustness of mechanism and control against vibration and impact.
C	Simple modifications to allow for restoration to current state and without removing driver's seat.
D	Structure and adjustment mechanism applicable to a variety of manufacturers and sizes.

Section D is the requirement for usability. The objective is to make it easy to set up and handle the robot on a conventional hydraulic excavator.

Robot design based on these concepts will be explained. First, from Concepts A and B, the operating lever of a hydraulic excavator must be controlled stably in an environment with vibration shocks. Therefore, pneumatic rubber artificial muscles were adopted as actuators from the viewpoints of vibration and shock resistance and the compactness and light weight of the system. A robotic arm with rubber artificial muscles placed antagonistically drives the lever. Pneumatic systems are generally inferior to high-precision positioning control. However, because of the hardware compliance characteristics due to the compressibility of air, the system is expected to be robust against external influences such as adjustment errors between the robot and construction machinery and vibration shocks in a real environment.

Next, specified low-power radio was adopted for wireless communication for Concept A, based on the following conditions: no radio qualification required, excellent real-time performance, and comfortable communication performance (data transfer rate and distance). Finally, from Concepts C and D, it was decided that the robot would be mounted on the driver's seat. This is intended to reduce differences in the positional relationship from the seat to each control unit among manufacturers and models, and to reduce the impact of vibration shocks on the robot by the seat's absorbing effect. The specification of each basic function is determined based on these items. Next, the details of the functions to remotely control the hydraulic excavator are determined. Functions 1, 2, and 4 are electrically controlled from the viewpoint of safety and usability, while function 3 is mechanically controlled from the viewpoint of field applicability. The engine key, safety lever, and forestry attachment switches are all operated by switching electrical contacts. Therefore, they can be switched by connecting a conversion coupler for each model externally. On the other hand, since the control lever mechanically drives the hydraulic valve, the robot needs a mechanism to directly drive the lever.

The operating lever is driven by a robot arm with pneumatic rubber artificial muscles placed antagonistically. Compressed air is supplied by an electric compressor driven by an onboard battery. This compressed air is supplied and exhausted to the rubber artificial muscle via an air valve to generate the contraction force and stroke. To enable simultaneous operation of all axes, the number of robot arms is the same as the levers on a hydraulic excavator (4 levers).

The operation remote controller has two joysticks for working (2 axes each) and two joysticks for driving (1 axis each) to match the levers of the hydraulic excavator. The robot arm controls the amount of lever operation of the construction machinery according to the amount of joystick operation. By operating the engine key dial, safety switch, and forestry attachment holder switch on the top of the joystick on the remote control panel, the robot can change the state of the electrical contacts connected to the construction machinery.

Finally, safety features were added to the robot for remote control of the excavator. As a safety function, an emergency stop mode is implemented that simultaneously executes two processes: forcing the excavator engine to stop and turning on the hydraulic lock when the emergency stop button is pressed or when the communication signal is interrupted for a certain period of time or longer.

Step(III):Test In this spiral, the operation of the robot's basic functions on the platform was first checked. It was confirmed that function 1. engine key, function 2. safety lever, and function 4. forestry attachment can switch the electrical contacts in the robot via wireless communication by operating the switches on the remote control. In function 3, compressed air is supplied to the rubber artificial muscle in response to the operation lever of the remote control, although the precise movement of the robot arm was difficult to achieve. As for the safety function, it was confirmed that the engine key and the circuit for the hydraulic lock operate normally when the emergency stop button is pressed or the communication signal is interrupted for a certain period of time or longer.

This prototype was constructed to enable control of antagonistic drive and simultaneous operation of multiple axes by extending a diverting board that can control the pressure of a single pneumatic rubber artificial muscle. However, due to the electrical noise immunity of the control board and the immaturity of the software, the robot could not fully reach its expected behavior. With further software improvements, the robot arm was confirmed to operate in response to the joystick on the remote control.

Next, the operation of the robot's basic functions was checked with the robot mounted on a hydraulic excavator. Functions 1, 2, and 4 were verified to be effective on the tabletop. In function 3, the control lever did not move properly in response to the actuation of the antagonistic rubber artificial muscle due to the previous issues and the effect of the many joint degrees of freedom of the robot arm. When the air was expelled from the rubber artificial muscle, the robot arm was pushing the control lever of the construction machinery under its own weight.

While many of these issues have been obtained, we believe that a teleoperated system for conventional

hydraulic excavators with a retrofitted robot is feasible and useful for emergency disaster recovery and for reducing major accidents in construction machinery operations.

Step(IV): Improvement Issues were discovered in the control board, software, and robot arm mechanism and installation method of the pneumatic rubber artificial muscles of this prototype. The control board had problems with synchronization of each axis and real-time performance. Therefore, to solve these problems, a dedicated board with a revised driver circuit and OS was developed. The joint degrees of freedom of the robot arm were reduced, and the structure was changed from a lower surface support to a top surface support to prevent the lever of the construction machinery from entering under the arm's own weight. These improvements were made to Prototype 1. Because of the large number of changes, this improved model was treated as Prototype 2 as a break in the project, and improvements were made on it.

Summary of spiral development In the above steps I-IV, the first spiral is explained in detail, and other 3 spirals were conducted. The duration from initial development to market release in this system is 27 months (2 years and 3 months), broken down as follows: Spiral-1 to Spiral-3 each took 7 months, while Spiral-4 took 6 months. Given that the average duration for these general periods is 41 months, it can be inferred that this development has achieved rapid productization.

Table 4 shows progress of requirement definition and achievability in each spiral. From this table, it can be seen that the degree of accomplishment at the time of the spiral changeover, as well as new and modified requirements definitions were made. In the end, all requirements were achieved and the target retrofit robot was completed.

Consideration of spiral development

This section discusses the effects and notes on the application of spiral-type development for construction robots. The effect of the method can be described as 3 points. The first is that smaller companies can define new and undefined requirements in areas in which they have no experience. The second is enabling the construction of systems with practical functionality in a real-world environment. The third is to increase awareness for sales promotion.

Requirements definition in this method consists of configuration by requirements analysis, addition and reconfiguration by testing, and validity evaluation by improvement. In this development, the basic functions were not changed from the settings of Spiral-1 and were confirmed to be configurable from the initial survey. The performance tests of the system were conducted repeatably, and it was confirmed that the set values could be changed and finally set to realistic targets required in real environments. Target values can be set for construction capability as a system performance. It is reasonable to set the target value to be achieved based on the evaluation during the testing of the previous spiral. Since usability was an issue for the preceding machine, it was confirmed that the configuration could be set up from the early stages of development. The other requirements are general items that are required from product realization to commercialization, but their specifics are highly dependent on the robot's application and are difficult to establish in advance. However, it is possible to define and realize such a system by solving user requests and on-site issues following the verification items for each phase as a guide.

Verification in a field environment allows the extraction of requirements to function in a real environment. The requirements are then validated during the improvement phase. Therefore, the robot functions in the real environment by satisfying verification in the field environment. In this development, the robot satisfies the requirements and is operating in the field. Development with a prototype not only makes it easier to reflect user opinions, but also enables the robot to gain recognition even before it is commercialized. As a result, it is very effective for sales promotion.

Finally, limitation of the proposed method is discussed. The spiral development has demonstrated the capability of developing new systems without relying on industry experience. However, due to the iterative nature of the spiral model in the development process, a challenge remains where functionalities added in the later stages of development may not undergo sufficient verification and improvement. To address this issue, it is considered necessary to combine an agile approach that involves iterative cycles for individual functionalities. This approach can ensure high-quality implementation without being dependent on the timing of adding functionalities. Furthermore, introducing the System Readiness Level (SRL) as a system evaluation metric into the development process is also considered a method to maintain high quality. Therefore, the introduction of SRL will be explored in the future.

Conclusion

This paper describes the effect of applying the spiral development to the development process of a new retrofit robot for tele-operation of conventional hydraulic excavators from development to commercialization. The spiral type development is divided into four steps: (1) requirements analysis to define robot requirements, (2) development (design and manufacturing) to realize

Table 4 Progress of requirement definition and achievability in each spiral

	Specification items		Spiral-1	Achievement	Spiral-2	Achievement	Spiral-3	Achievement	Spiral-4	Achievement
Environmental Condition	Operational temperature	0~50℃	Definition	–	←	–	←	○	←	○
	Operational humidity	Less than 90	Definition	–	←	–	←	○	←	○
	Supply voltage	DC12V/24V	Definition	○	←	○	←	○	←	○
	Impact strength	Max10G	Definition	–	←	–	←	○	←	○
	Vibration resistance	–	Definition	–	←	–	←	–	JIS1601D3B	○
Functions	Function 0: Emergency stop		Definition	○	←	○	←	○	←	○
	Function 1 Engine key operation		Definition	○	←	○	←	○	←	○
	Function 2: hydraulic lock lever operation		Definition	○	←	○	←	○	←	○
	Function 3: operation of control lever		Definition	×	←	○	←	×	←	○
	Function 4. ferrabuncha operation		Definition	○	←	○	←	○	←	○
	Function 5. neutral setting						Additional definition	○	←	○
	Function 6 Inclination angle display						Additional definition	○	←	○
	Function 7. fine mode								Additional definition	○
	Function 8. sensitivity adjustment mode								Additional definition	○
	Function 9. trim function								Additional definition	○
	Function 10. warning display								Additional definition	○
	Function 11. fall stop function								Additional definition	○
Specifications	Working lever range	±100mm	Definition	○	←	○	Redefinition ±110m	○	←	○
	Driving lever range	±150mm	Definition	○	←	○	←	○	←	○
	Positional accuracy	±25mm	Definition	×	←	○	Redefinition ±5mm	×	Redefinition ±2mm	○
	Response time	500ms	Definition	○	Redefinition 200ms	○	Redefinition 100ms	○	←	○
	Wireless comm distance	50m	Definition	○	Redefinition 100m	○	Redefinition 1km	×	Redefinition 200m	○
Developed robot										
Developed controller										
Developing period x number of people			7 months x 2 persons		7 months x 3 persons		7 months x 3 persons		6 months x 2 persons	
Type			Prototype 1		Prototype 2		Prototype 3		Operational prototype	

the requirements, (3) testing to evaluate the degree of achievement, and (4) improvement to solve problems. By repeating these processes, uncertainties in the development process are clarified step by step to realize the construction of a robot system in accordance with the operation in the field. In this development, 4 spirals were conducted before commercialization, and the following knowledge was obtained from this method.

- Newly entering smaller companies can apply this methodology to their development process
- Capable of extracting system requirements that could not be envisioned prior to development
- Development of robots for real-world environments is possible

The above mentioned development process is expected to further spread the development and construction of robots utilized in real-world situations.

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Author contributions
TK conducted all research and development. TK also mainly wrote the manuscript. KN was responsible for the critical revision of the manuscript. KN and HY supervised and advised on the concept of the study. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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