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ORIGINAL ARTICLE

A New Approach for Development of Civil Engineering Technology using Concept of Cyber-Physical Systems

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Abstract**:** The concept of Cyber-Physical Systems (CPS) was first proposed by the National Science Foundation in the United States in 2006. To optimize the overall process in industrial systems, CPS integrates physical and cyber spaces. In the CPS, a variety of data is collected and analyzed by sensors and networks, and then sent back to the physical space. To fundamentally improve the production system in the civil engineering construction industry, this paper addresses the establishment of a platform for monitoring, analysis, and simulation activities that is necessary for technology development utilizing CPS. In developing civil engineering construction technologies, a variety of monitoring data collected in physical space is numerically analyzed, optimized, and simulated in cyberspace. The findings are then returned to physical space, resulting in productivity improvements such as reducing labor, errors, and to eliminate waste by utilizing robots. Utilizing the monitoring data, authors are developing an application program which enables the positional estimation of heavy machinery from images that digitally record machine travelling paths. The monitoring data are also utilized for developing indices to analyze whether the production system can be optimized by adapting robots or powered suits. Furthermore, a simulation of machine operation has been performed to derive the most effective control for all procedures in the construction and production system based on the indices. In this manner, the authors would like to contribute to the efficient and sustainable implementation infrastructure renewal and maintenance by utilizing the CPS approach for civil engineering development.

Keywords: cyber-physical systems, super city, digitalization, optimization, simulation

1. Introduction

1.1 Overview of CPS

Current Japanese society faces a number of challenges, including a declining population and an aging population, and there is a risk that existing social systems such as the economy, organizations, infrastructure, and welfare may not function properly by the 2030s. To address these issues, the government is promoting Society 5.0.

"By making the best use of ICT and integrating

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cyberspace and physical space (real world.), we will share the "super smart society" that brings affluence to people as the shape of the future society, and strongly promote it as a "Society 5.0" while further deepening a series of efforts toward its realization, to realize a super-smart society ahead of the rest of the world." the Cabinet Office said in its 5th Science and Technology Basic Plan (January 22, 2016).

This approach combining cyberspace and physical space (real world) is called the CPS (Cyber-Physical Systems), and the concept was proposed by the National Security Forum (National Science Foundation) of the United States in 2006[1]. Collect to improve efficiently through entire process of the induce system various information in realistic space within cyberspace through sensors and networks, analyzing the data, and feeding back the result to the real space, it aims at efficiency improvement for all processes of the industrial system. Recently, in the field of city planning, it has been reported that it is necessary to prepare a layer model for each industry in cyberspace and to examine it beforehand in order to realize super city and smart city [2]. In addition, in the building construction field, the challenge which carries out the construction simulation on the cyberspace for the crane operation and rapidly carries out the construction in the real space [3].

However, there have been no reports of cases in which CPSs were introduced in the field of civil engineering technology development. Therefore, the authors have proposed the CPS concept at the stage of improving civil engineering construction methods and developing new technologies as drastic improvement of production systems in the civil engineering construction field as a goal.

1.2 Leading example of CPS in the field of civil engineering

It is not a new attempt to collect information in cyberspace, analyze, optimize and simulate construction methods in the civil engineering construction field. For example, in the information-oriented construction of large-scale underground space and structure forced to carry out difficult construction, though design and construction are carried out based on the prior geological information, the daily geological observation data and measurement data under construction are digitized real time in cyberspace, and the model is reexamined based on the data. In addition, validity of design and construction method is confirmed. By carrying out predictive simulation of deformation, and stress, along reviewing the model, which the construction is carried out. It is recommended to add accurate judgment in the information shared by the parties in various positions. Reconstruct big data related to enormous measurement, observation, design, and construction in the cyberspace. Fig.1 shows a conceptual diagram of the computerized construction cycle of the Horonobe underground facility at the Japan Atomic Energy Agency. As shown in the figure, it is necessary to always link construction data with

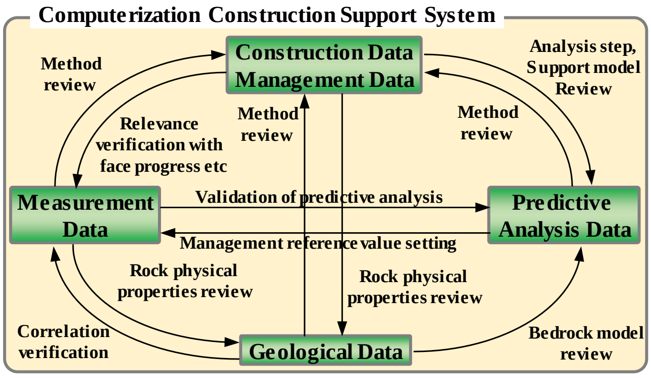

Fig.1 Relation of data in the construction of the Horonobe underground facility

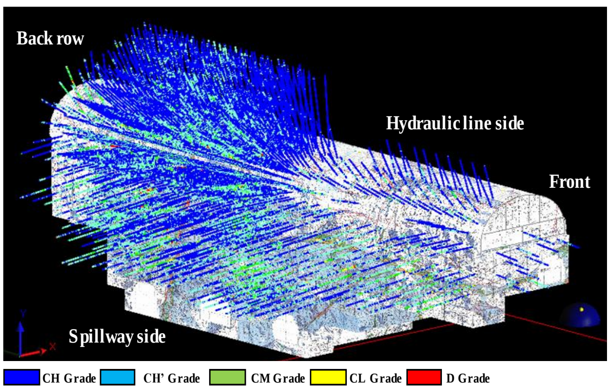

Fig.2 Example of data display at Kyogoku Underground Power Station

geological observation data, measurement data, and predictive analysis data (design). Within information-oriented construction, in order to analyze these related data, we developed a three-dimensional geological information and construction situation visualization system[4)]. Fig.2 shows an example of the display of geological observation data and measurement data during the computerized construction of Kyogoku Underground Power Station at Hokkaido Electric Power Co., Inc. using the system. Figure shows a geological observation sketch of a large-scale underground space and borehole logging data at the time of borehole drilling. The understanding of geological structure is promoted by displaying geological observation data and measurement data together.

1.3 New Approach of new civil engineering technology development method that introduced the concept of CPS

In the technology development of civil engineering construction, various data monitored in the real space are fed back to the real space in the form of improvement of workability by reduction of loss and waste and productivity improvement by robotization, etc. through numerical analysis, optimization and simulation in the cyberspace.

Fig.3 shows an image of civil engineering technology development method introducing CPS concept. First, the construction situation in the real space is monitored by GNSS (Global Navigation Satellite System), ICT (Information and Communication Technology) sensors, images, etc., and it is digitized and raised to the cyberspace. Second, the relation and effect evaluation of each data are carried out by multivariate analysis, etc. on the digitized data. As a result, it is examined whether the optimized construction method can be automated, while whether there is no loss and waste in the construction method is reexamined. In the automation, the robotization and application of the powered suit, etc. are examined considering the effect on the whole

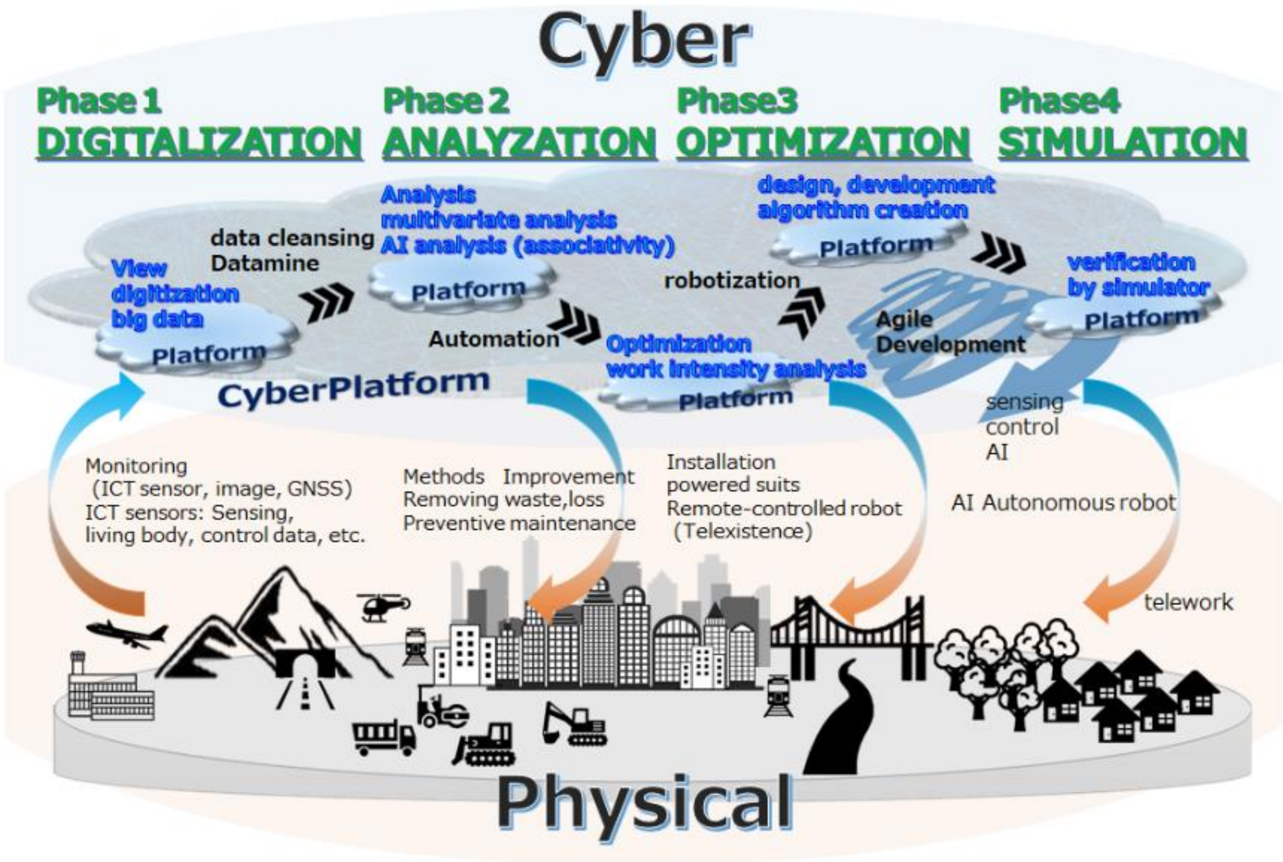

Fig.3 Conceptual image of civil engineering technology development method introducing CPS

production system and the fatigue rate of the manual work, etc. In the robotization, the simulation is carried out in order to examine whether the designed algorithm works as expected. The development up to this point is carried out in cyberspace, to run operation in the real space with robot attach, with sensors and manufactured based on the design verified by the simulation.

In this series of development work, we are developing an application which can measure the position of heavy equipment from the image to record the moving path way of digital data for the environment in which GNSS cannot be utilized in the monitoring. This is discussed in the next chapter "Digitization of construction status using AI image processing technology". There are no reported cases of this initiative in the past. This corresponds to "Phase 1" in Fig.3.The objective is to build a guideline whether manpower could be operating by robot or by just applying power suit for analyzing and evaluating the rationalization of the production system is capable or not. See Chapter 3, "Quantitative evaluation of work intensity as a decision indicator for automating work" for details. This corresponds to "Phase 3" in Fig.3. In addition, if the automation is judged to be the most efficient for all processes of the construction production system based on the guideline. The heavy machine control simulation is developed as an initial stage to confirm the validity of the algorithm of the automated machine. Details are given in Chapter 4 "Effectiveness of Simulation Technology in Construction Automation Development". This corresponds to "Phase 4" in Fig.3

2. Phase 1 & 2: Digitization and analysis of construction status using AI image processing technology

2.1 Strategies for digitization

IoT is introduced in various industrial fields, as solution for "productivity improvement problem", and drastic rationalization of the production system is promoted. For example, problems are extracted for relatively patterned works such as factories and plants, and problems are solved by developing new technology. However, due to complicated relation between construction heavy equipment and workers [5] in the construction work, it is difficult to plan the rational improvement measures of the production system. In order to analyze the relations of construction work improvement, flow line analysis seems to be indispensable, and it is necessary to acquire position information first. Though GNSS equipment generally used for acquisition of present position information can be applied in outdoor open environment, it is difficult to apply in indoor and unopened environment such as valley in mountainous area. Since GNSS equipment is expensive, it is not realistic to mount it on all construction heavy equipment. On the other hand, object detection and tracking using AI image processing technology have been studied as a technology to acquire position information using image data of a commercial camera recently[6].

Authors carried out technical verification for the purpose of developing a position measurement application operable under non-GNSS environment at low cost by using camera image data overlooking the field.

2.2 Configuration of positioning application

The configuration of this application is shown in Fig.4. It is composed by camera which overview the construction area and a PC which analyzes acquired moving image data.

The camera performance used is shown below.
Type: FDR-AX 40 4K (Made by Sony Corporation)
Number of pixels: 8.29 million pixels (3480 x 2160)
frame rate: 30 fps

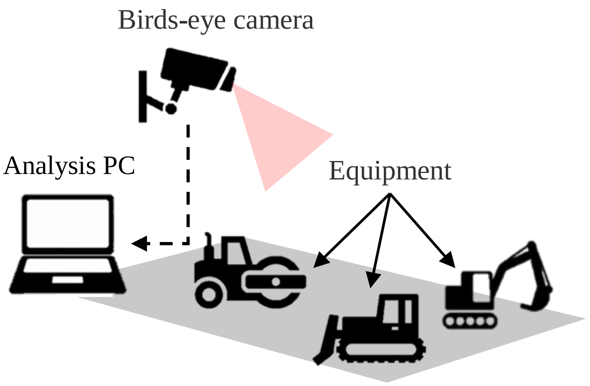

Fig.4 Configuration of Heavy Equipment Position Measurement Application

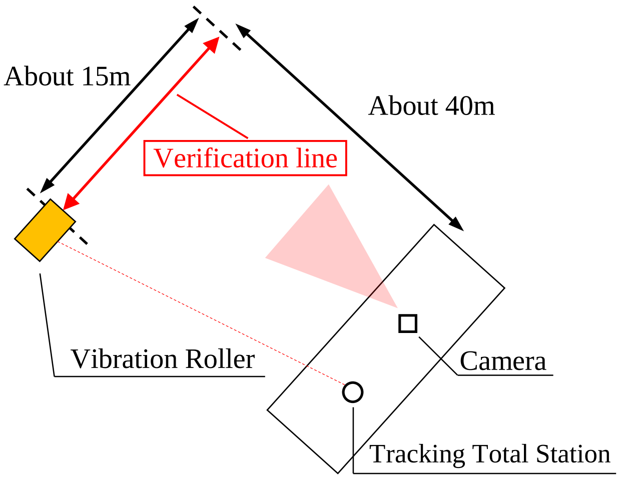

Fig.5 Experimental area plan

2.3 Outline of verification experiment

This experiment verifies whether the position analysis of the construction heavy equipment is possible from object detection of the construction heavy equipment by the AI image processing technology. A plan view of the verified experimental area is shown in Fig.5. A vibration roller is used as a heavy construction equipment as a detection object, vibration rolling pressure of about 15m is applied 3 times as a simulation. A tracking total station (Hereinafter, referred to "tracking TS") and a camera were installed at a place about 40m away from each other so as not to be affected by vibration. The tracking TS and the camera were synchronized beforehand, and the position analysis accuracy was confirmed from the comparison of both measured data.

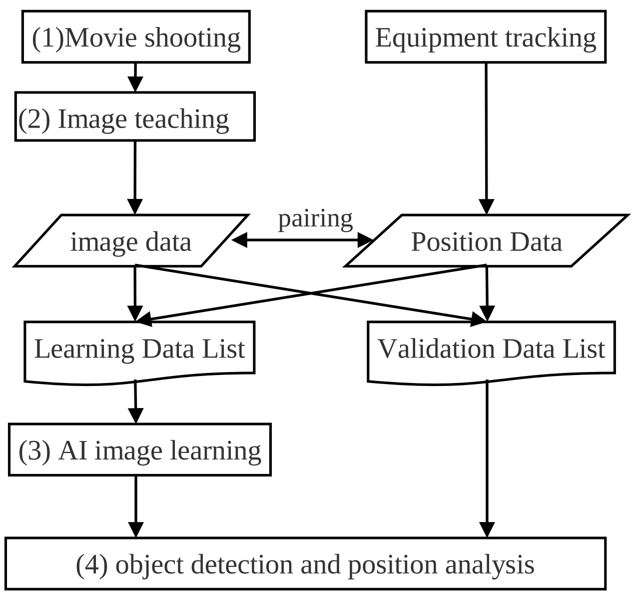

Fig.6 Validation Flow

2.4 Validation procedure

Fig.6 shows the flow of verification of position analysis accuracy from image data acquisition.

(1) Movie shooting and tracking of heavy equipment position.

A camera is used to take pictures of the vibration roller. The position of the vibrating roller is measured by the tracking TS. (Use as reference value for analysis)

(2) Image teaching data creation

Divide the movie into one image per second. The tracking type TS measurement coordinate and time are synchronized, and the image and position coordinate are paired.

(3) AI image learning

Using the learning data, the object detection of the vibration roller is learned.

(4) object detection and position analysis

The position is analyzed from the vibration roller detection result by the AI object detection, and it is compared with the tracking TS measurement coordinate.

2.5 Inspection result

The time series of the difference between the tracking TS coordinate and the analysis coordinate is shown in Fig.7, and the plane coordinate of the analysis result is shown in Fig.8. Comparison of the analysis coordinates with the motion path of the vibration roller shows that the difference is greatly shifted, up to a maximum of 1.3m, from Fig.7 especially for the position surrounded by the frame. It was confirmed from Fig.8 that these points were in the same plane. When this position was confirmed from the image, it was proven to be the position which overlapped with the worker. The average difference was about 40 cm except for the place where worker overlapped.

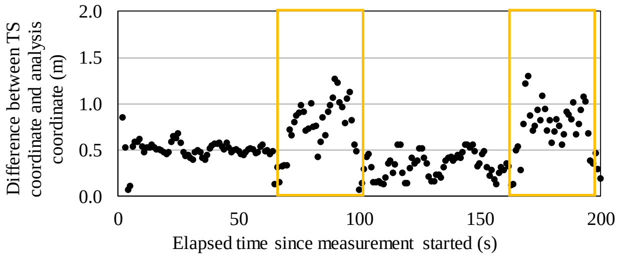

Fig.7 Analysis result time series

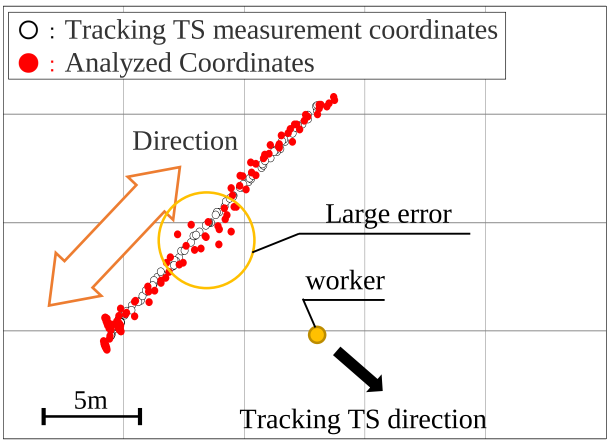

Fig.8 Position coordinate analysis result

2.6 Consideration

As a result of technical verification on heavy equipment position measurement using commercially available camera image, it was confirmed that the analysis coordinate value was about 40 cm in average with no obstacle, and that it could be used as position information for moving line analysis. Since the error tends to increase when it overlaps with other objects, it is necessary to improve the object detection accuracy by increasing the learning data and to reduce the case in which the analysis object overlaps with other objects by using multiple cameras. Based on this verification, the position measurement application is constructed, and the flow line analysis is carried out. One of the advantages of image processing is that it is possible to investigate the cause of such behavior. Taking advantage of this, we will analyze the relationship between construction heavy equipment and workers.

3. Phase 3: Quantitative evaluation of work intensity as a decision indicator for optimizing work

3.1 Method for quantitative evaluation

For the purpose of productivity improvement and labor environment improvement in the construction industry, we reported the robotization of manpower work with physical fatigue such as plasterer finishing work. Currently, which part of the manual work should be automated and how it should be robotized is done referring to the questionnaire to the worker[7].

However, since the questionnaire is based on human sense, individual difference occurs and will be difficult to evaluate equally.

Therefore, it is hard to evaluate the effect of automation and robotization on the whole construction and production system judging the effect, and therefore will cause problem obtaining company consensus. On the other hand, a technique to estimate the load on the human body by analyzing motion data measured by motion capture has recently been reported[8].

Then, we analyzed the motion data of the worker measured by the motion capture for the purpose of quantitatively evaluating the load of the worker in present work called the work intensity, and we tried the quantitative evaluation of the load to the human body by the work. This chapter describes the measurement results and the results of quantitative evaluation of the effect of the assist device.

3.2 Outline of subject experiment

%MVC (maximal voluntary control) is noticed as one of the indexes to evaluate the load objectively, and activity degree of the muscle [9]. MVC means the largest voluntary contraction force, and it is the largest force which the human exerts consciously and spontaneously. Since MVC varies from person to person and from muscle to muscle, the workload is evaluated as a percentage of MVC (%MVC). For the acquisition of motion data, 41 markers were attached to the whole body of the examinee, and the position coordinate data was measured at 100 Hz by VICON which is a 3dimensional motion measuring device. The subjects were males in their 20s, 170 cm in height and 60 kg in weight. The aim, purpose method of the experiment, etc. were explained, and the experiment was carried out up in sufficient informed consent. Using the acquired position coordinate data, %MVC was calculated by AnyBody Modeling System, a muscle force estimation software based on the musculoskeletal model.

3.3 Experimental result

The analysis was implement to "materials carrying operation", "reinforcing bar binding work", "lifting operation" in which the physical fatigue seemed to be big in the construction work (Fig.9). The outline of the operation is as follows.

materials carrying operation: carrying a cement bag (25 kg) on a walking board

Reinforcement binding operation: The operation of binding reinforcing bars in a kneeling position.

Lifting operation: lifting and lowering the board (16 kg)

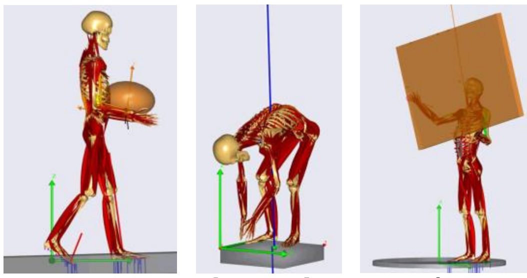

Fig.9 Image of a musculoskeletal model

Fig.10 shows the results of analysis of the maximum %MVC in each task to confirm which part of the body is used most. The average %MVC in the carrying work was 36.9%, and it was proven that the dispersion was big by walking, and that the load was put on the average with the heavy object. The time maximum application site was the lower limb, followed by the upper arm muscle. The average %MVC in the reinforcement bundling work was 24.6%, and the dispersion was small. It is judged that the work was done with the waist bent. Time maximum application site was erector spinae. The average %MVC in the lifting work was 40.0%, and the time maximum application site was the brachial muscle, and the time maximum %MVC became near 80%.

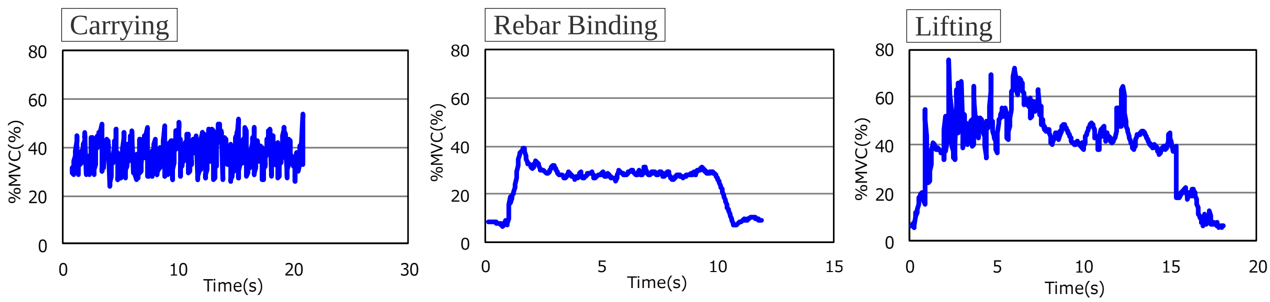

Fig.10 Maximum %MVC by Musculoskeletal Analysis

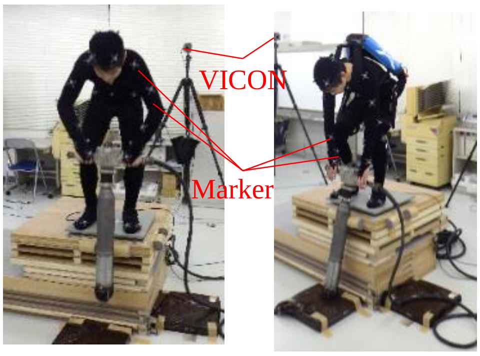

Fig.11 Motion Capture Status
(Left: device off ; Right: device on)

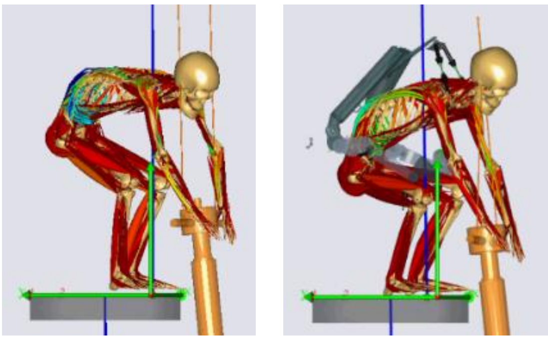

Fig.12 Musculoskeletal Modeling
(Left: device off ; Right: device on)

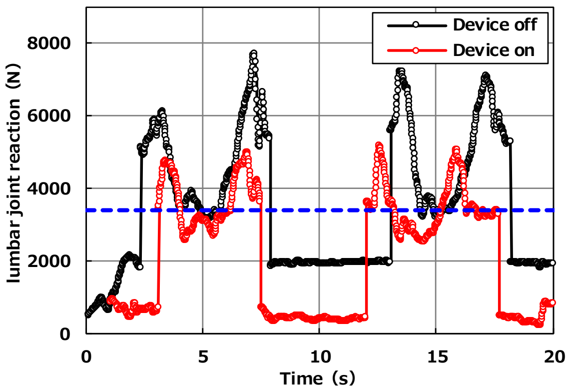

Fig.13 Result of lumbar joint reaction force

From the above, it is concluded that %MVC can be applied as an index to quantitatively evaluate the workload of each task. Here, the case in which the assist device was fixed was also examined on the assumption of improving the work environment referring to lifting work in which the activity quantity of the muscle was the largest in 3 works. Focusing in vibrator compaction work by the human power in the dam site, we won evaluate the load reduction human body by applying assist device.

3.4 Verification of effectiveness when applying assist device

Muscle Suit® (INNPOPHYS) was used as an assist device. With a vibrator weighing about 30 kg, data acquisition and analysis were carried out in the same method as described above for the work of lifting the vibrator from a low bent position and then lowering it to a distant place (Fig.11, Fig.12).

The results of analysis of the lumbar joint reaction (load on the waist) are shown in Fig.13. It is proven that the lumbar joint reaction force in the work is decreased by wearing the Muscle Suit®. The maximum value decreased from about 8,000 N to 5,500N, and the maximum load decreased by about 40%. On the other hand, National Institute of Occupational Safety and Health recommends that the compressive force of the 5th lumbar vertebra/sacrum should not exceed 3,400 N (dashed line in the figure) as a standard of the biomechanical risk of low back pain[10]. It was confirmed that the time exceeding the standard was reduced by about 44% by wearing the muscle suit, because the time exceeding the standard was 20 seconds/24 seconds for the work without the suit, while the time exceeding the standard was 8.1 seconds/3.8 seconds for the work with the suit.

3.5 Consideration

Motion data acquisition by motion capture and quantitative evaluation of worker load by musculoskeletal analysis were carried out, and the application effect of commercially available assist device was evaluated. Until now, only qualitative judgment was possible on the load of the work, but by adopting this evaluation technique, it is concluded that the judgment in the automation and robotization development of the work can be quantitatively carried out. We hope to contribute to the rationalization of many works by analyzing other works in the future.

4. Phase 4: Effectiveness of Simulation Technology in Construction Automation Development

In the development of automation of construction

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machinery, the authors 4 utilize simulation technology using computers (Fig.14). In order to plan or manage a production process such as the construction industry in which multiple works are complicatedly related, it is important to reproduce reality (physical space) in virtual space (cyberspace) and to judge this numerically and visually[11),12)]. It is judged that the utilization of simulation technology will become more important in the development of construction technology.

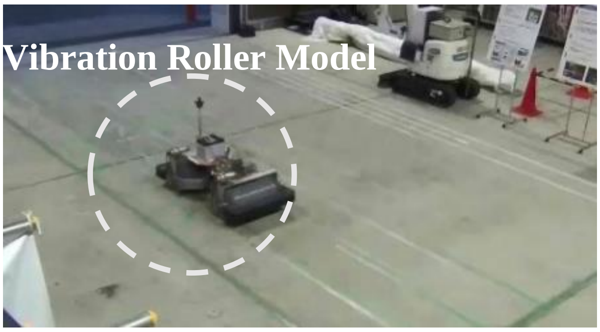
Fig.14 3D and VR Simulation

In this chapter, the effectiveness of the simulation technology in the construction machine automation development is described based on the development example of the autonomously controlled vibration roller.

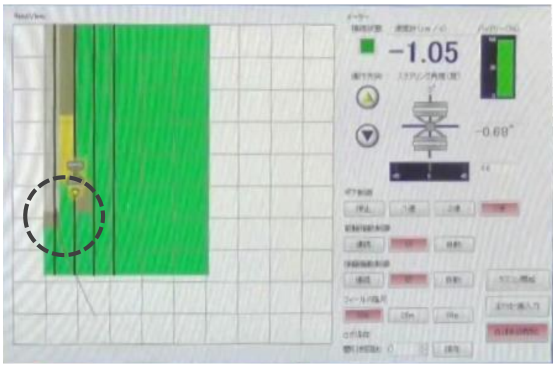
4.1 Outline of construction machine development

1) Development procedure

The overall execution flow of the autonomously controlled vibration roller development by the authors is shown in Fig.16 The equipment is a general-purpose 11-ton class vibration roller with autonomous



Model Operation Situation



Management System Screen

Fig15 Calculation Results of lumbar interphalangeal reaction force

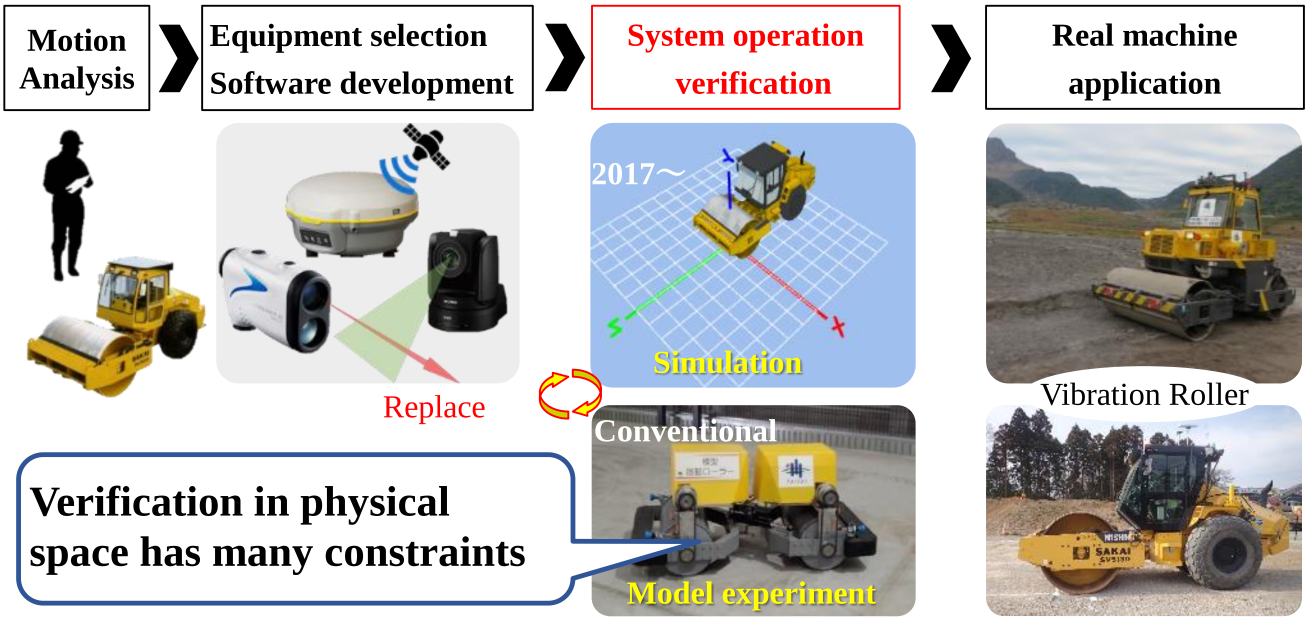


Fig.16 Overview of development（Vibration roller ）

control[13),14)]. Construction equipment automation development flow is divided roughly into 4 stages. First, the necessary operation of the construction machine in the work for automation is analyzed. Next, the sensing equipment for deciding the operation is selected, and the operation algorithm (control software) is developed. Next, the operation verification of the whole system is carried out at the stage when the construction of the control equipment software is completed, and if there is no problem, it shifts to the real machine application as a final stage.

In the development flow, the verification of the system operation was carried out by the model experiment so far, but the verification in the physical space takes time as described below, and there are many constraints in the safety. Recently, the simulation technology such as 3DVR has been rapidly improved, and the verification in the cyberspace becomes comparatively easy, so we have replaced the verification by the model experiment with the simulation verification since fiscal 2017.

2) Past model experiments

In the verification, 1/3 scale model (1.28 m long x 0.74 m wide) of the real machine was produced. This model has an articulation mechanism, and the sensing system is the same as the real machine. The verification field was provided indoors with a yard (12 m (W) x 7 m (W)). In the verification, the behavior of each element and the effect of friction coefficient were analyzed first, and then it was confirmed whether the model worked properly according to the instruction (Rolling pressure area and running times) of the management system (Photo.1).

3) Verification by simulation

An implementation image of the verification is shown in Fig.17. Commercially available drive simulator "UC-Win/Road"[15)] and physical engine "AgX Dynamics" were used as verification software. By combining all, it becomes possible to verify the effect of difference in mechanical characteristics and ground condition on the operation in addition to the basic operation confirmation of the construction machine.

4.2 Comparison between model experiments and simulation results

Verification, model experiment and simulation were compared (Table.1). 12 months required for the model experiment and 3 months for the simulation, which is a 4 times difference in the development speed. These were due to the following differences in the constraints at the time of verification.

The most noticeable difference in development productivity was the restriction of facilities and places. The model experiment requires a flat verification field with more than a certain width in addition to the model, and the simulation verification can be carried out in any place with PC. Therefore, for example,

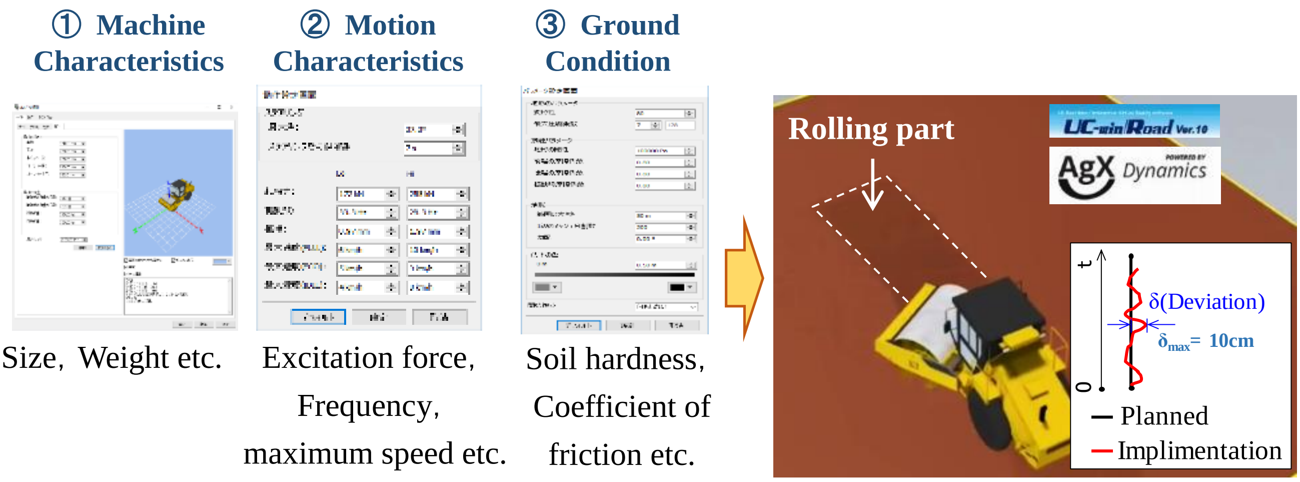


Fig.17 Model experiment

when a failure occurs in the system operation, preparation and environment improvement for the additional verification become unnecessary. Since the simulation verification is carried out in cyberspace, we do not need to consider safety, and the arrangement of the safety monitor with not be necessary as well. These effects were especially clear in the early stage of development with unstable system operation.

Table.1 Comparison of Validation Methods

		Model experiment	Simulation
Time required		12 months	3 months
Validation Constraints	Facilities	Model, PC	PC
	Place	Experimental yard	Anywhere
	Safety	Require inspectors	No inspectors

4.3 Consideration

In the verification in the physical space, there are many concerns such as facilities, places, safety, etc. however, cyberspace is not affected by these restrictions. The utilization of the simulation technology greatly improved the productivity of the construction machine automation development due to digitalization of all things. The authors consider that this is a new approach for development of civil engineering technology using concept of CPS. IoT is accelerated by miniaturization and cost reduction of sensors. By utilizing these data, the simulation can be more accurate, and the traffic between cyberspace and physical space can be smoothly transformed. We will develop a control system using AI for constructing verification platform of CPS in future. It is considered that the speedup of the learning process by the simulator is one of the important issues.

5. Conclusion

As a construction company with the field of the real space, we recognize that the most important mission in CPS of the whole construction industry to acquire and digitize the data.. As a general contractor, we hope to contribute to the development of the civil engineering industry in the future by developing and providing applications that can be used by a large number of engineers, such as improving productivity, inheriting skills, and using robots to realizing these targets, by developing a technology development platform utilizing CPS in the field of civil engineering technology development in cyberspace composed of the data thus obtained.

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