Basic Technology toward Autonomous Hydraulic Excavator

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Abstract

Civil engineering construction work has always been accompanied by a high proportion of tasks that are either dangerous or unpleasant or both. Enhancing the general working environment and boosting safety levels are critical issues for the industry. Meanwhile, the industry has been slow to embrace IT, and there is substantial scope for the use of technology to boost efficiency, cut costs and improve quality levels in construction. In a bid to address this issue, the Ministry of Land, Infrastructure and Transport launched a five-year project in FY2003 entitled Development of Construction Robots and Associated IT Systems.

This paper reports on the research and development work carried out by the authors in connection with the project. The project developed a three-dimensional space description method for civil engineering execution, which can now be applied to finished work control etc. and used by construction machinery. Foundation technologies needed for self-controlled excavation and loading by a hydraulic excavator have been developed and verified to the level that, under basic conditions, they have attained speed and precision equal to that by a human operator.

Keywords: execution technology, information technology, robot technology, three-dimensional information, construction equipment

1. Outline of, and Background to, the Project

Civil engineering work is still performed in inferior work environments and involves dangerous and grueling tasks. And the introduction of IT is behind that in other industries, demanding the development of technologies to increase work efficiency, cut costs, and improve quality. Some researches on this field have produced a number of results, such as the research about the Automatic Excavator. [4] [7] [8]

The Ministry of Land, Infrastructure, Transport and Tourism carried out the General Technology Development Project, Development of Robots and other IT Execution Systems, as a five year plan extending from FY 2003 to FY 2007. This project applied the most advanced information technology (IT) and robot technology (RT) to carry out two projects, Development of IT Construction Machinery Execution Technologies and Development of Execution Control Technologies Using 3D Information, in order to eliminate dangerous and grueling tasks, improve inefficient work, and deal with similar challenges facing the field of civil engineering.

The goals of the research were to apply IT, RT etc. to earthwork in order to achieve execution control such as control and inspection of completed work based on three dimensional design and land form information, plus IT execution including supporting and automating the operation of construction machinery (see Fig. 1) [12]

This report presents an outline of the achievements of this project regarding the self-controlled operation of hydraulic shovels.

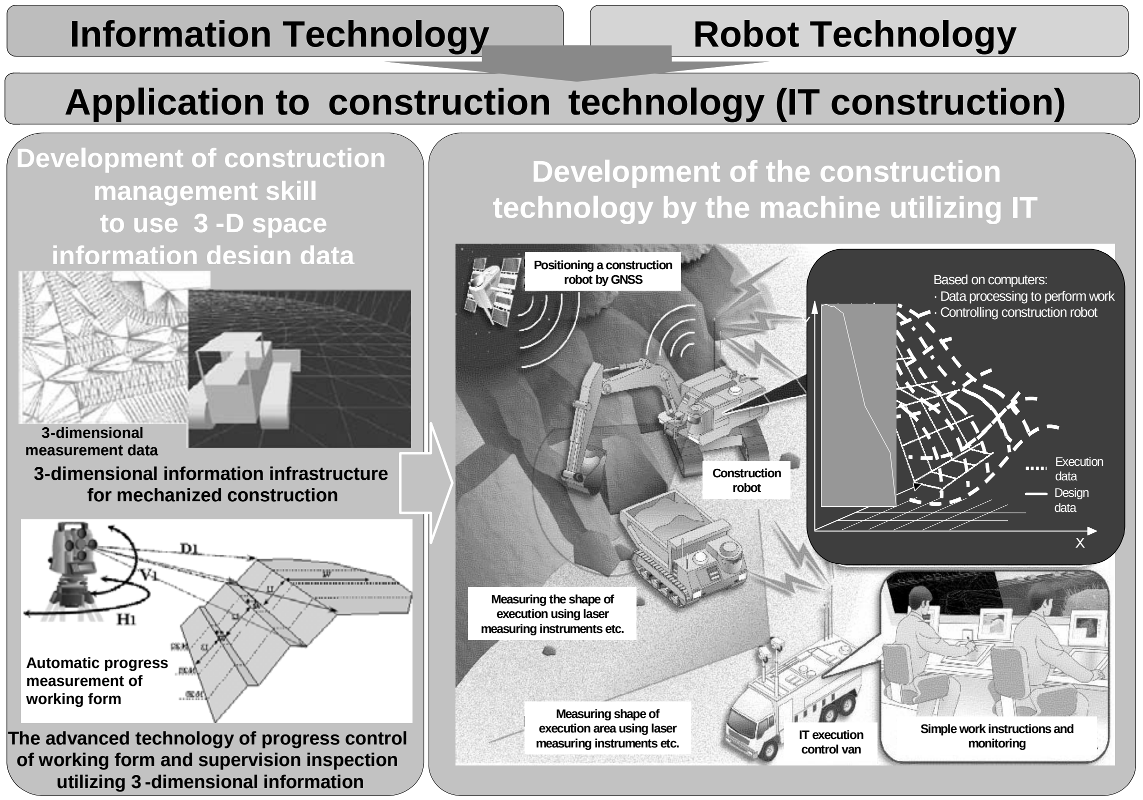

Figure.1 R/D of Advanced Execution Technology by RT and IT

The project was undertaken under the following policies.

1) Ministry of Land, Infrastructure, Transport and Tourism's Basic Technology Plan (2003 to 2007)
2) Integrated Science and Technology Policies: Next Generation Robot Related Policies (from July 2004)
3) Third Basic Science and Technology Plan (2006 to 2010)
4) Outline of the Promotion of Innovations in National Land and Transportation (May, 2007)
5) Information Integrated Construction Promotion Strategy (July 2008)

The Basic Science and Technology Plans are implemented to achieve the following research and development goals.

1) To apply three-dimensional design and land form information to develop IT execution systems for a robotic construction machine capable of automated excavation, and to improve construction site measurement and execution efficiency through remote operation by the end of 2007.
2) To apply automatic functions and measurement functions of construction machinery to improve safety and work productivity on construction sites and to achieve forms of execution capable of eliminating supplementary work by human workers by the end of 2010.

2. Development of Execution Control Technologies Using Three-dimensional Information

The goal is to perform more efficient execution control using three-dimensional design data and land form information obtainable in three dimensions as execution control information. The project has constructed execution control data which permits planar execution control to be installed in robotic construction machinery, prepared guidelines and handbooks for completed work control applying three-dimensional information [9], and has prepared written required development specifications necessary for the private sector to develop total stations (below called TS) [1].

2.1 Contents of the research which has been undertaken

(1) Clarification of the work to be improved and construction of an information model using three-dimensional design information

1) A proposal has been made to improve work between customers and contractors by IT—design verification, finished work control, supervision and inspections etc.—centered on three-dimensional design information which is a premise of an IT execution system.
2) An information model which shares both design and execution information between CAD and measuring equipment has been constructed.
3) Corroborative testing (4 locations) has verified the installation of finishing stakes and finished work control methods using three-dimensional information
4) Effectiveness of three-dimensional design information in executions—shortening the time required for preparatory work such as coordinate calculations etc.—has been confirmed.

(2) Improvement of information models using three-dimensional basic design information

1) Present three-dimensional measurement technologies (GPS, TS, three dimensional scanners, etc.) were studied, confirming the effectiveness of TS based finished work control.
2) Three-dimensional basic design information installed in measuring instruments has improved descriptive methods (information models) capable of responding to any changes of lateral section shapes from among design specifications or framework architecture such as widths or road alignments of structures

(3) Verification at construction sites

1) On-site trials of finished work control were performed using TS incorporated into basic design information (at six sites).
2) For the trials, three-dimensional design information was prepared, and at the site, this three-dimensional design information was compared with the finished work measurement results, verifying the series of procedures called automatic preparation of finished work control ledgers.

2.2 Research achievements

(1) Three-dimensional space data conversion specifications

By defining basic design information which consists of shape structure elements, basic design elements, and basic coordinate system elements, the research constructed three-dimensional design specifications which can be applied to TS-based finished work control at construction sites. (See Fig. 2) And based on the defined basic design information, three-dimensional design information needed by robotic construction machines was completed as three-dimensional space data conversion specifications (skeleton data). Three-dimensional space data conversion specification was expressed data elements based on land-XML used in the construction field. [2]

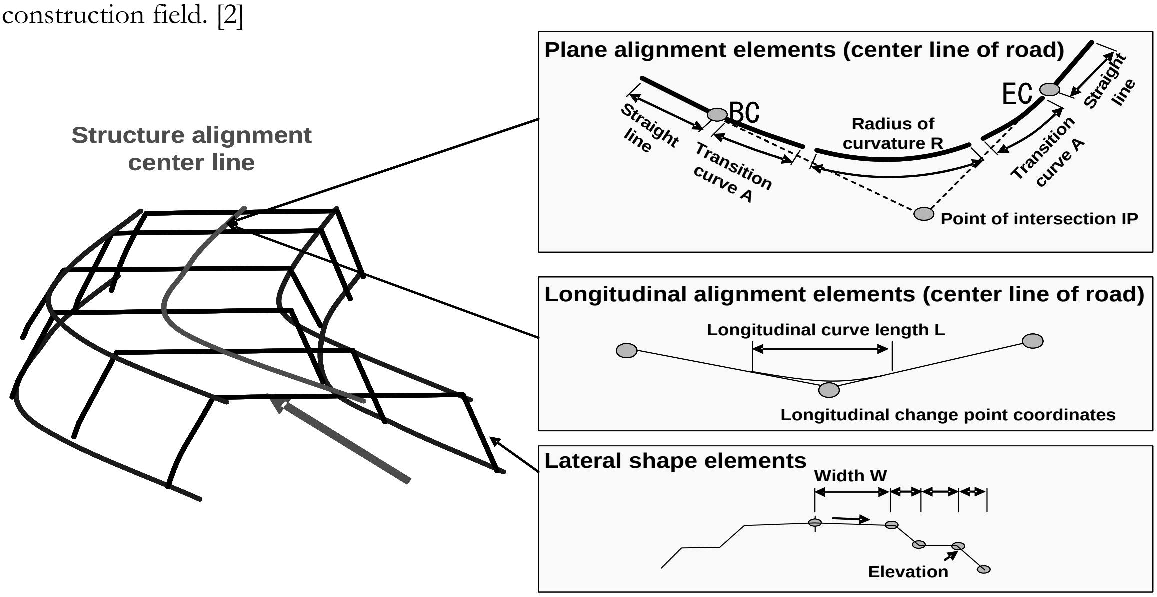

Figure 2. Three-dimensional Design Information

(2) Finished work control technologies and completion inspection technologies applying three-dimensional design information

Determining a new finished work measurement method based on TS incorporated in basic design information has completed the development of finished work control technologies and completion inspection technologies which apply three dimensional design information. (See Fig. 3) With this method, it was possible to confirm discrepancies between design values and measured values on site by calculating the slope length, width, length and height of berms similarly to the present method based on distance from and comparable height difference from the road center line. And it has also been verified that TS based measurements can be made more efficiently than measurements using levels or measuring tapes.

(3) Required specifications of equipment needed to handle three-dimensional information

Judging from results of the on-site trial, conditions necessary for TS to perform finished work control have been clarified as required hardware conditions and as required software conditions. And these have been summarized as specifications required by three-dimensional information application instruments in order that all measurement instrument makers will be able to develop equipment

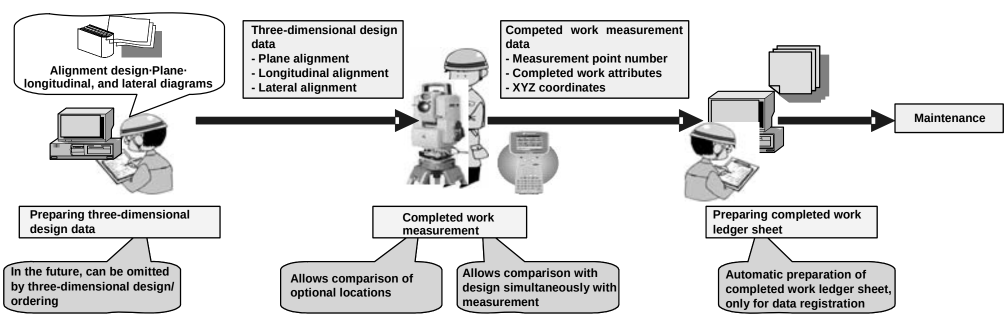

Figure 3. Finished Work Control Technology Using a Total Station

3. Development of Self-controlled Excavation and Loading Technologies for Hydraulic Excavators

3.1 Outline

To create practical IT execution technologies for construction machinery, the basic technologies which are its foundations will be developed. Specifically, the research will develop technologies to display three-dimensional design information and three-dimensional land form information as it changes according to the execution on an operation screen to provide work location, work contents, and other simple instruction information on a screen.

The goal is to introduce this as a work support system which improves execution efficiency of normal construction machinery and at the same time, develop IT execution technology based on robot construction machines such as hydraulic excavators which apply IT and robot technology to perform executions automatically.

The object of the research was to create foundation technologies in order to introduce IT and RT wherever possible within a practical range to earthwork at extremely dangerous work sites such as disaster restoration and disaster prevention projects (sediment control projects for example), as technologies necessary for execution processes to excavate, load, and transport soil using hydraulic excavators or crawlers which are representative general purpose construction machines. This was verified by a virtual site test as a prototype system. And the challenges revealed by the tests will be the grounds for future development.

The research and development is hypothesized as a two-stage process based on the maturity and practicality of the technologies.

1) The first stage goal is to develop a system to support work by presenting operators of construction machinery (remote control etc.) with the goal of the work (design) and present situation (land form) as three-dimensional information and with the position of the machine. This system is intended to be technology which will soon reach the practical stage at actual unmanned execution sites etc.
2) The second stage goal is to create a prototype of a robot construction machine which, when a remote operator provides simple work instructions including the location, range, and contents,

performs self-controlled work to a certain degree based on three-dimensional information concerning goals of the work (design) and present situation (land form).

"To a certain degree" in the above paragraph means that the operator intervenes to operate the machine remotely when it is difficult for the machine to perform self-controlled operation because, for example, an unexpected situation such as a large rock occurs. And self-controlled work means that the bucket, boom and other working parts of the hydraulic excavator plan the work and perform self-controlled excavation and loading work while revising the plan according to the situation.

The goal of the research and development is a system permitting a machine to, based on three dimensional design and shape information (three-dimensional space data conversion specifications), measure the land form of the ground as it is altered by the work, plan the excavation and loading work according to the measurements and to control the machine so it performs self-controlled work with approximately the same precision and at about the same speed as an experienced operator.

3.2 Contents of the research and development

To achieve this goal, three kinds of technology were developed: (1) technology which recognizes the surrounding environment as three-dimensional information necessary for self-controlled execution, (2) technology which displays three-dimensional information necessary for the work (man-machine interface), and (3) technology to automate execution (control technology).

This was done under limiting conditions: that soil and ground conditions be almost uniform at the research institute test site, the work contents be trench excavation and loading, the shape of the work be based on design information, the work range be designated, and the movement be remotely controlled. Figure 4 is a schematic diagram of the prototype which was developed, and Figure 5 shows an exterior view of the hydraulic excavator and the locations where sensors are installed.

The basic concept of this research and development is not accumulating the essence of advanced technologies even if at great cost, so if it achieves its goals, it is a success; rather it is to achieve the minimum level of target functions at the lowest possible cost by, instead of using special basic technologies, applying technologies which are as long-established as possible. Because it is a rapidly progressing field of technology, the functions were divided into sub-systems and components to construct it by simplifying the replacement of these with higher functioning or less expensive sub-systems and components in order to easily apply new technologies to each sub-system or component. [13] The development, which had a deadline for completion, was done by omitting model tests to use actual construction machinery from the beginning. The hydraulic excavator used as the base machine was, small during the testing period and its equipment installation capacity was large, so a 12t class machine was used. And even though it as a test machine, as safety measures, the testing was performed carefully using emergency stop devices and monitoring communications. [3]

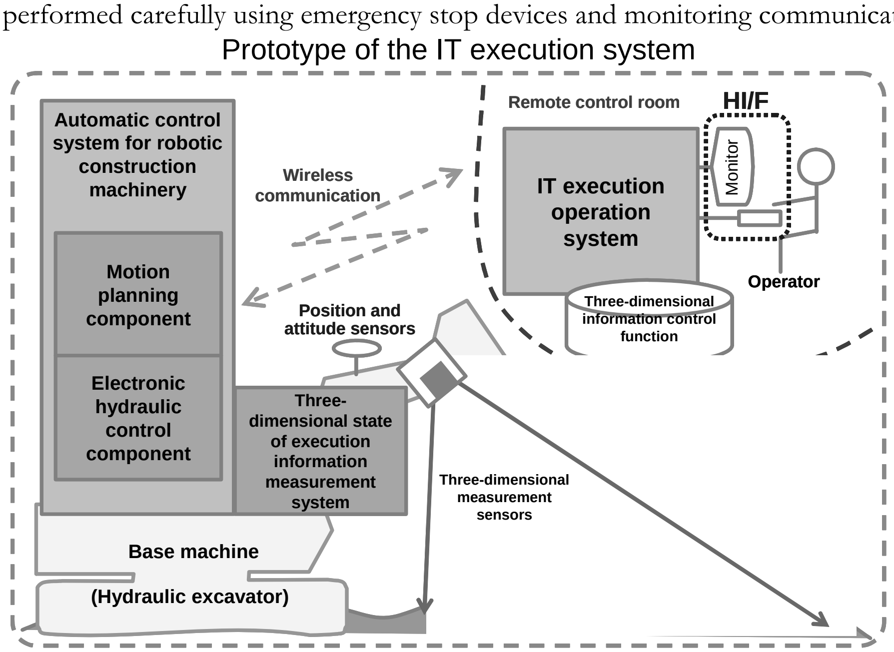

Figure 4. Schematic Diagram of the System

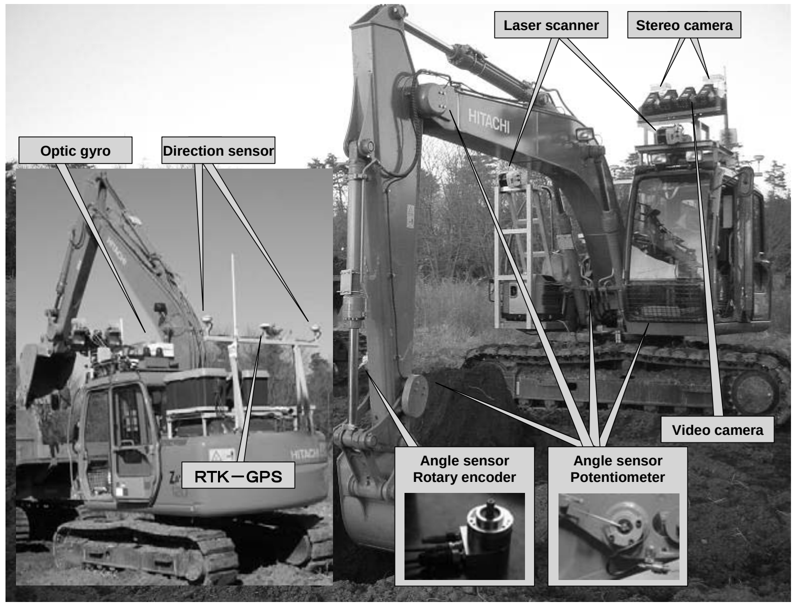

Figure 5. Hydraulic Excavator: External Appearance and Locations of Sensors

3.3 Outline of the prototype

(1) The three-dimensional state of execution information measurement system

The location of the machine is measured by RTK-GPS, its direction, inclination, and oscillation by optical fiber gyros, the directional gyro drift correction is done by a GPS phase difference direction meter. The accuracy of Optic gyro measuring attitude angle is ±(0.2°+1% of angle). And the ground is measured by a laser scanner (real time) and a stereo camera (finished work confirmation) etc. The maximum measuring range of the laser is 80m with 10mm measurement resolution. The measurement is done by performing time management and synchronization to convert the machine coordinate system and world coordinate system. [11]

(2) Display and operating systems

The results of measurements of machine position, design, and ground surface measurements are displayed by computer graphics to support autonomous setting, instructions, monitoring, and other remote operations. And the moving images obtained by the camera are superimposed on the design lines. [14]

(3) Three-dimensional information control system

Design data is stored by three-dimensional space data conversion specifications. The design and ground surface measurement results are maintained by converting them to simplified meshes (5 - 10cm) and providing them to the various components.

(4) Automatic control system

The internal sensors in the working devices (bucket, boom, arm) are a rotary encoder, potentiometer, and stroke sensor. The control performance achieved with the encoder that the resolution is 14bits and the linearity error is ±1/2·LSB. The automatic bucket movement plan generating algorithm [6] and hydraulic control technology were developed with reference to operator operations analysis results [5] [10].

4. Verification by the Prototype

A prototype test on a simulated site on the grounds of the institute verified the system’s functions by using a hydraulic excavator and a crawler dump truck to perform mechanized earthwork: excavation and loading soil. (Fig.6, Fig.7) To perform accurate movements preventing collisions with the crawler dump truck, the cycle time was set at approximately 30 seconds for preliminary excavation and approximately 40 seconds for finishing excavation, achieving finishing excavation precision of 5cm, verifying and confirming it as a foundation technology. The challenges were achieving smooth movement, shortening cycle time, and dealing with the problem of soil which could not be scooped up spilling from the bucket

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Figure 6. Excavation and Loading

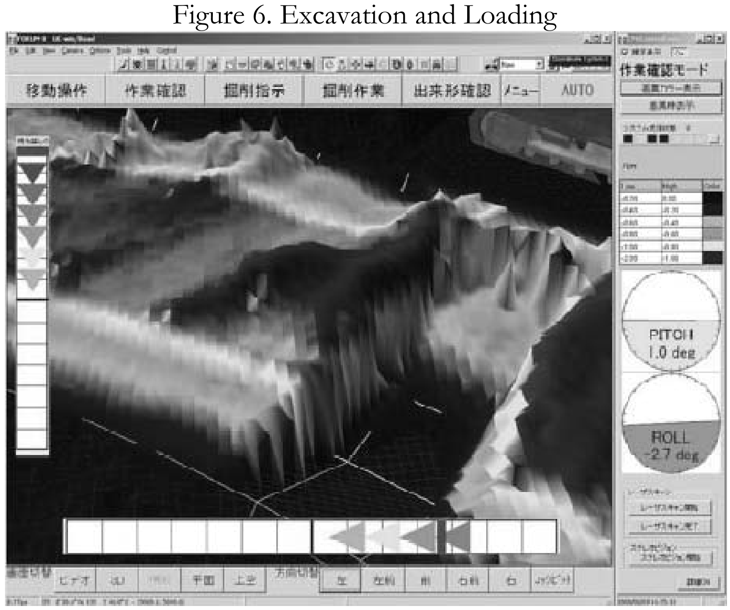

Figure 7. Display of Camera Measurements After Excavation

5. Conclusions

This project successfully established IT construction of earthwork—execution control including finished work control and inspections and support for and automation of the operation of construction machinery—using IT and RT and by applying three-dimensional design and land form information

Future endeavors in the area of execution control technologies using three-dimensional information will achieve finished work control technology using RTK-GPS by developing finished work control technologies for work categories other than earthwork and measuring instruments other than TS. It will be necessary to support information circulation using finished work control technologies for uses other than execution.

Future endeavors in the field of IT execution technology for construction machinery will permit its application to diverse soil conditions and work contents, simplifying expansion of its functions. Technologically, evaluating ground properties in real time to reflect the results in movement planning and control, and achieving methods of presenting easily expandable automatic movement planning creation rule description methods. And it will be necessary to clarify effective operation support, particularly execution methods, by making use of self-control functions and measurement functions.

Acknowledgments

The authors received assistance with this research from many members of organizations such as the Ministry of Land, Infrastructure, Transport and Tourism, the Research Committee for IT Execution Systems Based on Robots Etc. (Committee Chairman: Professor Yuta of Tsukuba University), Surveying Instruments Manufacturer's Association, Japan Construction Mechanization Association, Advanced Construction Technology Center, the Construction Robot Committee of the Japan Society of Civil Engineers, and the Unmanned Construction System Association and others. We are deeply grateful to them all for their support. And we also wish to thank everyone who assisted with the testing.

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