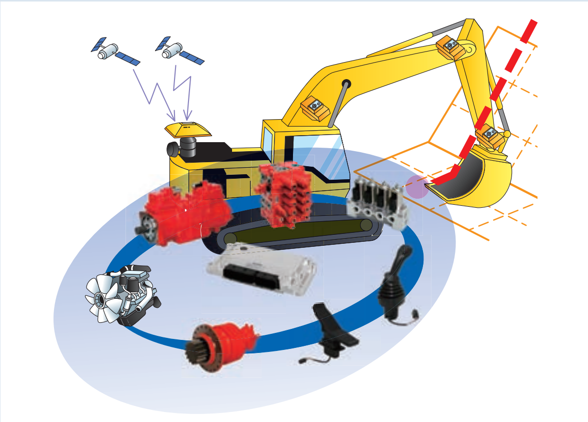
Development of Systems for ICT Hydraulic Excavators That Enable the Realization of Computer-Aided Construction



The demand for ICT construction machinery is increasing as it enables the realization of highly efficient and highly accurate computer-aided construction with ICT (Information Communication Technology) and IoT (Internet of Things) technology for enhanced productivity at construction sites. Leveraging its expertise as a hydraulic equipment manufacturer, Kawasaki is developing hydraulic systems and machine control technologies that can achieve a good balance between control accuracy and operating speed in ICT hydraulic excavator systems. For future systems, Kawasaki is also working toward automation and autonomy with the focus on innovative hydraulic systems.

Introduction

Because of the increasingly serious labor shortage at construction sites due to a shrinking labor force of experienced workers, computer-aided construction is increasingly adopted to enhance productivity.

In Japan, the national government has been promoting i-Construction, which is a new framework aimed at enhancing productivity at construction sites, since 2016, and there is an increasingly interest in computer-aided construction.

1 Background

Construction processes consist of survey, design, construction, supervision, inspection, and maintenance. Computer-aided construction focuses on the construction process, using ICT and IoT technology to achieve highly efficient and accurate construction. In addition, electronic data obtained through construction are used for other processes for enhancing productivity and ensuring quality throughout all the construction processes. Recently, the demand for ICT construction machinery, which is the tool for realizing computer-aided construction, is increasing rapidly.

2 ICT construction machinery

ICT construction machinery incorporates machine guidance technology, which displays on the monitor the difference between the current position of construction machinery estimated with the global navigation satellite system and vehicle sensors and the target value for construction, and machine control technology, which automatically controls construction machinery in real time to minimize the difference between the current position and target value, both of which construction machinery manufacturers are developing. Today, machine control technology, which assists the operator in performing grading work, has already been put on the market and is becoming common. This technology was first adopted for bulldozers, which are mainly used for grading work, and is now being adopted for hydraulic excavators, which are used for many different kinds of work. Kawasaki is focusing on researching and developing ICT hydraulic excavator systems, for which it is difficult to adopt machine control technology, as it provides an opportunity for Kawasaki to leverage its strength.

The main role of ICT hydraulic excavator systems is to control the movement of each axis of the boom, arm, and bucket making up the hydraulic excavator attachment so that the bucket tip follows the desired trajectory. ICT hydraulic excavator systems consist mainly of a hydraulic system, which controls the movement of each axis with hydraulic cylinders as shown in **Fig. 1**, and machine control technology, which estimates the posture based on information from the angle sensors arranged on the attachment to control the bucket tip position.

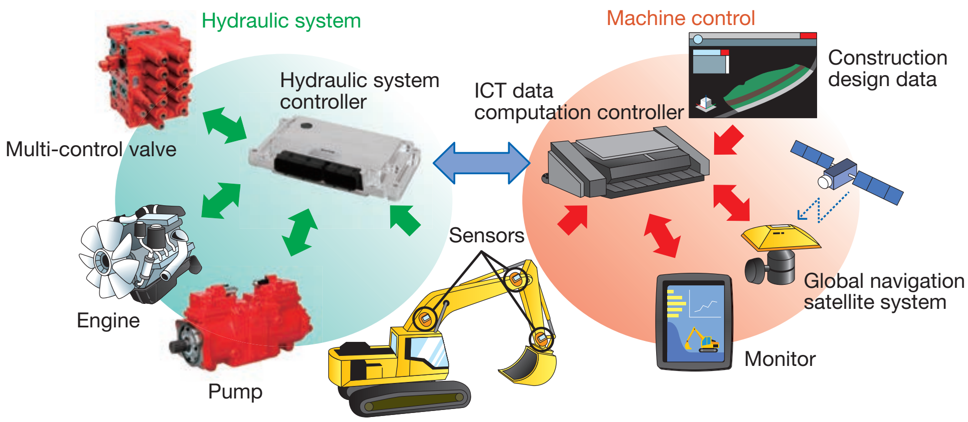


Fig. 1 System configuration of ICT construction machinery (hydraulic excavator)

3 Development goal and policy

For differentiation from competitors, using hydraulic components and hydraulic controls, which are our strengths, is essential, and we decided to develop optimal hydraulic components and machine control technology for ICT hydraulic excavator systems with "high accuracy, high efficiency, and low fuel-consumption" as our key words. One of our goals is to strengthen our ability to propose systems to customers and offer value-added products through these developments.

We have been developing products for hydraulic components used in conventional hydraulic systems for the purpose of reducing fuel consumption and enhancing efficiency. Therefore, multi-control valves, which play a core role in controlling hydraulic components, are developed with a focus on reducing pressure loss and increasing actuator speed. However, ICT hydraulic excavator systems are required to have high accuracy, as it is important to minimize errors between the target and actual values in construction, so it is difficult to meet the requirements with the conventional hydraulic component characteristics and hydraulic circuit configuration.

That is why we decided to develop a hydraulic system that achieves a good balance between accuracy and speed by improving the characteristics and circuit configuration of hydraulic components — mainly multi-control valves. In addition, we decided to develop our own machine control technology by optimizing the component characteristics and configuration and using robot control technology, which is excellent for having the trajectory follow the target value for construction so as to overcome differences in hydraulic system control between conventional hydraulic systems and ICT hydraulic excavator systems.

4 Technical challenges

Trajectory tracking is adopted as a basic function for industrial robots and is widely used in industrial fields, including automotive assembly lines and semiconductor production equipment. However, to achieve the same control for hydraulic excavator attachments the following must be taken into consideration.

- Non-linearity: Control is affected by hydraulic oil compressibility and leak flow rate.
- Self-weight: The size and weight of the attachment are much larger than general industrial robots.
- Delay in response: Actuators are driven via the hydraulic oil discharged from the hydraulic pump.

① Compensation for non-linearity

Hydraulic systems, in which hydraulic cylinders are driven, have strong non-linearity attributable to hydraulic characteristics, such as compressibility, leak flow rate, and hysteresis. To enhance the ability to track a trajectory, the speed of each axis needs to be controlled in an accurate and responsive manner, but the non-linearity is an obstacle to achieving this.

In addition, hydraulic excavators extend their heavy attachment forward and stand on unstable surfaces, and so do not always have a balanced weight configuration. Therefore, minor factors, such as rapid attachment acceleration or deceleration, cause body vibration.

Regardless of body size, even slight vibration causes a large displacement in the bucket tip position, so reducing body vibration is vital to achieving precise construction. However, if the controllability of each axis deteriorates due to non-linearity, the manipulated variable increases accordingly, inducing body vibration.

For this reason, compensating for non-linearity is necessary to achieve high body stability and trackability.

② Compensation for self-weight

Industrial robots compensate for the torque of each axis based on the dynamic calculation results to compensate for the effect of their own weight, thereby improving trajectory trackability. Hydraulic excavators have heavy, large attachments, and so are more greatly affected by their own weight. In addition, hydraulic cylinders have non-linearity specific to hydraulic components, so their torque cannot be controlled as precisely as the torque of electric motors used in robots. Hydraulic excavators are configured so that hydraulic oil is supplied to multiple actuators from one oil pressure source. When multiple axes operate in conjunction with one another, compensating for individual axes requires controlling hydraulic oil allocation precisely. Therefore, the gravity compensation for industrial robots cannot be applied, and compensation specifically for hydraulic systems is required.

③ Compensation for delayed response

Industrial robots have their axes driven directly by electric motors but hydraulic excavators have their actuators driven via hydraulic oil discharged from hydraulic pumps, causing a relatively large delay in response.

For conventional hydraulic excavators, this response delay is compensated for by the operator based on their experience. For example, in grading work, the boom is moved up and down in conjunction with the movement of the arm, but the operator knows from their experience that at the start of operation, it is too late to operate the boom after confirming the arm operation and operates the boom and arm almost at the same time.

Machine control technology requires the ability to track various trajectories and high responsiveness like experienced operators have, so delays in response needs to be compensated for.

5 Efforts we have made so far

(1) Development of hydraulic systems

Compensation for non-linearity: Hydraulic systems use their own weight as energy to return some of the hydraulic oil at the outlet to the inlet, thereby achieving a good balance between high-speed operation and high energy efficiency. At this time, the amount of hydraulic oil returned to the cylinder inlet (the regeneration flow rate) changes depending on the posture and load, which is a major cause of non-linearity.

Therefore, we established the technology to accurately estimate the regeneration flow rate by using the pressure sensor on the cylinder, thereby achieving improved controllability with speed control that takes the regeneration flow rate into account. **Figure 2** shows the configuration of the regeneration section of the hydraulic circuit. **Figure 3** shows a schematic of the regeneration flow rate estimation logic.

The regeneration flow rate is estimated based on the pressure sensor value of the cylinder and the estimated opening values of the regeneration valve and regeneration cut valve. At this time, the estimation accuracy of the control flow rate of the regeneration valve is important. We adopted a new calculation method, thereby achieving improved estimation accuracy.

For stable, efficient operation of the cylinder, it is important to balance the flow rates at the inlet and outlet of the cylinder. With the developed method, this balance can be maintained, even when the regeneration flow rate changes, by compensating for the cylinder inlet flow rate based on the estimated regeneration flow rate.

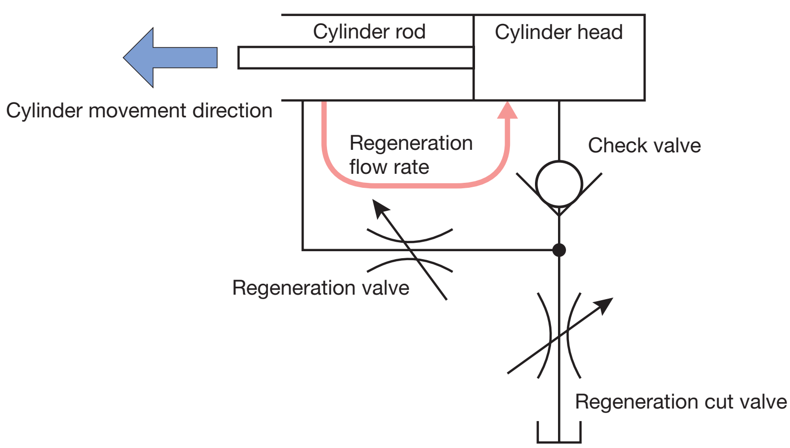


Fig. 2 Hydraulic circuit configuration (regeneration section)

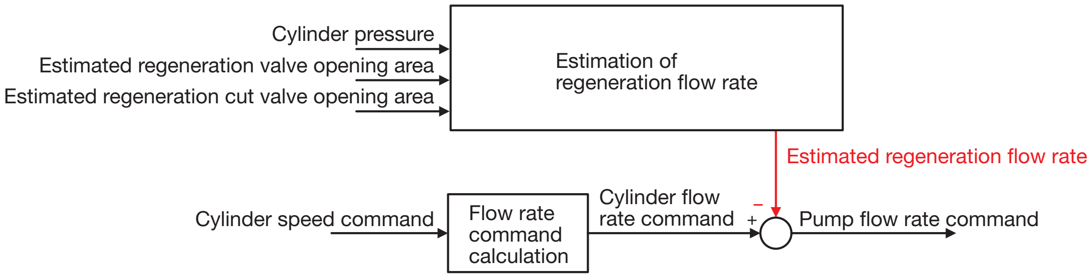


Fig. 3 Estimation logic for regeneration flow rate

This has enabled efficient regeneration and linear cylinder response.

Compensation for self-weight: We developed a gravity compensation method with flow control using an independent metering valve (IMV) and a pressure sensor. The control method with an IMV controls the inlet passage meter-in MI and outlet passage meter-out MO individually and optimally controls the MI and MO according to the operating state, thereby providing improved controllability of cylinder speed. This control method has higher flexibility than conventional control methods.

The gravitational action on the link mainly influences the MO-side cylinder pressure. Gravity compensation is given with precise MO control that uses the characteristics of the IMV and accounts for cylinder pressure.

The target speed of each axis is converted to the target flow rate for the MO. The required opening area is calculated based on the target flow rate and the differential pressure of the MO valve obtained from the cylinder pressure sensor. The MO valve is electronically controlled so that the actual opening area follows the required opening area, thereby allowing the cylinder speed to precisely follow the target value. At this time, compensation is applied to the electronic control of the valve, including valve characteristics, thereby achieving higher and more stable control accuracy. Such precise control of the MO of each axis has made it possible to compensate for the effect of gravity and at the same time optimize hydraulic oil allocation at the time of complex operation, thereby enabling independent control of each axis even in hydraulic systems using the same hydraulic oil source for different axes.

This has achieved gravity compensation that can mitigate the effects of posture and load on hydraulic systems.

(2) Development of machine control technology

The automatic grading assist control is a machine control technology and automatically moves the boom up in relation to the movement of the arm when the bucket tip is about to dig deeper than the target leveled ground surface by the operator’s operation as shown in **Fig. 4**.

Also, this control automatically moves the boom down when the bucket tip is about to move away from the target leveled ground surface. To achieve such operations, the controller constantly calculates the postures of the

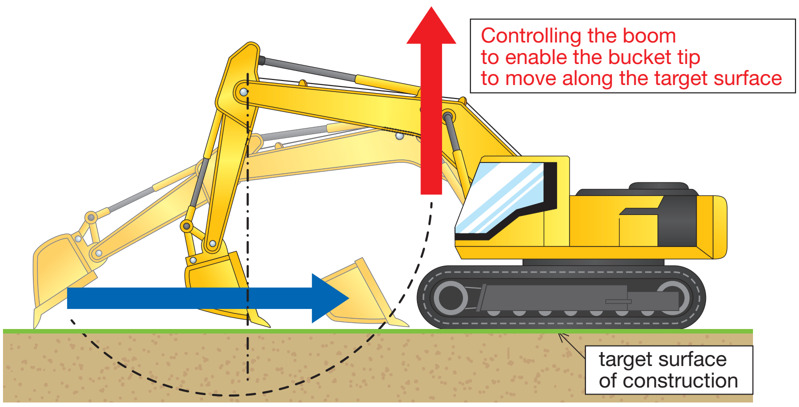


Fig. 4 Machine control technology (automatic grading assist control)

hydraulic excavator and attachment based on sensor information.

To accurately move the arm, boom, and bucket of a hydraulic excavator, the hydraulic oil from the hydraulic pump is discharged at the optimal flow rate and is allocated optimally to each actuator by the multi-control valve.

To accurately move the arm, boom, and bucket of a hydraulic excavator, the hydraulic pump discharges the hydraulic oil at the optimal flow rate and the multi-control valve controls the flow rate optimally to each actuator.

In addition, position feedback control is performed so that the bucket tip position calculated based on the signals from the sensors installed on the attachment follows the target leveled ground surface.

Compensation for delayed response: As shown in **Fig. 5**, with the attachment extended, the boom moves up more than the operator's operation calls for. When the arm is nearly vertical to the ground, the amount of upward boom movement is smaller.

At this time, if the control gain for the boom is constant with the attachment extended, the boom cannot follow the operation of the arm due to the delayed response, resulting in the tip digging in too much. When the arm is nearly vertical to the ground, boom operation is more sensitive to arm operation, causing hunting due to the delayed response. To solve this problem, we adopted a control for compensating for the manipulated variable of the boom according the posture of the hydraulic excavator. This control has achieved stable, smooth grading work with the attachment operation speed maintained.

6 Efforts for future hydraulic excavator systems

Many construction machinery manufacturers and surveying instrument manufacturers have put semi-automatic systems for assisting operators by means of

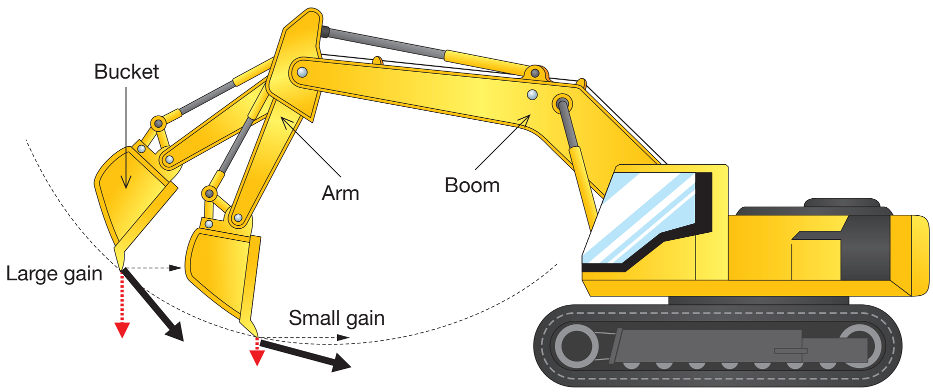


Fig. 5 Boom control correction based on hydraulic excavator posture

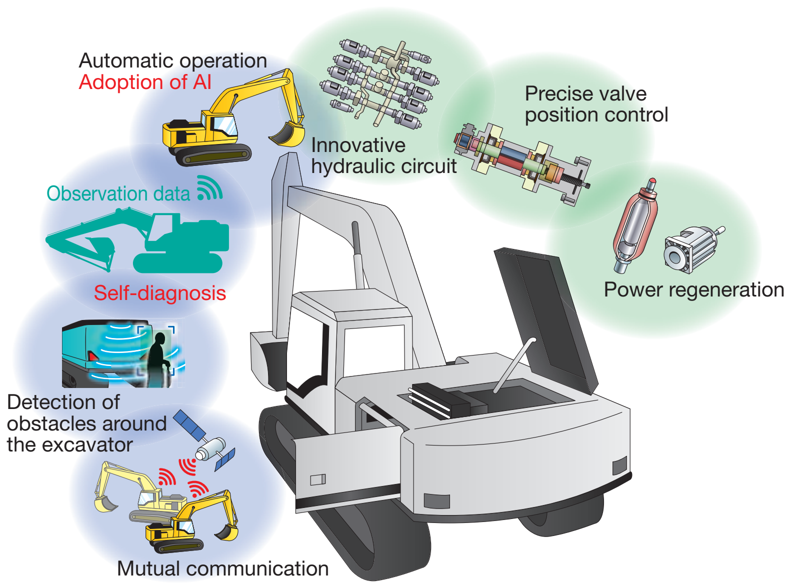


Fig. 6 Concept of future system

machine control on the market and are conducting research and development for automation and autonomy as the next step.

Kawasaki is also developing machine control systems with the aim of developing systems that use innovative hydraulic systems at their core and support automation and autonomy. Using hydraulic technology, which is one of Kawasaki's strong points, we are developing innovative hydraulic systems suitable for automation and autonomy as shown in **Fig. 6** for differentiation from competitors.

(i) Innovative hydraulic system

With the aim of enhancing both performance and cost efficiency, we are conducting research and development on hydraulic systems suitable for automation and autonomy. More specifically, we are working to further reduce pressure loss, reduce fuel consumption and enhance operational efficiency with energy regeneration, and achieve a good balance between high maneuverability and high trackability. We are also conducting research on hydraulic components and systems that enable improvement of maneuverability and controllability with precise, linear attachment operation, and further cost efficiency improvement through the integration and elimination of functions, and redesigning of the configuration and structure.

(ii) Automation and autonomy

Taking a comprehensive look at construction sites, research and development are underway on unmanned construction where multiple construction machines are automatically linked with one another. This represents the transformation of construction sites into the equivalent of an automated factory. Kawasaki is conducting research and development on robotizing construction machines by using the technologies it has accumulated for industrial robots. More specifically, Kawasaki is conducting research aimed at realizing ICT hydraulic excavator systems having higher work efficiency and finishing accuracy than experienced operators, including the system for hydraulic excavators themselves to learn autonomously and create optimal operation plans, the system for detecting humans and obstacles around the excavator and adjusting the operation plan, and the system for detecting the soil condition and adjusting the excavation method and pattern.

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Conclusion

We are developing the machine control technology for assisting operators as an effort to develop ICT hydraulic excavator systems.

We will be working to further enhance our capabilities of developing ICT hydraulic excavator systems as well as proposing these systems to customers and developing the most suitable components for these systems, thereby contributing to improving the performance and functionality of industrial vehicles, including hydraulic excavators.