# Development of Electro-hydraulic Actuators for Robots

*The first industrial robot in Japan (Kawasaki-Unimate) was hydraulically actuated, but since the late 1980s, electric motor actuation has been replacing hydraulic actuation. In recent years, however, humanoid robots, which are increasingly expected to be used mainly at disaster sites, need to be durable and powerful, and hydraulic actuation has been recognized once again.*

*Kawasaki is developing Hydro Servo Muscle, which is an electro-hydraulic actuator that is characterized by its high impact resistance and power density and is intended to be applied to the legs of Kaleido, which is a humanoid robot Kawasaki is developing.*

## Introduction

In recent years, there are increasing expectations for life-size humanoid robots, which do various tasks at disaster sites and in extreme environments in place of humans by using tools for humans.

## 1 Background

Hydraulic actuation technology has mainly been used for construction machinery that requires high power and high environment resistance, and electric motor drive technology has been used in the robot field where high speed and high accuracy are required. Recently, however, the trend is to use hydraulic drive for humanoid robots and other robots that require powerful movements in severe environments.

## 2 Humanoid robots

Amid such circumstances, Kawasaki is developing humanoid robots as other manufacturers are. Currently, Kawasaki's humanoid robot has a total height of 1.75 m and a weight of 84 kg, and it has 32 degrees of freedom in total for all the joints, including the legs and arms, driven by electric actuators. Achieving the same size as humans requires pursuing size and weight reduction in each part and eliminating projections that humans do not have to prevent interference in each section. Also, low-speed, high-thrust motion is required for standing up, and high-speed, low-thrust motion is required for walking.

Therefore, actuators for humanoid robots are required to have small size and weight, a good balance between high-speed, low-thrust motion and low-speed, high-thrust motion, high reliability, and high impact resistance.

## 3 Overview of actuators

### (1) Development concept

We decided to develop actuators intended mainly for use in the legs as shown in **Fig. 1** where both high speed and high thrust are required. For electric actuators, there is a risk of damaging the gear reduction mechanism due to unexpected impact during work, but for hydraulic actuators, which have higher impact resistance, it is possible to provide humanoid robots with a function to avoid damage by using oil compressibility and a highly responsive pressure relief mechanism.

### (2) Equipment configuration and specifications

**Figure 2** shows the equipment configuration and hydraulic circuit of the electro-hydraulic actuator. **Table 1** shows the specifications of the electro-hydraulic actuator. The servo motor, hydraulic pump, valve unit, and hydraulic cylinder have been integrated into one unit, thereby forming a compact construction without piping between hydraulic devices. In addition, a closed-circuit configuration has been adopted that feeds oil to the cylinder according to

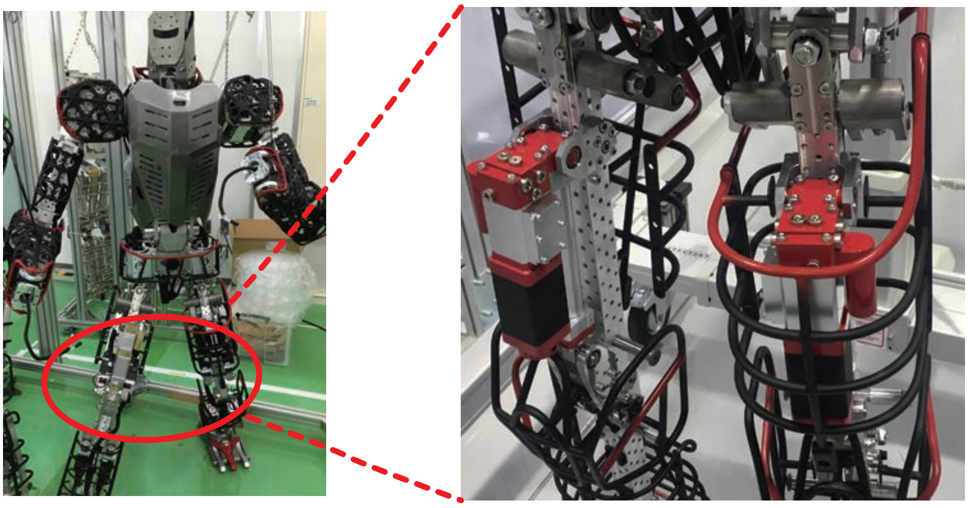
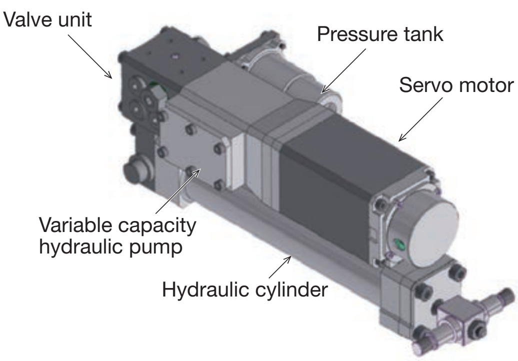
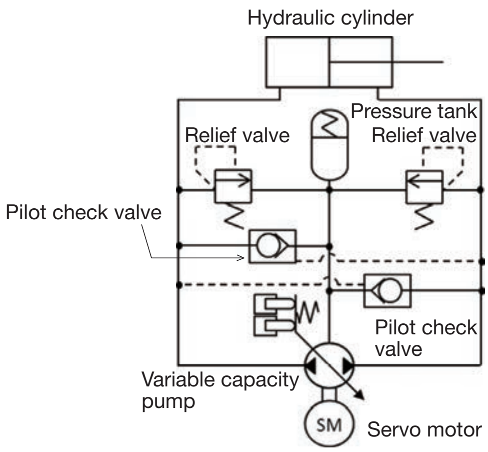


Fig. 1  Applying this technology to the legs of humanoid robot Kaleido




(a) Equipment configuration




(b) Hydraulic circuit

Fig. 2  Configuration of electro-hydraulic actuator

Table 1 Specifications of electro-hydraulic actuator

| | |
|---|---|
| Maximum thrust 〔N〕 | 6, 000 |
| Maximum speed 〔mm/s〕 | 200 |
| Head diameter 〔mm〕 | 22 |
| Rod diameter 〔mm〕 | 8 |
| Stroke 〔mm〕 | 156 |
| Impact resistance function | Yes |

the servo motor speed.

This actuator, like other electric actuators, can be driven by using a robot controller. By detecting the leg joint angle with a separate encoder, the servo motor is controlled to position the cylinder so that the desired angle can be achieved.

## 4 Details of development

In order to achieve size and weight reduction of the actuator, a good balance between high-speed, low-thrust motion and low-speed, high-thrust motion, and high reliability as well as high impact resistance, we developed the following technologies and methods.

**(1) Size and weight reduction**

(i) Developing a compact valve unit

To minimize the valve unit size, we set the number of valves to the minimum value required to realize the required functions and developed a new manifold containing specially designed valves and oil passages. The following parts need to be developed for the valves that make up the valve unit shown in **Fig. 3**.

① Relief valve

To release excessive external force that the actuator has received immediately and accurately by oil pressure, there is a need to achieve high responsiveness and reduce override characteristics, which cause the relief pressure to increase as the flow rate increases.

② Pilot check valve

When the actuator retracts, the valve is opened with low pump discharge pressure to return extra oil from the head caused by the difference in cylinder area to the pressure tank. In addition, the pressure loss is minimized to allow oil from the tank to flow smoothly into the actuator when the actuator advances.

To achieve the above functions and performance, we developed a compact cartridge valve. We reduced the number of oil passages in the manifold to a minimum and arranged the valves so that the minimum required thickness could be achieved around the oil passages, thereby achieving a manifold size of less than 40 mm square, which is the same as the servo motor size. In addition, we designed the internal diameter, length, and crossing shape of oil passages so that the smallest pressure loss could be achieved.

(ii) Integrating the valve unit, unit cover, and tank into one unit

Common hydraulic actuators consist of valves, cylinders, a pump, a tank, and other blocks connected to one another. Integrating these blocks into one unit eliminates the need to seal between blocks and provides enhanced flexibility in the layout of oil passages, thereby achieving further size reduction.

Therefore, we integrated the valve unit, cylinder head cover, pump valve cover, and tank connection block into one unit as shown in **Fig. 4**, taking the following into account.

① Optimizing the oil passages connecting the parts

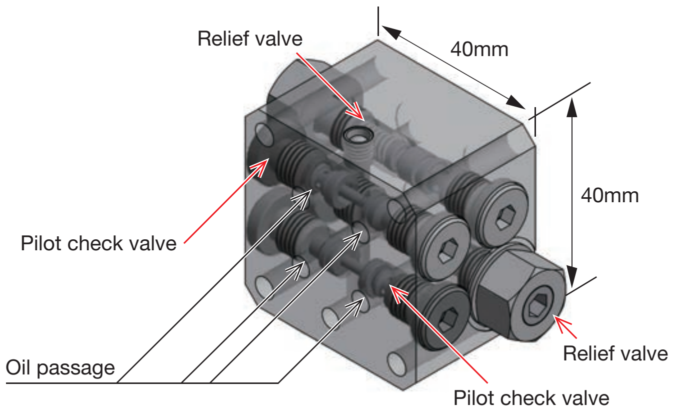



**Fig. 3 Valve unit**

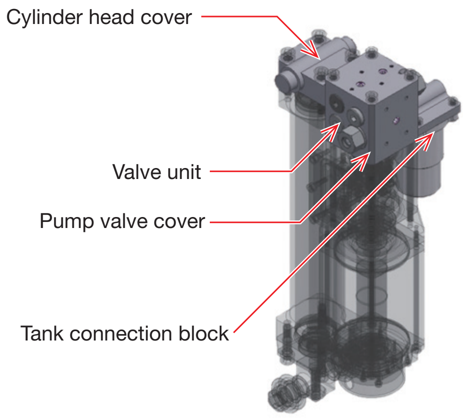



**Fig. 4 Integration of components**

The parts were connected linearly with the valve oil chamber, thereby achieving an efficient piping layout..

② Rethinking the tank volume

Tanks designed in conformity with general industrial machinery standards are too large. For application to robots, we set the tank volume to 1.1 times the minimum required volume rather than 4.2 times.

With these efforts, the distance between the actuator mounting position and pump mounting position was significantly reduced.

(iii) Integrating the hydraulic pump and servo motor into one unit

Initially, the hydraulic pump and the servo motor, which drives the hydraulic pump, were arranged coaxially with each other, and the shafts were spline-coupled. However, while using belts and gears reduces drive transmission loss, it leads to size increase and causes insufficient strength in the joints. To solve this problem, we integrated the drive shafts of the pump and motor into one unit as shown in **Fig. 5**. For this integration, we optimized the flange shape for connecting the pump and motor, oil seals, and bearings.

For the bearings used for the pump and motor, we used the same bearing in the middle between the pump and bearing, thereby reducing the number of parts and size. In addition, to prevent stress from being generated in the shaft, we adopted a slide bearing on the pump-side shaft end.

**(2) Achieving a good balance between high-speed, low-thrust motion and low-speed, high-thrust motion**

To achieve a good balance between high-speed, low-thrust motion and low-speed, high-thrust motion, which is required for humanoid robots, we needed a variable capacity hydraulic pump. Based on the swash plate piston pump technology we have accumulated in making construction machinery and industrial machinery, we developed a variable capacity swash plate piston pump with displacement from 0.75 $cm^3$ to 1.5 $cm^3$ as shown in **Fig. 6**.

This pump can supply high-pressure hydraulic oil to the actuator without causing an overload in the servo motor by optimally controlling the pump capacity according to the load pressure of the actuator. In addition, this pump has a mechanism to control the pump capacity in a stepless fashion according to the load pressure by optimally balancing the oil pressure generated on the piston and the spring load holding the slash plate angle. This mechanism not only efficiently converts the output from the servo

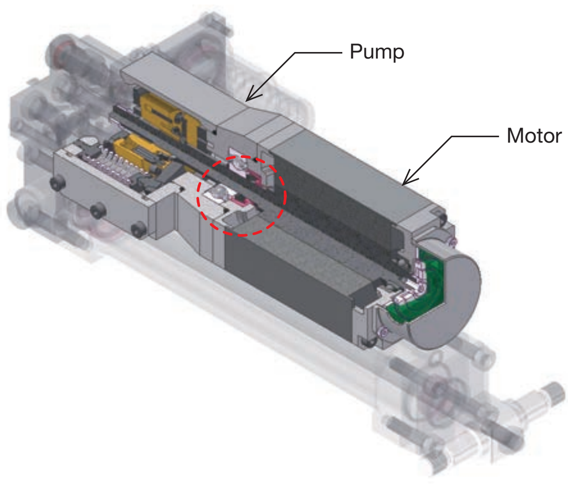



**Fig. 5 Integration of shaft**

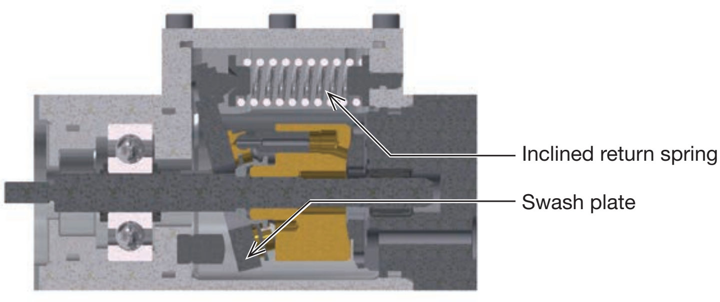



**Fig. 6 Swash plate type variable displacement axial piston pump**

motor to hydraulic energy, but also provides a simpler swash plate drive mechanism without a solenoid switching valve, thereby contributing to size and weight reduction.

The conventional system uses a solenoid switching valve to adjust the capacity in two steps; therefore, in order to allow the pump to operate continuously without causing an overload in the servo motor, there is a need to switch the capacity from high to low when the pressure rises, wasting some of the power. The pump we developed this time adjusts the capacity in a stepless fashion when the pressure rises and converts the power from the servo motor efficiently to hydraulic energy, thereby achieving high-speed, high-thrust motion in the entire pressure range with less power.

**(3) Improving reliability**

(i) Vibration damping control of the hydraulic cylinder

**Figure 7** shows a block diagram representing position control in the servo motor control system of this actuator. The actual position data is fed back with an encoder, and

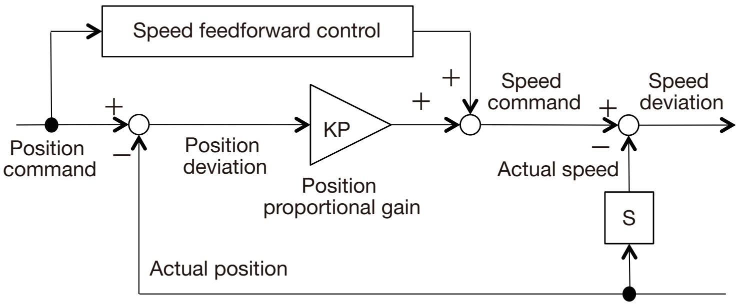



**Fig. 7 Block diagram of position control**

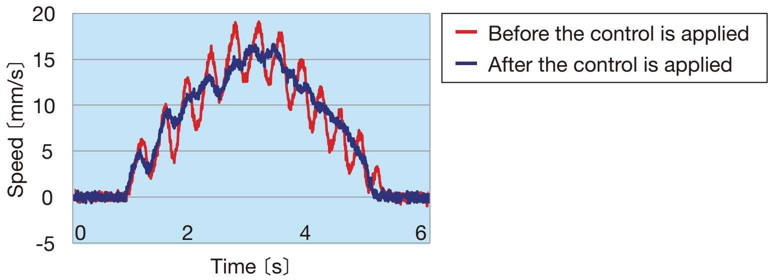



**Fig. 8 Effect of vibration suppression control**

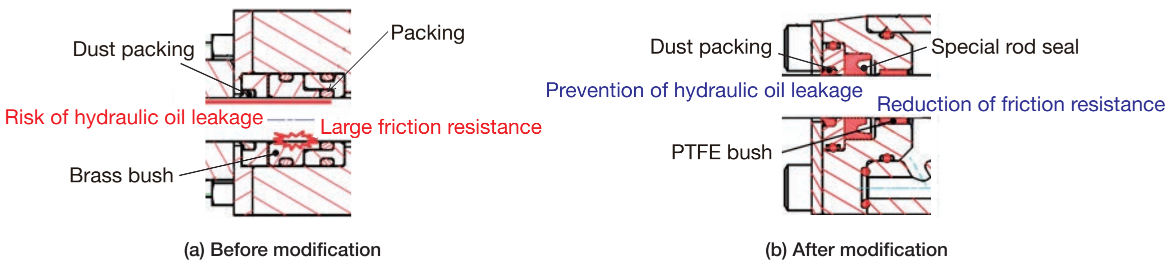



**Fig. 9 Modification of cylinder bearing rod**

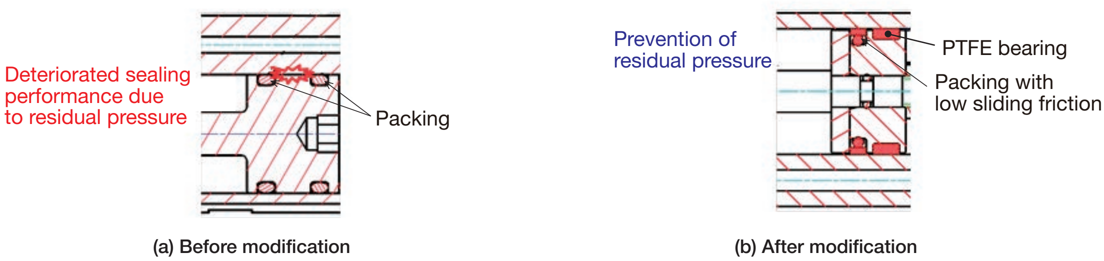



**Fig. 10 Modification of cylinder bearing piston**

speed commands are given to the motor based on the deviation between the actual position and position command. Because the position proportional gain is adjusted so that the responsiveness can be maintained even at high loads or speeds, the position proportional gain becomes too large at low loads or speeds, causing persistent vibration or hunting. This is attributable to a delay in the actuation of the hydraulic cylinder after the servo motor is activated and oil is discharged.

To prevent this, we developed a function to detect a low load or speed based on the motor current and motor speed and appropriately adjust the position proportional gain and gain in speed feedforward control. **Figure 8** shows the waveforms of the hydraulic cylinder speed at low load and speed before and after this control was applied. As shown in the figure, continuous vibration has been reduced significantly.

(ii) Modifying the cylinder bearing

We modified the cylinder bearing rod and piston. The rod initially consisted of a brass bush, seals, and dust packing, but with this configuration, there is a risk of hydraulic oil leaking if an external impact load is applied in the axial direction of the rod. In addition, the brass bush has a large frictional resistance. Therefore, we adopted a specially designed rod seal with enhanced pressure resistance as shown in **Fig. 9** and changed the bush material to PTFE, thereby eliminating the risk and problem.

The piston was initially structured so that it was supported and sealed by the piston seals. Depending on the operating conditions, however, there was a risk that hydraulic oil may intrude between two seals, resulting in deteriorated sealing performance due to residual pressure. To solve this problem, one PTFE bearing and one piston seal were arranged next to each other as shown in **Fig. 10**.

## Conclusion

Mounting electro-hydraulic actuators on humanoid robots is the challenge we are facing to achieve synergy between the hydraulic technologies and robot technologies Kawasaki has. Not only can this actuator be used for robots, but for autonomous mobile systems, production lines, and industrial machinery. As public relations efforts, we exhibited this actuator at IFPEX2017 and IREX2017 as a reference exhibit and registered its trademark as Hydro Servo Muscle.

Some people say that hydraulic technology is already mature. However, we will be pursuing size and weight reduction and user-friendliness to realize a system where both hydraulic technology and electric technology can be used, thereby creating something new.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