1. Introduction

Industrial robots are increasingly being used in next-generation on-site manufacturing systems in response to global competition. The background to this progress includes: 1) Increased automation for securing a stable factory work force; 2) Shift to the cell production system to handle multi-product production to cope with the diversification of consumer tastes; 3) Demand for a manufacturing system that realizes low-cost design and operation in a short time; and 4) Demand for advanced work automation such as high-definition assembly, soft object conveyance, and high-speed handling.

However, this type of advanced work is difficult to automate, and so it is necessary to build an intelligent system that uses various sensors such as force sensors and vision sensors.

To meet these demands, we have developed a cell production system in which the assembly of thermal relays is automated by a robot equipped with an intelligent function (Fig. 1).

This report describes the function and control of an especially important force sensor system among intelligent systems, and an example of its application to robots.

2. Function and Control Methods of Force Sense System for Robots

2.1 Force sense function

The force sense function provides the sense of force to a robot by using the information from a 6-DOF (degrees of freedom) force sensor. This function can be used to perform advanced work that needs fine force adjustment/sensing and labor saving on teaching, which have not been possible by robots up to now. The main features are as follows.

(1) A robot can be softly controlled and moved while imitating an object workpiece, and as a result, it is easier to fit machine parts requiring accuracy.

(2) Since a robot can move while pressing an object with a constant force in any direction, polishing and buffing can be performed.

(3) The softness and contact sensing conditions of the robot movement can be changed during the movement of the robot, so when the softness is changed during pin insertion, the robot can be controlled so as not to damage the surface of the workpiece at the initial insertion, and then the pin can be inserted firmly by stiffly controlling the robot.

Fig. 1 Cell manufacturing system using a robot (2011 International Robot Exhibition)
(4) The contact conditions can be sensed, interrupt signals can be produced, and the movement of the robot can be changed. Accordingly, when a force that may damage the workpiece is sensed, this feature is useful for error recovery such as changing the movement direction.

(5) Position and force information can be acquired at the time of contact, and therefore, position sensing can be performed with high accuracy by contact. In addition, the contact state of the workpiece and the robot hand, which are hard to view in the teaching work, can be checked. This reduces the teaching work.

(6) The force data in synchronization with the position data is stored as log data and can be easily displayed in a graph using PC S/W (RT ToolBox2) for a robot, which is useful for analysis when an error occurs.

(7) Log data can automatically be transmitted to a personal computer via FTP for storage in a database, making it possible to trace the assembly quality later on.

(8) If a sensor detects any force beyond the setting value, the robot can be stopped to protect the workpiece and the force sensor.

2.2 What is force sense control?
This function controls the robot so as to reach preset values of reaction force and softness when the robot contacts surrounding objects.

2.2.1 Force control (control of press force)
When a force command is set in the force sense control, the robot works autonomously while correcting the position so as to obtain the reaction force [N] set up in the force command beforehand when the force control is enabled. However, the robot works in the direction opposite to that of the force command value when an external force does not act on the robot (when not contacting). The working speed at this time is proportional to the force control gain (* refer to Section 2.3.1).

2.2.2 Stiffness control (control of softness)
The softness of the robot in the stiffness control is set using a stiffness coefficient. The larger the value, the stiffer the movement of the robot, and vice versa.

Figure 2 is an example of a case where stiffness control is applied only to the tool Z-axis. When the stiffness coefficient of the Z direction is 0.5 N/mm and the teaching position is 5 mm below the contact surface, the force F generated on the contact surface is as follows:

\[ F = 0.5 \text{ N/mm} \times 5 \text{ mm} = 2.5 \text{ N} \]

2.3 Adjustment of force sense control
To accurately perform force sense control, it is necessary to suppress the responsiveness (gain) of the force sense control, and the vibration (damping).

2.3.1 Force sense control gain
The force sense control gain is a parameter for adjusting the responsiveness of the force control. The higher the setting value, the higher the responsiveness for a force command and stiffness command (refer to Table 1). However, if the value is raised too much, the working state becomes unstable due to hypersensitive reaction at the time of contact.

<table>
<thead>
<tr>
<th>Object stiffness (N/mm)</th>
<th>Force sense control gain</th>
</tr>
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<tbody>
<tr>
<td>1.0</td>
<td>100.0</td>
</tr>
<tr>
<td>10.0</td>
<td>8.0</td>
</tr>
<tr>
<td>100.0</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Since this force control gain is affected by the stiffness of a contact object, it is desirable to change the gain setting depending on the object. However, when the force sense control gain is zero, correction by force control is not performed, and the normal position command is performed. Therefore, when changing the gain setting during work, it is possible to switch over from stiffness control to position control and vice versa.

Gain adjustment example
(1) Move the robot at a low speed (= JOG OVRD 5%) in the JOG mode in the axial direction where the force sense control (force command control or stiffness control) is enabled, and let the robot touch a work object.

(2) Lower the gain when the robot shows such behavior as rebounding on the side opposite to the moving direction at the time of contact.

2.3.2 Damping coefficient
When using the force control (force command control or stiffness control) and the behavior of the robot vibrates, the damping coefficient is adjusted. The bigger the value, the greater the vibration suppression effect. However, the corrective action for a sudden force
change at the moment when contact is made with a workpiece, etc. becomes slow, and so the force acting on the workpiece increases. The actual damping adjustment is changed as needed after adjusting the force sense control gain mentioned above.

### 2.4 Force sense function and monitoring

The force sense functions can be set as indicated in Table 2. Using these functions, the motion change, the labor saving on teaching by monitoring the force sense data, and the logging of force sense data can be performed.

#### Table 2 Force sense function list

<table>
<thead>
<tr>
<th>Function classification</th>
<th>Details</th>
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<tbody>
<tr>
<td>Force sense Interrupt signal</td>
<td>Monitors the state for a force sense setting value. (Rising and falling signals for force sense setting can be acquired.)</td>
</tr>
<tr>
<td>Data latch</td>
<td>Holds the sensor data and position data of the instant when the force sense setting value is exceeded.</td>
</tr>
<tr>
<td>Force control (TB) Contact sense</td>
<td>Stops the jog movement at the instant the designated force (moment) is exceeded.</td>
</tr>
</tbody>
</table>

#### 2.4.1 Ease of teaching by force sense function

If a sensed value exceeds the value set beforehand during the force sense control, JOG motion automatically stops and a buzzer sounds to notify the operator. This protects the workpiece and the force sensor. In addition, the color of the force sensor data display field in the teaching box can be changed to ensure visual recognition.

Moreover, the teaching work is simplified because a robot can be softly controlled by the stiffness control to teach the insertion completion position while the robot imitates the insertion shape.

#### 2.4.2 Force sense monitoring function

The force sense monitoring function can be used to display the current value and the maximum value of the force sensor in real time. For example, it is possible to teach the position while watching the state of contact with a workpiece and viewing the data displayed on the force sense monitor. Moreover, the force sense monitor includes an edit display of the force sense parameters, and the changes and settings of the control modes and control characteristics of the force sense control can easily be confirmed (Fig. 3).

#### 2.4.3 Log file and viewer function (RT ToolBox2)

As for the log file of force sense data, the relationship between the position and force is easily displayed in a graph by pressing the button on the main screen of the force sense control of ToolBox2 RT (Fig. 4). In addition, it is possible to transfer to a PC via FTP the files of logged data on the robot controller by an exclusive instruction, and to trace the assembly quality at a later date.

#### 2.5 Force sense control S/W

Figure 5 shows a block diagram of the force sense control S/W. Sensor data processing is performed to receive the force sensor data from the force sense I/F unit S/W via SSCNET III; force sense control is performed using the data; and the logging of force sense data is performed in the motion control unit of the robot body control S/W in real time (Fig. 5). The control flow is shown in Fig. 6.

The processing of force sense control is corrected by using the latest force sensor data for the position command generated in a motion task to output the data to a servo. The force sensor data is transmitted via SSCNET III communication at a fixed cycle. In order to reflect the latest data in the processing of force sense control, sensor data processing that is executed at a fixed cycle is newly added, and the acquisition and acceptable values of force sensor data are checked.
3. Application Example of Force Sense System

3.1 Insertion work
With the horizontal direction softened, the insertion work is performed in a push-in direction (Fig. 7). If a force exceeding the designated value is applied at the time of insertion, an error signal can be generated to stop the motion, which makes it easier to carry out the insertion work and error sensing.

3.2 Polishing work
A robot searches for an object while moving in the Y-axis direction (Fig. 8). When the tool finds the object, it moves in the X-axis direction while applying a constant force to the object. If a force exceeding the designated value is applied, an error signal is generated to stop the motion.

3.3 Connector insertion work
A connector is searched for on the X-Y plane (Fig. 9). When the connector is found, the X-Y coordinate values of the center position are calculated for the insertion.

4. Conclusion
We have described the function and control of an especially important force sensor system among intelligent systems, and examples of its application to robots. The force sensor can be used for the fitting work of machine parts for which accuracy is required, for buffing and polishing work, and for connector insertion work, etc. Moreover, a broad range of applications can be achieved such as the usage for error recovery operation, labor saving on teaching, and failure analysis using the log data when an error occurs.

We will strive to enhance the response of the force sensor and make the application easier to use for greater customer satisfaction.