Application of i-WRIST™ to the Robot Wrist Joint

1. Introduction

Industrial robots have been making a significant contribution to factory automation in manufacturing by increasing productivity and production volume. In manufacturing facilities, production line efficiency has been pursued through the deployment of robots, special-purpose machinery and workers. However, due to a shortage in the labor population, the demand for automating refined manual operations, which has been traditionally difficult with conventional robots, is increasing.

NTN adopted its proprietary parallel link mechanism to develop a compact i-WRIST™ (previously known as Parallel Link High Speed Angle Control Equipment (1-5)) which has a wider operating range with two degrees of freedom for fast and highly accurate angular positioning, and is actively pursuing the development of broader applications in a configuration with a linear motion actuator. In this article, we describe the application of i-WRIST™ to actuator for robot wrist joints.

2. Overview of parallel link mechanism

2.1 Basic configuration

Fig. 1 shows a conceptual diagram of the parallel link mechanism (hereafter, link mechanism) of i-WRIST™. The link mechanism takes three rows of link systems, which consist of a base-end side arm, central link and top-end side arm, (the 1st - 3rd in Fig. 1) placed parallel between the base-end part (which serves as the base) and top-end part (which is used to install the end effector), making each link system joint a turning pair. The structure of this unit has pre-loaded angular contact ball bearings for the turning pair to reduce friction and to eliminate the gap in the joints.

The attitude of the top-end part is defined by the bend angle $\theta$, which is the inclination angle between the central axis of the base-end part and central axis of the top-end part, and the revolving angle $\phi$ around the central axis of the top-end part looked at from the central axis of the base-end part.

The attitude of the top-end part ($\theta$ and $\phi$) is determined by fixing the attitude of two base-end side arms in each link system. i-WRIST™ uses synchronous control of three motors to improve repeated positioning accuracy and rigidity.

Fig. 1 Conceptual diagram of i-WRIST™ mechanism

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2.2. Features

The following are the main features of the link mechanism when it is applied to actuators for robot joints.

(1) **Wide operating range**

It has a very wide operating range with a maximum bend angle $\theta$ of 90° and revolving angle $\phi$ of 360°×n (unlimited), which allows for a wide range of approaching options to the subject from different angles.

(2) **High-speed/highly accurate operation**

Fast and highly accurate movement, particularly for small attitude changes compared to multi-joint robots.

(3) **Lightweight/compact operable parts**

Positioning accuracy is improved in high speed operation by reducing weight and moment of inertia of operable parts through shifting the driving parts to the base-end side. This also makes the link mechanism more compact, which is desirable for avoiding interference of the apparatus even when the operable range is broad.

(4) **No singularity in operating range**

Teaching can be done relatively easily because there is no need to care for singularity.

(5) **Easy handling of cables and tubes**

Cables and tubes for hands and grippers to be installed at the top-end part can be run through the internal space of the link mechanism, which allows them to be easily handled. In addition, cables will not be twisted even with continuous rotation in one direction.

2.3 Comparison with other types of robots

Table 1 shows a comparison of the robot combining i-WRIST™ and linear motion actuator with general vertical multi-joint robots and parallel link robots.

Fig. 2 shows the wrist joint (3-axis of top end) of a general vertical multi-joint robot.

The vertical multi-joint robot (Table 1B) has advantages such as larger operating range and heavier transferable load; however, reducing the tact time for small movement is difficult because of the large movement of multiple joints that results from even a small attitude change. Since the wrist joint of the vertical multi-joint robot consists of three rotational joints (revolving axis, bend axis and rotational axis), and the revolving axis needs to be moved a greater distance.

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**Table. 1 Comparison of other type robot**

<table>
<thead>
<tr>
<th>Structure</th>
<th>i-WRIST™</th>
<th>Linear motion actuator</th>
<th>Vertical multi-joint robot</th>
<th>Parallel link robot</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Features</strong></td>
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<tr>
<td><strong>Strong area</strong></td>
<td>Non-contact work, assembling of small objects</td>
<td>Welding, transfer</td>
<td>Transfer (pick and place)</td>
<td></td>
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<td><strong>Advantage</strong></td>
<td>- High speed positioning with small change of attitude</td>
<td>- Wide operating range</td>
<td>- Faster parallel movement</td>
<td></td>
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<tr>
<td></td>
<td>- No singularity in operating range</td>
<td>- Heavier transferable load</td>
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<tr>
<td></td>
<td>- Cables can be run through link internal space (Cables not twisted even when revolving operation is repeated)</td>
<td>- Smaller footprint when not in use (robot arm can be folded)</td>
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<tr>
<td><strong>Challenges</strong></td>
<td>- Certain footprint is required even when not in use</td>
<td>- Slower positioning speed with small change of attitude (depending on attitude)</td>
<td>- Larger equipment size relative to operating range</td>
<td></td>
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<tr>
<td></td>
<td>- Lighter transferable load</td>
<td>- Singularity in the range (special knowledge and experience needed for teaching)</td>
<td>- Certain footprint is required even when not in use</td>
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</table>
distance even for a small attitude change of the top end, smooth and quick motion is not its strong point. Therefore, it is not suitable for applications requiring fast and detailed assembling operation.

In addition, due to singularities in the operating range, operators with special knowledge and experience are required for teaching. Furthermore, robots with powerful and high-speed operation, other than collaborative robots, require fencing around the entire operational range for safety, which results in a larger required footprint.

General parallel link robots (Table 1C) are used mainly for pick and place applications due to their fast and parallel operation. The size of the entire equipment including driving mechanism and required footprint are large compared to the operating range.

Therefore, these robots do not usually fit in the existing space replacing workers for assembly work.

The robot proposed by NTN which combines the i-WRIST™ and a linear motion actuator (Table 1A) provides fast positioning speed and small overall movement for a small change of attitude. The i-WRIST™ is characterized by smooth and quick movement in any direction as its compact and lightweight parallel link mechanism at the top end has two degrees of freedom. Compared to the wrist joint of a vertical multi-joint robot which requires large movement of the revolving axis closer to the base for positioning, the i-WRIST™ is able to perform fast operation in all directions, which allows a shortening of tact time compared with the wrist joint of a vertical multi-joint robot. The vertical multi-joint robot's operating axes are serially configured; therefore, when the joint closer to the base (revolving axis of the wrist joint) needs to be moved a greater distance, the moment of inertia will be large preventing fast movement. On the other hand, i-WRIST™ can achieve high-speed and smooth movement because the moment of inertia is reduced by the compact parallel link mechanism. In addition, as the required space for installation is relatively small, it is considered to be a good fit for automating the process previously operated by workers.

3. Deployment for robot wrist joints

3.1 Actuator for wrist joints

We have made a prototype actuator (hereafter, actuator) for the robot wrist joint). Table 2 shows the main specifications of this prototype.

The actuator shown in Fig. 3 is made by reducing the size of i-WRIST™ in the radial direction for lighter weight and adding one degree of freedom for rotating the overall i-WRIST™. A concentric reducing mechanism is used for the rotating mechanism for rotating the overall i-WRIST™, so it is called the gear-drive type (hereafter, GD type).

In addition, the maximum bend angle of the link mechanism is 90°. Together with the revolving angle \( \phi \) of the i-WRIST™ and rotating angle \( \theta_z \) of the rotating mechanism, the rotation of the rotating mechanism can be converted to rotation around the rotating angle of the top-end part, equiangularly, in any bend angle.

Fig. 4 shows the structure of the revolving pairs serving as connections between the base end part and base end arm. The base end arm is connected to the output axis of the reducer unit installed on the base

![Diagram of actuator](image)

**Table 2** Specification of wrist joint actuator with GD

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (outer diameter x height)</td>
<td>( \phi 145 \times 278 \text{ mm (overall)} )</td>
</tr>
<tr>
<td></td>
<td>( \phi 102 \times 115 \text{ mm (link)} )</td>
</tr>
<tr>
<td>Weight</td>
<td>3 kg</td>
</tr>
<tr>
<td>Degree of freedom</td>
<td>3</td>
</tr>
<tr>
<td>Operating angle range</td>
<td>Bend angle: 90°  Revolving angle: 360° x ( \pi ) (unlimited)</td>
</tr>
<tr>
<td></td>
<td>Rotating angle: 360° (-175° to 175°)</td>
</tr>
<tr>
<td>Repeated positioning accuracy</td>
<td>( \pm 0.05^\circ ) or less</td>
</tr>
<tr>
<td>Transferable load (weight)</td>
<td>0.5 kg</td>
</tr>
<tr>
<td>Motor output</td>
<td>30 W x 3 (link)</td>
</tr>
<tr>
<td></td>
<td>50 W x 1 (rotating mechanism)</td>
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</table>
end part through the output side rotation drive. The rotation of the attitude control motor transmitted to the input axis of the reducer unit through the transmitter mechanism, such as gears and belts, is reduced by the reducer unit and transmitted to the base end arm through the rotation drive of the output side. The input rotation drive fixed on the base end arm is rotatably connected to the input axis of the reducer unit through the bearings. As such, the actuator a compact configuration while improving the supportive rigidity of the base end arm by incorporating the reducer unit within the base end arm structure which supports both ends of the rotational axis of the base end arm. In addition, the impact of backlash within the transmission mechanism can be reduced by placing the transmission mechanism on the input side of the reducer unit.

The GD type rotating mechanism has an advantage in placing the reducing mechanism of high reduction in compact configuration. However, since the motor for controlling angular rotation is positioned so that the rotating axis of the rotating mechanism is concentric with the central axis of the base end part, the drive mechanism does not have internal space. Therefore, the benefit of running the cables and tubes through the internal space of the link mechanism is not attainable.

On the other hand, the BD type, which uses a belt drive, places the motor of the rotating mechanism through the belt offset from the center of the rotating mechanism and therefore, can provide a large internal space. Fig. 5 shows the structure of the BD type. The BD type uses the belt for the link mechanism, as well, which allows the motor for attitude control to be positioned offset in parallel to the input axis of the reducer unit so that the height of the link mechanism is reduced. In addition, the ability of running cables for the motor for attitude control of the link mechanism through the internal space of the drive mechanism makes cabling work very easy and broadens the operating range of the rotation angle.

3.2 Linear motion dual-arm robot

Fig. 6 shows a linear motion dual-arm robot, which is configured with two sets of the combination of this actuator and a linear motion actuator with orthogonal axes (XYZ stage). In order to automate the existing manual work, the actuators are inclined at 45° toward center relative to vertical axis (Z axis) to facilitate collaborative work of the two arms. This linear motion dual-arm robot controls the attitude and position of the end effector with this actuator and the XYZ stage, respectively. It is able to perform various works by operating XYZ movement maintaining the attitude (asynchronous operation), and through synchronous movement of this actuator and the XYZ stage (synchronous operation).

The asynchronous operation allows for the approach attitude to be determined by controlling the attitude of the grabbed work with this actuator, then transfer it horizontally with the XYZ stage, which is
easily predictable by the operator when teaching. Therefore, it is suitable for assembly work. Fig. 7 shows operation of insertion/removal of shaft. The operation consists of insertion and removal of the shafts through holes in different angles, which is performed by determining the attitude of shafts toward the holes by this actuator and inserting/removing the shafts in linear motion with the XYZ stage.

The synchronous operation facilitates refined motion of the top end of the end effector. Fig. 8 shows placing of seals on a curved surface and Fig. 9 shows attaching/removal of O-rings, as some examples of the applications. In these examples, 3D tracing motion on a curved or plane surface, which has been difficult to automate, is achieved by the coordinated trajectory control with this actuator and the XYZ stage, in a combination of the parallel link mechanism and linear motion actuator.

As shown in these examples, NTN is currently pursuing application of i-WRIST™ to robot wrist joints for use in assembly tasks.

4. Conclusion

We have made an actuator prototype for a robot wrist joint based on the proprietary parallel link of two degrees of freedom with addition of one rotational degree of freedom, which achieves shape and motion close to the human wrist joint. In addition, we have built a prototype of a linear motion dual-arm robot that combines this actuator and a 3-axis linear actuator and are pursuing the development of robots which can achieve refined manual work by taking advantage of the smooth and fast operation unique to the i-WRIST™, verifying differences from vertical multi-joint robots and parallel link robots.

As we move forward, we will explore further downsizing this actuator and the entire system and pursue collaborative work with human workers by adding features such as a collision detection function. We are poised to contribute to the evolution of automation/robotics in manufacturing, to enable replacement of manual work, such as assembly of small parts, which has been difficult with conventional robots.
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