Approach to Development of Robotic Joint-Related Products

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In recent years, the robot industry has been expanding due to the market demand for improved productivity and labor savings. In particular, those represented by smaller size robots, typically collaborative robots, are expected to grow rapidly in the future. For various devices incorporated into robot's joints, such as reduction gears and rotary encoders, many bearings are used. This paper outlines **NTN**'s latest developments for these applications.

1. Introduction

In recent years, robot replacements for human workers have become popular worldwide as a way to resolve labor shortages and stabilize product quality. There has been particularly active capital investment in the automotive and electronic components markets due to increased demand relating to IoT (Internet of Things). The robot market is also expanding in Japan due to further growth in demand, due to labor shortages brought on by the decreasing birthrate and aging population, and labor-saving driven by surging personnel costs in developing countries.

Typical examples of robots include: industrial robots installed on manufacturing lines for welding, painting, transfer, and other tasks; field robots that work outdoors at locations such as farms, at sea, and disaster sites; and service robots that interact with people in medical and nursing care settings, and the home and workplace. There is expected to be particularly rapid dissemination of compact robots such as collaborative robots that work with human workers, and service robots to cope with diversification of services.

NTN has developed numerous bearing and sensor related products as mechanical components for use in robotic joints[1)-5)]. Here we will introduce our efforts to develop products for compact robots that will see market growth going forward.

2. Robot market needs

In addition to the basic function of robots—grasping objects at determined positions and working accurately—recently, market needs have been growing in the following areas:

① Increasing productivity by reducing tact time (higher speed)
② Improved positioning accuracy and repeatability during work transfer (higher precision)
③ Simplification of teaching (improved operability)
④ Securing work space by reducing the footprint of robots (greater compactness)
⑤ Improved line operation rate by lengthening maintenance intervals (improved reliability and maintainability)

3. Robot structure and joint mechanisms

Vertical articulating robots which perform the same movements as the human arm, from the shoulder to the wrist, are one typical type of robot **(Fig. 1)**. These robots need to transfer heavy objects at high speed to a determined position with high accuracy. This requires not only driving force and rigidity of each joint, but also accurate positioning control. Therefore, high-rigidity precision reduction gears with high torque density are used at joint locations, and positioning is performed through feedback control using angle detection by rotary encoders **(Fig. 2)**.

In compact robots, it is essential to reduce the size and weight of these joint mechanisms, and strain wave gearing and lightweight, compact rotary encoders are used as compact precision reducers (outer diameter φ 100 mm or less).

NTN is working to develop products such as bearings for use in rotational supports of strain wave gearing and multi-track magnetic rings enabling detection of absolute angle and rotation speed.

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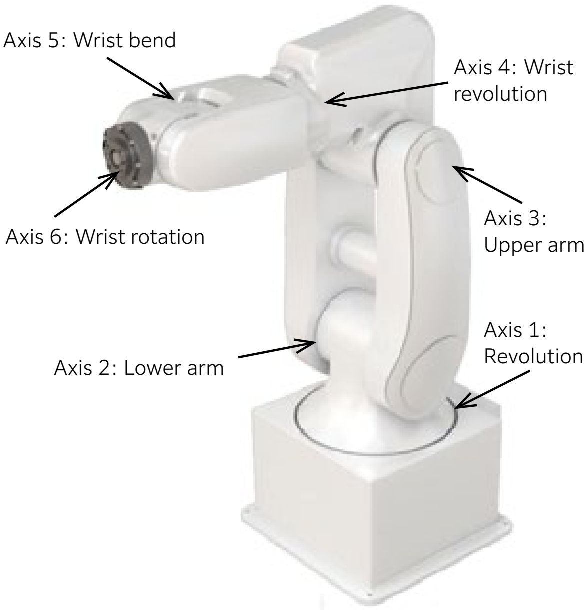


Fig. 1 6 axes articulating robot

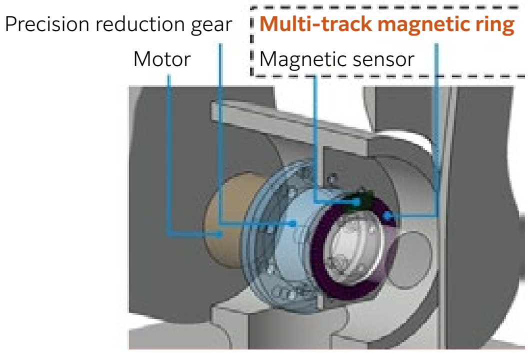


Fig. 2 Structure of robotic joint part (2nd axis: Lower arm)

4. Development of bearings for strain wave gearing

4.1 Points where bearings are used in strain wave gearing

Fig. 3 shows a sample schematic diagram of the structure of strain wave gearing (unit type) that can amplify output torque of a servomotor (reduce speed) and apply a moment load. A thin section elastic ball bearing (which plays the role of the wave generating mechanism) and cross roller bearing (which supports the moment load on the output side) are used in this reducer.

Now the operating principle of this reduction gear will be explained. It consists of a thin section elastic toothed gear (external gear) made of a thin, elastic metal ring with gear teeth. It incorporates a thin, elastic ball bearing into which an oval shaft is inserted. The elastic toothed gear is in contact with the thick, rigid internal gear and the major axis of the oval. This provides a unique reducing mechanism cleverly utilizing the elastic deformation of the external gear. The operating principle is shown in **Fig. 4**. If the internal gear is fixed while the oval shaft rotates clockwise once, the external gear rotates counterclockwise by the difference in the number of teeth between the external gear and the internal gear (e.g. the external gear has two less teeth) which is extracted as the output. Here, the diagram at right in **Fig. 4** shows the situation where the oval shaft has rotated through half a turn and the external gear has moved counterclockwise by one tooth. This reducer has a concentric and simple structure with compact form factor and provides a significant reduction ratio of 1/30 to 1/320. Since both teeth are simultaneously engaged like wedges, providing a high contact ratio without backlash, the reducer is characterized by averaged gear errors, high angle transmission accuracy, and high torque capacity. Also, a cross roller bearing is used for the main bearing supporting output rotation of the external gear, and since this bearing is compact and has high moment stiffness, it also ensures the positioning accuracy, which is the most important characteristic for a robot.

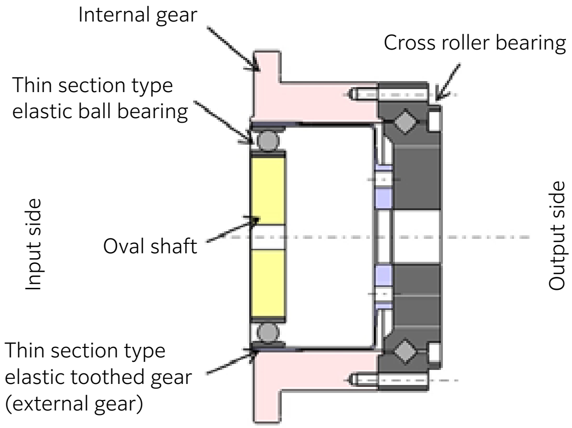


Fig. 3 Structure of strain wave gearing (Unit type)

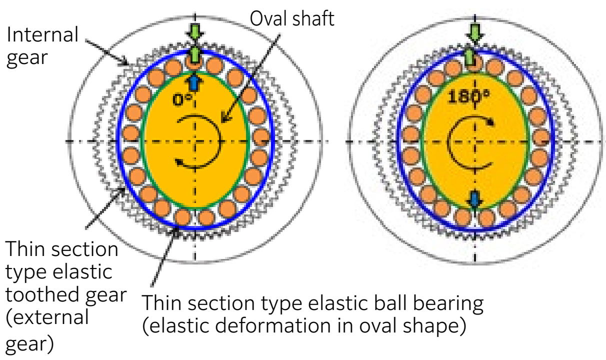


Fig. 4 Operating principle of strain wave gearing

The highly-robust, specialized design of the thin section elastic ball bearing and cross roller bearing is essential to maintain stable performance and operation of the reducer and achieve high reliability.

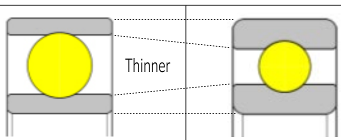
4.2 Thin section elastic ball bearing

The engaging reaction force from the gear is supported in the oval deformed state so that the thin section elastic ball bearing used in strain wave gearing provides torque transmission as a wave generating mechanism. At this time, the inner ring engages tightly with the oval shaft, and rotates while being deformed into an oval, and the deformed state of the outer ring repeatedly changes via the rolling element. In addition to the preload due to this oval deformation, reaction from the gear during torque transmission also acts on the inside of the bearing. In other words, a thin section elastic ball bearing needs to have the following characteristics to accurately transmit high torque over the long term.

① Longer life through high load capacity design (improved rolling fatigue life)
② Flexibility in response to elastic deformation of the inner/outer raceway
③ Improved fatigue strength against cracking of the outer ring

To satisfy these conditions, the basic design uses a larger rolling element, thinner inner and outer rings, and an increased rolling element filling rate. **Table 1** shows a comparison of cross-section form with the 68-series standard product, a typical thin section bearing series. The thin section elastic ball bearing has thinner inner and outer rings than the 68-series. The rolling element ratio with respect to the cross section (cross section ratio) is roughly 1.2 times larger, and the load capacity is about 1.4 times larger. This design allows realization of both elastic deformation and higher load capacity of the inner and outer raceway.

Table 1 Features of thin section elastic ball bearing

Schematic diagram	 Thin section elastic ball bearing	68-series
Cross section ratio	1.2	1
Load capacity ratio	1.4	1

* Cross section ratio, load capacity ratio: Ratio taking 68-series to be 1

Here, we strive for ① "Longer life through high load capacity design (improved rolling fatigue life)" and to ensure tensile and compressive stress amplitude are applied due to repeated elastic deformation of the outer ring via the rolling element during operation. We must take into account not only rolling fatigue life, but also fatigue strength against cracking of the outer ring. **Fig. 5** shows an example of outer ring stress analysis. Analysis was done using a 1/4 cut model of the outer ring, while taking into account elliptical deformation and external load. On the major axis side, the outer ring is pushed to the diameter expansion side via the rolling element, and thus tensile stress is produced at the outer ring outer diameter. On the minor axis side, the rolling element is unloaded and contracts in diameter, and thus compressive stress is produced at the outer ring outer diameter. Furthermore, during operation the deformed inner ring rotates, and the stress distribution of the outer ring changes moment to moment in the rotation direction. The major and minor axes are alternately interchanged, and thus it is evident that repeated tensile and compressive stress are applied to the outer ring outer diameter. **NTN** has achieved ① Longer life through high load capacity design (improved rolling fatigue life), ② Flexibility in response to elastic deformation of the inner/outer raceway, and ③ Improved fatigue strength against cracking of the outer ring, by developing an understanding of the correct stress situation through this type of stress analysis, and thereby selecting the optimal thickness for suppressing stress amplitude, and optimizing the corner shape design to prevent stress concentration.

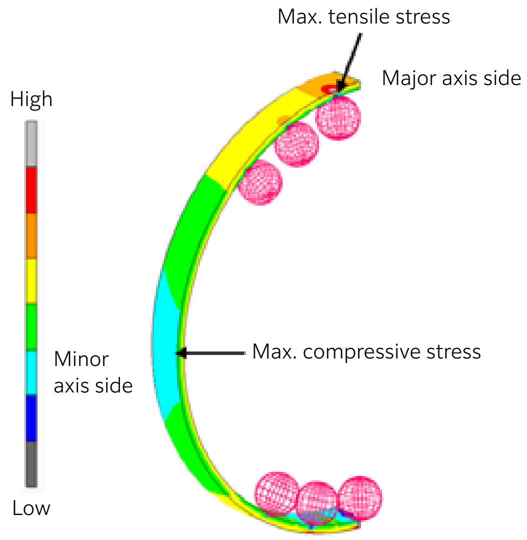


Fig. 5 Outer race stress analysis of thin section elastic ball bearing

Also, in a thin section elastic ball bearing, the inner and outer rings are extremely thin, and thus one issue for manufacturing is how to suppress deformation during machining and heat treatment. However, we have commercialized a thin section type elastic ball bearing through thin machining technology previously cultivated by **NTN** and optimization of heat treatment conditions **(Fig. 6)**.

Fig. 6 Cut model of thin section elastic ball bearing

4.3 Cross roller bearing

Main bearings used in strain wave gearing must directly support the moment load acting on a robotic joint, and, even when holding a large moment load, they must have high moment stiffness and support rotation with long-term stability while suppressing axis inclination and bearing internal stress (contact stress). Therefore, the bearing must have ① greater compactness, ② higher moment stiffness, and ③ longer life. To achieve these functions, a cross roller bearing is used which has no cage, and a larger number of rollers arranged with alternating contact angles **(Fig. 7)**.

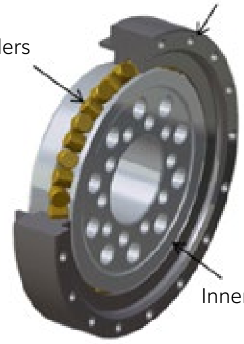
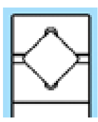
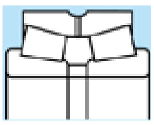
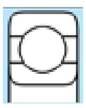


Fig. 7 Structure of cross roller bearing

Table 2 shows a comparison when tapered roller bearings and deep groove ball bearings are used, as typical bearing types other than a cross roller bearing, for the main bearing of strain wave gearing. Tapered roller bearings have outstanding moment stiffness and load capacity, but use of two rows is a reqirement for supporting a moment load in both directions. This results in issues in terms of compactness. Deep groove ball bearings are compact, but there are issues in terms of moment stiffness and load capacity. Thus, the cross roller bearing is the most functional for this application.

Table 2 Comparison of bearing types for strain wave gearing main shafts

Type	 Cross roller bearing	 Tapered roller bearing	 Deep groove ball bearing
① Compact	○	×	○
② High moment stiffness	○	○	×
③ High load capacity (long life)	○	○	×

To achieve ② "high moment stiffness" with a cross roller bearing, the design must increase internal preload, and thus the bearing internal gap is set to a negative gap (preload). On the other hand, increasing preload involves an increase in contact stress, and thus reduction in service life must be considered. **Fig. 8** shows the relationship of moment stiffness and life to preload. With increasing preload, there is also an increase in moment stiffness. Life, on the other hand, tends to increase in the low preload region due to suppression of preload loss in response to an external load. In the high preload region, life tends to decrease due to an increase in contact stress. **NTN** has achieved: ① greater compactness while simultaneously realizing ② higher moment stiffness and ③ longer service life by setting the optimal preload range.

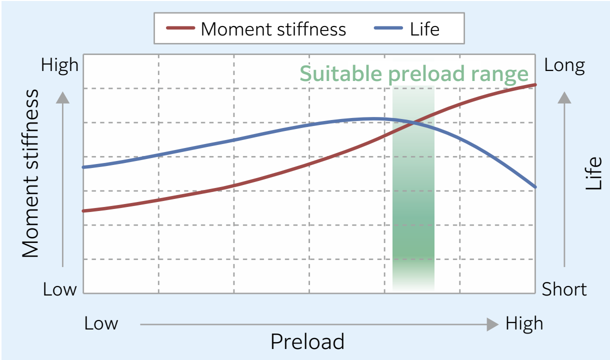


Fig. 8 Moment stiffness and lifetime at preload for cross roller bearing

5. Development of multi-track magnetic ring for rotary encoders

5.1 Application of multi-track magnetic rings to robotic joints

To achieve accurate positioning control of robots, it is necessary to detect the rotation angle, rotation direction, and rotation speed on the output side of the motor which drives the joint with high accuracy. That output is used for feedback control.

Rotary encoders are broadly divided into two types: optical and magnetic. The optical type has high position detection accuracy and resolution, but has low environmental resistance because it is affected by aspects of the ambient environment, such as temperature variation, dust, and oil. The magnetic type, on the other hand, is highly resistant to environmental aspects, and can be used in ordinary work environments.

NTN has developed a multi-track magnetic ring for use with absolute angle detection type rotary encoders[3] **(Fig. 9)**.

Fig. 9 Multi Track Magnetic Ring

This multi-track magnetic ring uses thin, press-formed core metal, and is hollow with a large diameter. Therefore, it is ideal for robots whose wiring passes through hollow shafts such as joints, and helps to save space. **Fig. 10** shows an example using multi-track magnetic rings and iC-MU[6] series sensor ICs at robotic joints.

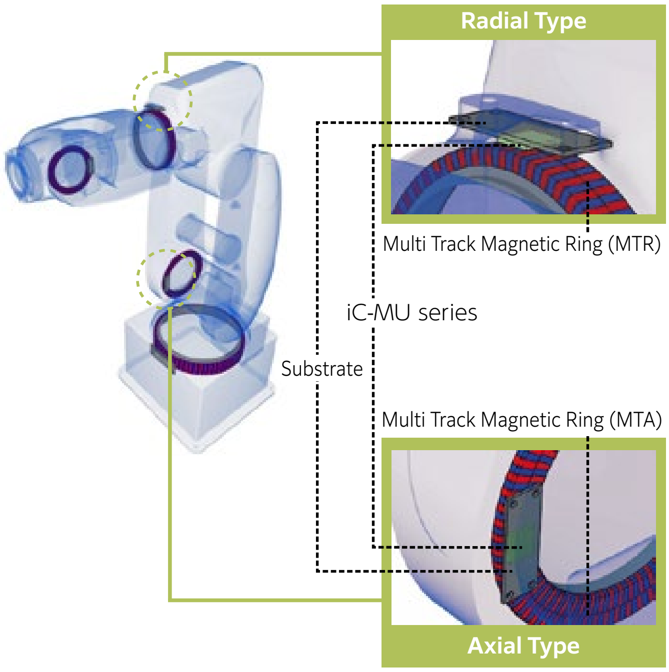


Fig. 10 Application example of Multi Track Magnetic Ring in robotic joint

5.2 Multi-track magnetic rings

The multi-track magnetic rings developed at **NTN** consist of different numbers of magnetic poles arranged in two tracks, and we have realized high-accuracy magnetization by accumulating magnetizing technology for the magnetic rings used in bearings with rotational sensors.

The iC-MU **(Fig. 11)** used in a set with a multi-track magnetic ring provides a Hall element and signal processing circuit in a single package. It reads the phase difference of the magnetic poles in the two tracks with different numbers of magnetic poles, and can detect the absolute angle by internally calculating. Using parameter setting inside the iC-MU, it is also possible to generate highly-divided output up to a maximum of 20 bits (resolution: approx. 0.00034°). **Fig. 12** shows the results of measuring absolute angle error under ideal conditions, where the relative positional deviation between the multi-track magnetic ring and iC-MU is minimal. An angle error of ± 0.025° is achieved, although this is only a reference measuring result.

The multi-track magnetic ring introduced in this article is the OFF-AXIS type, in which the inner diameter part is fixed to the axis outer diameter part. **NTN** has also commercialized an ON-AXIS type angle sensor unit, in which a magnet is fastened to the axis end[4]. Also, as rotation detection technology and application products, **NTN** has commercialized bearings with rotational sensors[5] **(Fig. 13)**, hub bearings with sensors, and other products.

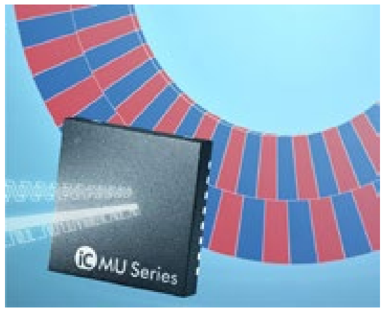


Fig. 11 Image of Combination of iC-MU and Multi Track Magnetic Ring
(Conceptual illustration, provided by: iC-Haus GmbH)

Fig. 13 Integrated Rotation Sensor Bearing

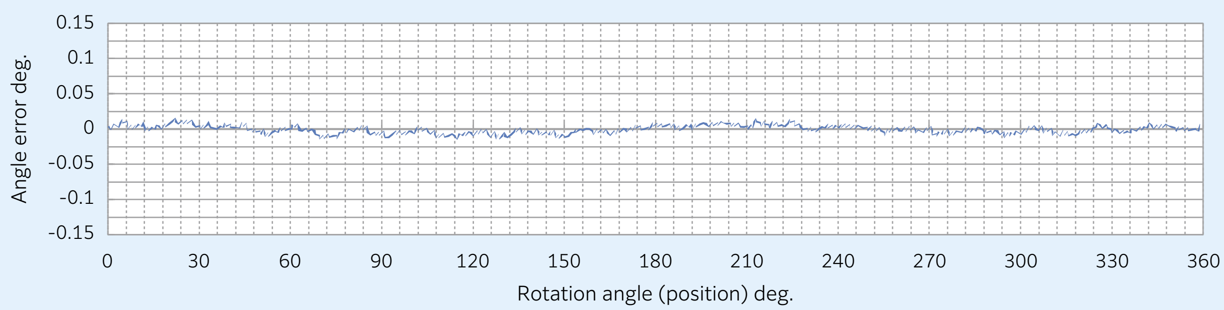


Fig. 12 Angular accuracy measurement result when combining the Multi Track Magnetic Ring and dedicated iC-MU

5.3 Developing a multi-track magnetic ring series

After starting mass production of multi-track magnetic rings, first of the radial type with 64/63 polar pairs (inner diameter 44 mm, outer diameter 51.5 mm, width 8.2 mm, weight 10.7 g), an axial type was added with 64/63 polar pairs. **NTN** has also developed a compact type with 32/31 polar pairs (MTR32 and MTA32) **(Fig. 14)** with an eye toward non-robot applications, such as electric tools and compact motors to support self-driving automobiles. To meet market needs, **NTN** is developing a series of multi-track magnetic rings with the model names shown in **Table 3**.

Going forward, we will consider marketing an ultra-compact type with 16/15 polar pairs and a large type with 128/127 polar pairs to meet user needs.

Fig. 14 Comparison of 64/63 pole pairs and small size 32/31 pole pairs

6. Summary

NTN is developing products applicable to robotic joints, and this article has introduced those efforts. Going forward, needs for compact robots are expected to diversify due to expansion of the service field and diversification of collaborative work with people, and product development will be needed to cover these new needs.

NTN will keep a close eye on industry trends, and continually move forward with product development suited to market needs.

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Table 3 **NTN** Multi Track Magnetic Ring corresponding to sensor IC (iC-MU series) of iC-Haus

Multi Track Magnetic Ring	Pole Pair Number (Main Track / Sub Track)	Pole Pitch of Main Track (mm)		
		1.28	1.50	2.00
Multi Track Magnetic Ring	32/31	MTR32 MTA32	MTR32-1 MTA32-1	MTR32-2 MTA32-2
	64/63	MTR64 MTA64	MTR64-1 MTA64-1	MTR64-2 MTA64-2
Magnetic Sensor made by iC-Haus		iC-MU	iC-MU150	iC-MU200

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