「C3 eMotion」インテリジェントアクチュエータユニットの開発

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Development of the C3 eMotion, Intelligent Actuator Unit

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ロボットの多様化・高機能化ニーズにこたえるべく，モーター，減速機，駆動回路，ブレーキ，アブソリュートエンコーダをパッケージ化した，インテリジェントアクチュエータユニット「C3 eMotion」を2020年４月にリリースした．「C3 eMotion」は，２つのアブソリュートエンコーダを組み込んだ「ダブルエンコーダ構造」を採用．独自の制御技術との組み合わせによる様々な機能を有する．本稿では，「C3 eMotion」が持つ技術的特徴について解説する．

In April 2020, Nikon released the intelligent actuator unit, “C3 eMotion,” that packages a motor, reducer, drive circuit, brake, and absolute encoders to meet the needs for diversification and high functionality of robots. The “C3 eMotion” includes Nikon’s original “double-encoder arrangement,” which incorporates two absolute encoders, and various functions that combine the original control technology with the double-encoder arrangement. This article describes the technical features of the “C3 eMotion.”

Key words ロボット用関節ユニット，ダブルエンコーダ構造，高精度位置決め，トルク検出，制御技術
robotic joint unit, double-encoder arrangement, high accuracy positioning, torque detection, control technology

1 Introduction

The modularization of robot components to strategically accelerate their development is being discussed in the robot industry [1]. It is believed that these efforts will facilitate freely conceived robot configurations, and help satisfy diversification and high-functionality requirements. In this paper, we elucidate the features and technical elements obtained by applying the double-encoder arrangement and original control technology of the “C3 eMotion [2]” (Fig. 1 C3 eMotion), an intelligent actuator unit, which was released in April 2020 to meet these needs.

Fig. 1　C3 eMotion

2 Hardware configuration

Conventionally, to configure the joints of an articulated robot, it is necessary to separately prepare each of the constituent element components, such as motors, encoders, reduction gears, and brakes, and then incorporate them into a robot base and robot arm. In addition, reduction gear and motor output characteristics, including encoder specifications, need to be designed according to the operating speed and inertia of the robot; consequently, a high level of technical skill is required to freely manufacture robots. Therefore, constructing a robot system still involves the purchase and use of robots manufactured by dedicated robot manufacturers. However, robot applications are becoming diversified; hence, there is a significant increase in the global needs for freely configurable robots, which are not exist.

C3 eMotion was released with the intention of realizing three objectives: “connect,” “control,” and “cooperate.” To facilitate freely-conceived robot configurations, an all-in-one package has been adopted by C3 eMotion, which combines a motor, reducer, brake, absolute encoder, and motor driver board in a single housing (Fig. 2). This packaging eliminates the need for the design and assembly of individual compo-

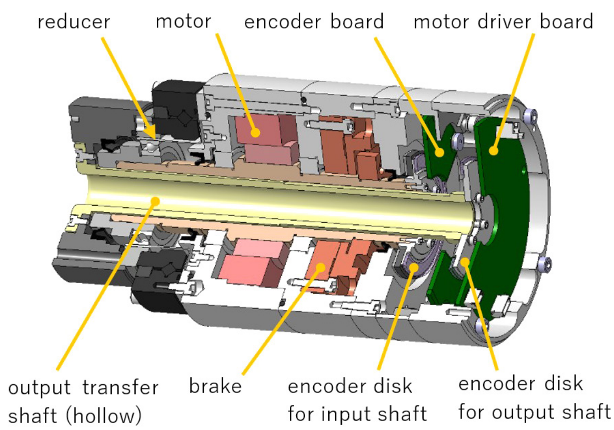

Fig. 2 Internal configuration of C3 eMotion

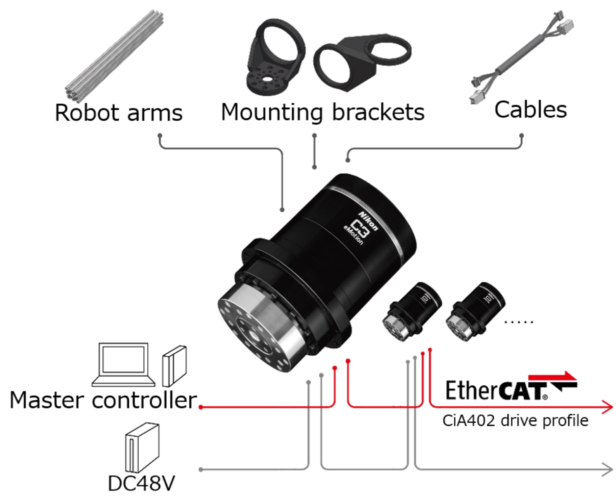

Fig. 3 System configuration

nents when configuring a robot, and allows the C3 eMotion to be treated as a single robot joint module. In addition, because this construction has the closest positioning of the motor driver board to the motor, it does not require power cable wiring to drive the motor within the mechanism of the robot, which reduces wiring, and is also advantageous in addressing noise emissions.

Furthermore, in addition to the absolute encoder for the input shaft (motor drive shaft), C3 eMotion also employs "double-encoder arrangement" with a high-resolution absolute encoder on the output shaft. Motor rotations are decelerated by the reducer and transmitted to the output shaft. The rotation information of the output shaft is transmitted through the hollow interior of the motor shaft by an output transmission shaft, and is read by an encoder mounted on the end face opposite the output shaft. The output shaft encoder and the encoder reading the rotation information of the input shaft are installed next to each other. Their rotation information is transmitted to the motor driver board via serial communication. The motor driver board is located in the immediate vicinity of the encoder, and it controls the motor rotation and brake based on the command values from a Master controller, as well as the information from the two encoders. The placement of the encoder and driver board minimizes the length of the encoder's communication cable, and keeps electronic boards (e.g. the encoders) away from the grease-containing reducer that shock and vibration from the robot arm is applied directly.

Fig. 3 shows the system configuration of the C3 eMotion. Because C3 eMotion can be adopted as a robot joint module, it facilitates the configuration of a robot by connecting multiple C3 eMotion units with a robot arm. The communication between the motor driver board and Master controller is handled by the EtherCAT® [3] serial communication corresponding to the CiA402 drive profile. EtherCAT® is capable

Table 1 Main Specifications

Model No.		IAU-15 (under development)	IAU-30 (under development)	IAU-60	IAU-200	IAU-300 (under development)
Power supply voltage	V	48				
Instantaneous maximum torque	N·m	4.8	30	55	200	400
Rated torque	N·m	2.4	10	30	95	130
Rated speed	min^{-1}	35	30	20	15	15
Maximum speed	min^{-1}	60	40	40	20	20
Reduction ratio	–	100	81		101	
Encoder *Input shaft only for IAU-15	Input shaft: 24 bits/rotation, 16 bits for multi-turn Output Shaft: 24 bits/rotation					
Output shaft encoder accuracy	arc-sec	–	± 15 or less			
Torque detection range (F.S.)	N·m	–	14	30	130	280
Torque detection accuracy	%	–	±5 F.S.			
Driver/Communication Method	–	Built into actuator/EtherCAT® CiA402				
Outer diameter	mm	ϕ50	ϕ70	ϕ80	ϕ110	ϕ142
Overall length	mm	73.4	161.1	164	179.7	185
Weight	kg	0.6	1.6	2.1	4.9	8.5

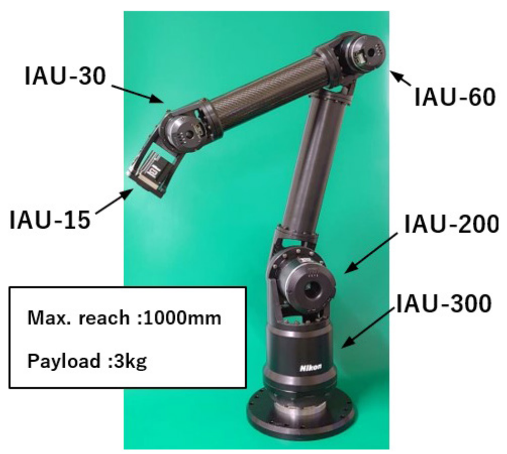

Fig. 4 Example of 5-axis robot using C3 eMotion

of daisy-chain connection, and is suitable for the multiaxial connection of C3 eMotion via a robot arm. Table 1 presents the main specifications of C3 eMotion. Presently, two versions of C3 eMotion, IAU-60 and IAU-200, have been released, and three other versions, IAU-15, IAU-30, and IAU-300 are under development. Fig. 4 shows an example of an arm robot configuration, using these five types.

This robot has a long-reach design of 1000 mm, although it has a low payload, as well as features not seen in commercially available robots, such as using plastic for the arm.

3 Double encoder structure

Angular transmission errors triggered by machining errors or friction are present in reducers that employ gears. C3 eMotion adopts the strain wave gear reducer widely employed in robots and other industrial equipment. In addition to angular transmission errors, the strain wave gear reducer has nonlinear friction and spring characteristics, including structurally generated hysteresis [4]. In conventional semi-closed control systems, these errors and spring characteristics appear as substantial position errors at the tips of robots. Manufacturers specializing in robots have improved the rigidity of robot arms compared to standardized robots, and have adopted techniques for estimating and correcting robot tip position errors to improve position accuracy [5]. Such high-precision technologies are difficult to apply, for example, when constructing freely-configured robots combining robot constituent elements in which system integrators have been modularized.

As aforementioned, C3 eMotion employs “double-encoder arrangement” with an encoder on the output shaft side (Fig. 5). An absolute encoder with a 24-bit resolution is employed on the output shaft encoder. An accuracy of ± 15 arc-sec or less is ensured via error compensation. Improved positioning accuracy is expected because the impacts of Angular transmission errors and nonlinear spring characteristics can be eliminated by adopting a control system, using output shaft rotation information.

In addition, because the reducer exhibits nonlinear spring characteristics and can be regarded as a torsional elastic body, the torque can be easily measured by measuring and converting the relationship between the magnitude of torsion and torque beforehand.

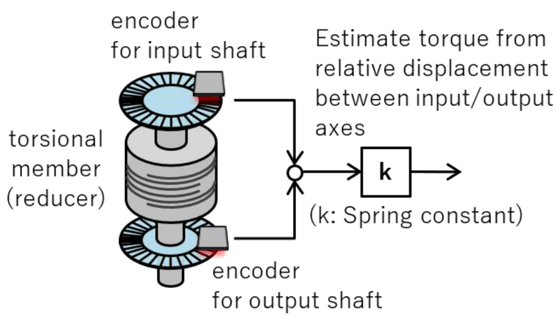

Fig. 5 Double-encoder arrangement

4 Original control technology

In applications typified by laser welding, such as vehicle body welding and electrode connection of battery modules installed in electric and hybrid vehicles, there is an increasing demand for highly accurate TCP*1 positioning in robots; hence, the demand for high accuracy in the TCP*1 positioning of robots is steadily increasing.

Nikon has already cultivated highly advanced and precise control technologies, including the ultra-precise and accurate device stage-control typified by a semiconductor and flat panel display (FPD) lithography equipment. C3 eMotion performs motor control by providing position, speed, and torque commands from an upper level controller via EtherCAT® communication, and it has been equipped with an original control suited to it by applying the control technology developed by Nikon.

As demonstrated in the “double-encoder arrangement” optimally designed for C3 eMotion in the previous section, the original high-precision positioning control is characterized by adopting a control algorithm to properly combine two types of position information according to operating conditions: information from an encoder for detecting the motor drive shaft position (reducer input side encoder) and information from an absolute encoder for detecting the position of the C3 eMotion output shaft, which is the reducer output (reducer output shaft encoder; Fig. 6).

This proprietary Nikon mix control makes it possible to combine the advantages of both full-closed and semi-closed controls, thereby leading to improved positioning accuracy. In fully-closed control, the feeding back rotation information read by the reducer output shaft encoder facilitates the elimination of error factors triggered by the reducer, such as reducer angular transmission errors, as well as reducer twisting originating from load fluctuations owing to the weight of the robot arm and its change in posture. In con-

*1 Tool center point. Center when controlling an end effector.

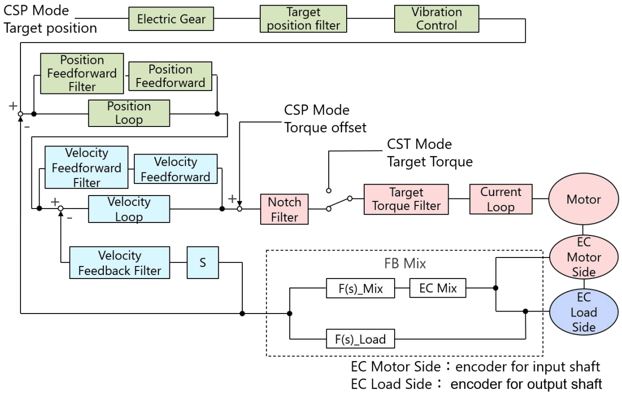

Fig. 6 Control block diagram

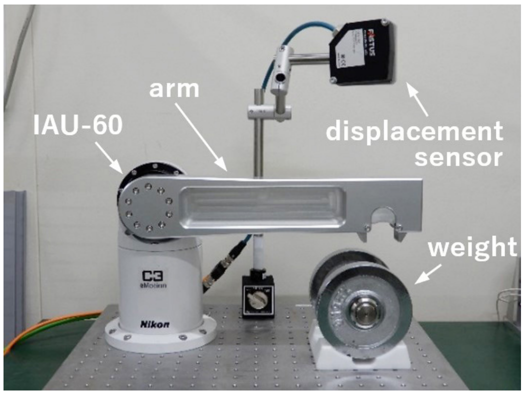

Fig. 7 Positioning performance verification device

trast, in the middle and high-speed ranges, the output shaft rotation information triggers a decrease in stability because the phase is delayed. Therefore, we adopt an original control system that achieves both improved positioning accuracy and stability by combining and feeding back input shaft rotation information.

5 High-accuracy positioning

Fig. 7 presents the positioning performance verification device for C3 eMotion. An arm was attached to the IAU-60, each of the weight lifting actions were performed with semi-closed and mixed controls, and the position of the arm tip during each scenario was compared. Fig. 8 presents a graph of the comparison results. From Fig. 8, deviations of 0.16 mm or more in the positioning command values from deflections can be observed owing to reducer transmission errors or applied load during semi-closed control operations without the output shaft encoder. However, in the case of mixed control with a double-encoder arrangement, reduced accuracy factors such as reducer torsion and angle transmission errors are cancelled, the deviation from the positioning command value is 0.01 mm or less, and a higher positioning performance than that of the semi-closed control case is demonstrated under load conditions.

When C3 eMotion is adopted as a robot joint, the reducer torsion and angle transmission error per the number of shafts accumulates in the robot tip. These accumulated errors are eliminated by adopting mixed control, using output shaft information; and the positioning accuracy at the robot tip can be expected to improve. An articulated robot with a 5 kg payload capacity incorporating C3 eMotion (Fig. 9) is adopted to repeatedly evaluate positioning performance with semi-closed and mixed controls when a 0.5-kg and 5-kg weight is attached to the robot tip. The reach of this robot is 830 mm, and it is evaluated at its maximum reach. When

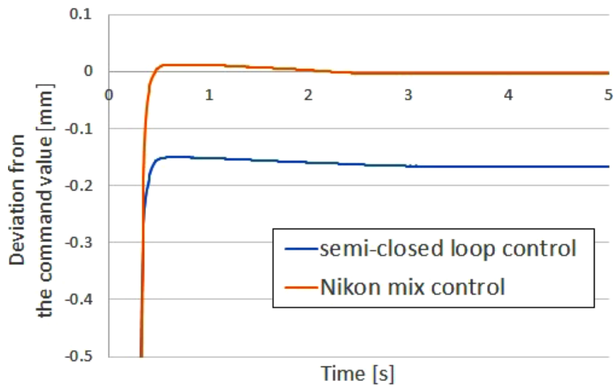

Fig. 8 Experimental results of positioning with each control loop

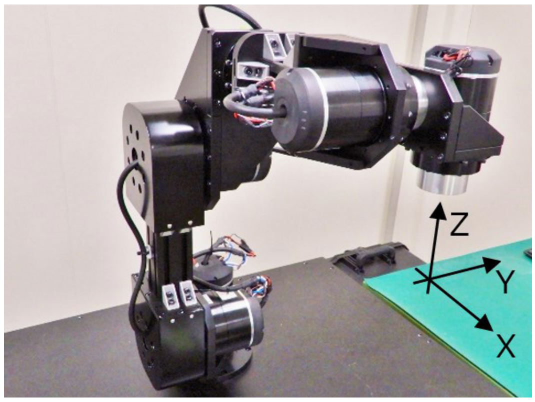

Fig. 9 Articulated robot (payload: 5 kg) for accuracy evaluation

semi-closed control is adopted, position changes are generated by reducer torsion from load. In contrast, during the application of mixed control, positioning is stable even if load conditions are altered.

Based on these results, the decrease in positioning accuracy is expected to be minimized in robot applications, such as work or end effectors, in which the tip mass changes when configuring arms of different lengths and mases with C3 eMotion.

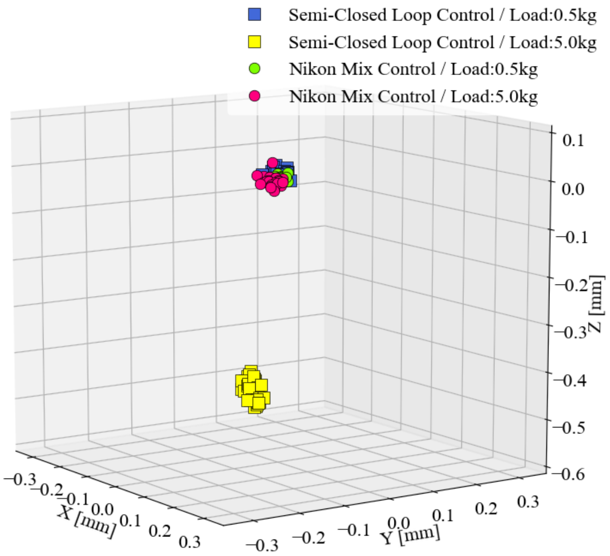

Fig. 10 Positioning evaluation results with robot

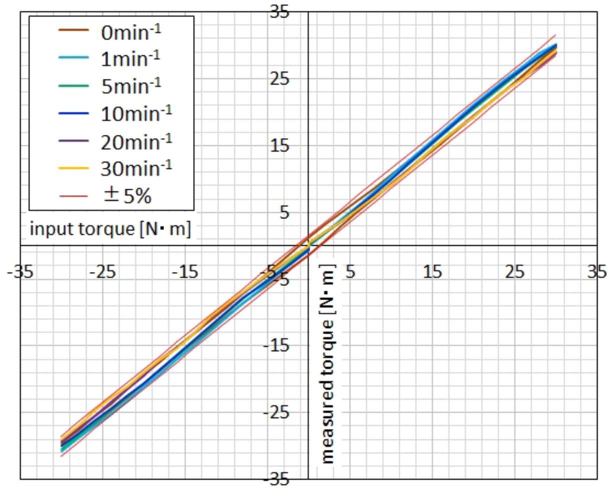

Fig. 11 Torque detection per revolution (IAU-60)

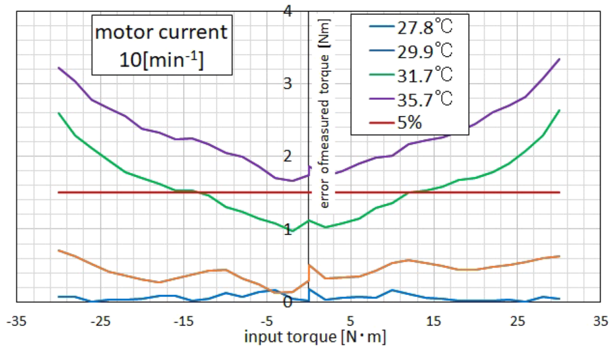

Fig. 12 Temperature−torque error characteristics (motor current detection)

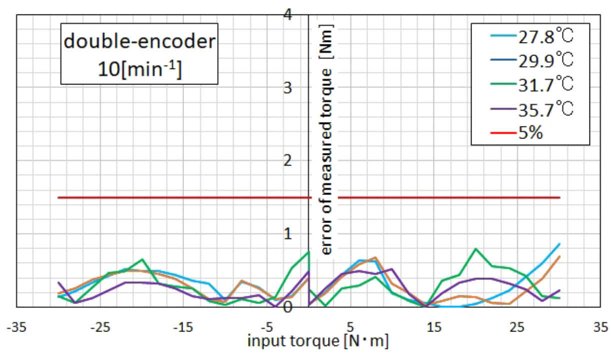

Fig. 13 Temperature-torque error characteristics (double encoder)

6 Torque detection function

As described above, in a double-encoder arrangement in which the reducer is regarded as a torsional elastic body, the torque can be detected by measuring and converting the relationship between the torsion amount and torque beforehand. However, errors owing to the eccentricity of the encoder disk are present in the encoders of the input and output shafts, and angular transmission errors are also present in the reducer. Therefore, accurate torque detection is impossible even if the output values of the two encoders are simply compared. In C3 eMotion, the output shaft encoder is corrected to an accuracy of ± 15 arc-sec or less using an external reference. Furthermore, an angle-correction value, including the angular error value obtained by comparing the output value of the corrected output shaft encoder with the output value of the input shaft encoder, is recorded beforehand, and the angle transmission error triggered by the reducer is also corrected. This facilitates the reduction of error in the entire encoder system, and improves torque detection accuracy.

Fig. 11 presents a typical example of torque detection values for the external input torque. Because the torsional characteristics of the strain wave gear are nonlinear, the spring constant adopted for torque conversion is converted using an approximate curve. In this example, the torque detection value is stable, regardless of the output shaft rotation speed, and errors in the torque detection value remain within the range of ± 5%.

In a typical servo motor system, torque is detected by the torque converting motor current values. Fig. 12 illustrates an example of the temperature characteristics of torque detection errors in terms of the motor current value conversion in IAU-60. Furthermore, the rotational speed when acquiring data is 10 min^{-1}. Owing to the temperature dependence of the motor winding and motor drive circuit element resistance, as well as the viscosity of the grease and lubricating oil in the mechanism, the motor current value varies depending on the temperature. Therefore, to accurately detect torque, complicated processes, such as correction by temperature, are required. In the double-encoder arrangement, the reducer torsion amount, which is less temperature dependent, is directly measured by the encoder, thereby enabling stable torque detection independent of temperature (Fig. 13).

7 Conclusion

In C3 eMotion, various components, including a motor driver with proprietary Nikon built-in control technology, are packaged and daisy-chained by EtherCAT® to facilitate multi-axis connectivity. In addition, high-precision positioning and a torque detection function was realized by a double-encoder arrangement and original control technology. C3 eMotion adopts these technologies to enable freely-conceived configurations of articulated robots that could solely be realized in the past by manufacturers specializing in robots. Nikon intends to expand its C3 eMotion lineup in the future to satisfy diverse demands and launch peripheral devices such as special-purpose upper level controllers corresponding to typical robot configurations. In addition, we hope to contribute to the development and evolution of robot technology via the higher precision and further enhancement of precision.

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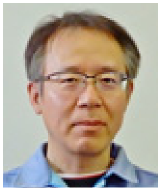

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