CASE 56

Functionality Evaluation of Articulated Robots

Abstract: In this study we assessed robot functionality. There are still a number of problems to be solved for obtaining a clear-cut conclusion; however, we have determined that we may be able to evaluate robot functionality by measuring electricity consumption of an articulated robot.

1. Introduction

Many multijoint robots have the function of grasping and moving an object located at an arbitrary position with perfect freedom, as human arms do. Robots used primarily for product assembly are called industrial robots. Each arm of an articulated robot moves in accordance with each joint angle changed by a motor and aligns its end effecter to a target. That is, the movement of a robot's end effecter is controlled by an indicated motor's angle. We used the vertical articulated robot shown in Figures 1 and 2 and instructed it with angular values so that it could move by recognizing both angular and positional values.

Using Cartesian coordinates (X, Y, Z) (Figure 1), and joint coordinates (J_1, ... , J_5) (Figure 2), we can express the position of this robot. In this case, the locating point of this robot is the center point of the flange at the end of the robot's arm (point P in Figure 1), whose coordinates are indicated on the controller.

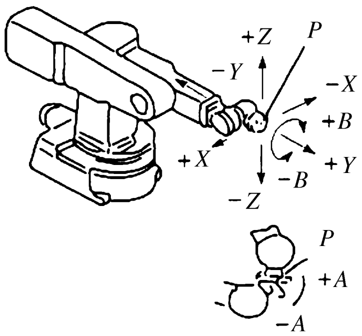
2. Robot Arm's Displacement

For the robot used for our study, we instructed successive positions of the end effecter so that it could move according to our target path. There were two major instruction methods: one a method of giving digital information related to positions, the other a method by which an operator instructs a robot as to target positions by moving the robot with controller buttons. For each arm's rotational angle as a signal, M, we adopted the latter method. On the other hand, we measured end effecter's displacement as a characteristic, y, by using a coordinate measuring machine after the robot moved automatically by following the program code. Using these signals and characteristics, we evaluated the robot's functionality.

In this study, to obtained the characteristic, y, we evaluated the locating performance of the end effecter as follows. First, we attached a pen at point P (center point) on the flange in such a way that it was parallel with the flange (Figure 3), of the experimental device. Second, a three-dimensional wall consisting of three plates was set up within the range of the robot arm. Third, a piece of paper was attached on each plate. Fourth, by manipulating the robot arm, we plotted four points on paper with the pen attached at point P of the robot (Figure 4). While we plotted points A, B, and C by manipulating the robot with the controller buttons, point D was plotted by automated movement of the robot based on the program code. After connecting points A and B with a line, we defined the line as the Y-axis of the robot. Then we set point C as the origin for locating. Since it was difficult to measure points located by the robot based on the coordinate origin of the robot, we set up another point as the origin (in Figure 4, point C). Therefore, point D was regarded as a located point that was translated with a certain amount of displacement from point C by the robot arm.

Since a located point is expressed in the Cartesian coordinated system (in this case, Y and Z

Taguchi's Quality Engineering Handbook. Genichi Taguchi, Subir Chowdhury and Yuin Wu



When we perform motion *A* in the Cartesian coordinate system, the position of the center point on the flange (point *P*) never changes position, as shown on the right, but the robot's posture changes.

Figure 1
Robot's movement in Cartesian coordinate system

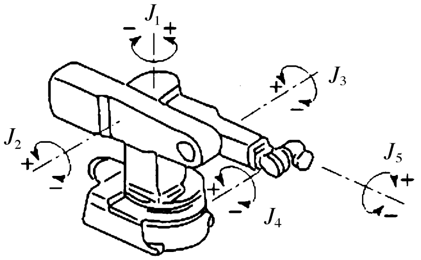


Figure 2
Robot's movement in joint coordinate system

coordinates), by transforming its coordinates through geometric calculation, we computed the position of the end effecter relative to the rotational center of the arm. Next, we detail the calculation procedure.

Since point *P* did not coincide with the pen's center point (Figure 5), when we transformed the Cartesian coordinates to the rotational coordinates, we defined the angle between the horizontal line and the line connecting the pen's center and the rotational center of joint J_4 as α_4 when the flange was set up in a vertical orientation. Next, we defined the length from the pen's center to the rotational center of joint J_4 as L_4. As illustrated in Figure 6, if we set the *Y*-axis directional displacement to GH_Y and the *Z*-axis directional displacement to GH_Z between points *G* and *H*, we obtained the following equations:

$$GH_Y = L_4 \cos \alpha_4 - L_4 \sin \alpha_4 \qquad (1)$$

$$GH_Z = L_4 \sin \alpha_4 - L_4 \cos \alpha_4 \qquad (2)$$

Using these two equations, we can calculate L_4 and α_4 as follows:

$$L_4 = \sqrt{\frac{GH_y^2 - GH_Z^2}{2}} \qquad (3)$$

$$\alpha_4 = \cos^{-1} \frac{GH_y + GH_Z}{2L_4} \qquad (4)$$

Focusing on two arms moved with rotation of

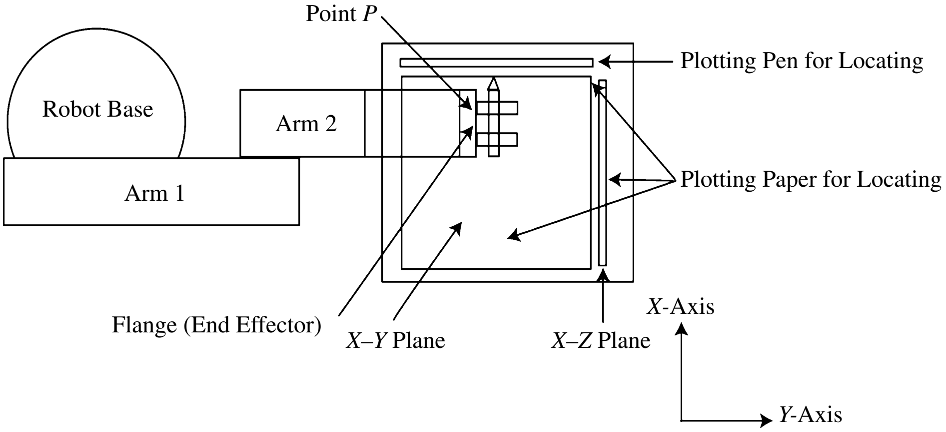


Figure 3
Positions of robot and box (wall)

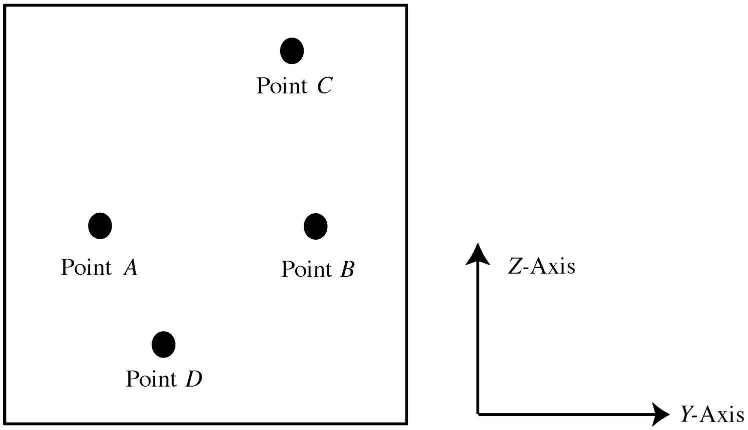


Figure 4
Plotting sequence for displacement of robot arm

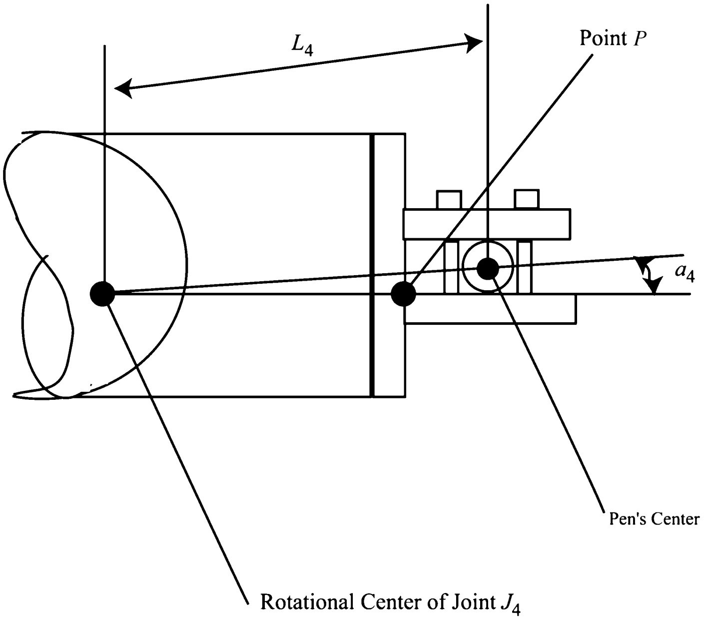


Figure 5
Relationship among pen's center point, point P, and rotational center of joint J_4

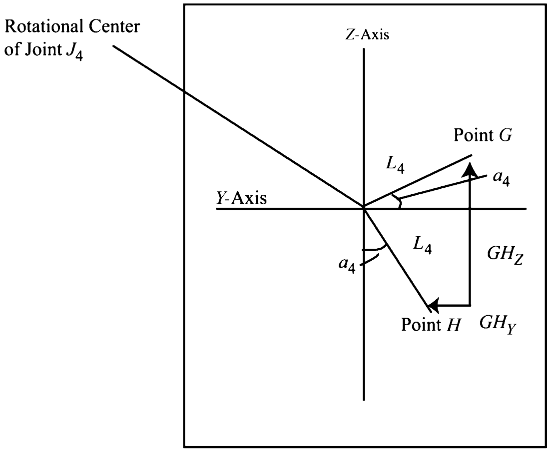


Figure 6
Relationship between pen's center point and rotational center of joint J_4

joint J_2, we set the length of arm 1 to L_2 and its angle to θ_2, the length of arm 2 to L_3 and its angle to θ_3 (Figure 7). In addition, defining the coordinates of the origin for locating as (O_Y, O_Z), we had the following equation:

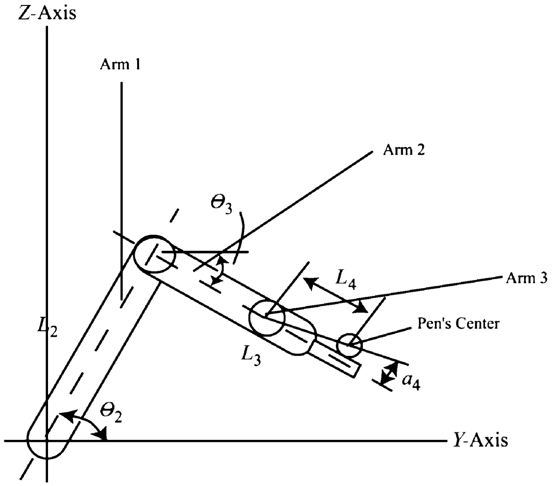


Figure 7
Relationship between pen's center point and rotational center

$$Y + O_Y = L_2 \cos\theta_2 + (L_3 + L_4 \cos\alpha_4)\cos\theta_3 - L_4 \sin\alpha_4 \sin\theta_3 \qquad (5)$$

$$Z + O_Z = L_2 \cos\theta_2 + (L_3 + L_4 \cos\alpha_4)\sin\theta_3 - L_4 \sin\alpha_4 \cos\theta_3 \qquad (6)$$

Using the equations addressed above, we performed coordinate transformation.

Next, let's discuss measurement and the modification method of errors. After adhering point-plotted papers on the table of a coordinate measuring machine, we measured coordinates of points using a microscope. Our study of measurement errors in the coordinate measuring machine by using die-cast parts with unknown dimensions revealed that the level of errors was approximately 10 mm. Since 10 mm is equivalent to 0.001° in terms of the rotational angle of joint J_2 and the minimum instruction unit of the robot is 0.01°, the errors in the coordinate measuring machine were considered much smaller than those in the robot.

Nevertheless, because the pen held by the robot plots points on the paper in our evaluation method, we should consider the following effects related to the robot arm's locating: (1) effect caused by the slant of paper attached to the table of the coordinate measuring machine, and (2) effect caused by the slant of a box (walls) onto which paper is attached. If we measure pertinent slant angles beforehand and perform geometric coordinate transformation, we can eliminate the foregoing effects.

3. Robot Locating Performance

According to the measurement method discussed so far, we evaluated errors in robot locating. However, it was difficult to set up control factors because we used only one robot. Thus, substituting factors originally regarded as error factors for indicative factors, we studied additivity of factor effects.

Setup of Signal and Indicative Factors

Defining the angular change setting values of arms 1 and 2, *M* and *M*′ as signals, and the angular changes of arms 1 and 2, *y* and *y*′ for automated movement based the program code as characteristics, we proceeded with the experiment.

Table 1
Signal factors regarding arm's angle (deg)

	Level		
Factor	1	2	3
Angular change setting value of joint J_2	−5	−10	−15
Angular change setting value of joint J_3	−5	−10	−15

$$y = \beta M \tag{7}$$

$$y = \beta' M' \tag{8}$$

In Table 1 we tabulated signal factors and levels. In the table, M corresponds to the setting values of joint J_2 while M' accords with the setting values of joint J_3. In addition, although we could not widen ranges of signal factor levels due to the constraint of our experimental device, we judged them to be sufficient for our evaluation. All indicative factors are shown in Table 2. These factors are allocated to columns 2, 3, and 4 in an L_{18} orthogonal array.

Indicative factor A, arm's posture, was selected so that we could investigate the difference between two cases where arms 1 and 2 start to move from a folded posture and from an extended posture. As shown in Figure 8, if we begin to move the arm from a folded state, we set up a point closer to the robot position as the locating origin. If we begin to move the arm from an extended state, we set up a point far from the robot position as the locating point. Next, indicative factor B, acceleration, indicates the magnitude of acceleration until the velocity of the robot arm reaches a constant value from zero, when it is manipulated automatically by the program code. Indicative factor C, constant velocity, represents the magnitude of velocity after the velocity of the robot arm becomes constant by following the program code. Three levels of constant velocity, 6, 12, and 18%, represent mean the ratio of a selected velocity to the maximum movement velocity of the robot arm.

Calculation of SN Ratio and Sensitivity

For this study we used an L_{18} orthogonal array. Since procedures for analyzing data for joints J_2 and J_3 were identical, and additionally, a procedure for analyzing data in each row was also the same, as one typical example, we show the analysis of data in the first row in the case of joint J_2 in Table 3. In the table, M_1, M_2, and M_3 represent values when angular values at joint J_2 are set to −5°, −10°, and −15°, respectively. Similarly, M'_1, M'_2, and M'_3 indicate values when angular values at joint J_3 are set to −5°, −10°, and −15°, respectively.

When the robot used for this study locates a target position, there is a technical constraint that we cannot move only one of joint J_2 or J_3. Therefore, setting the angular value at joint J_2 to a signal, we can regard joint J_3's movement caused by joint J_2's movement as an error. Similarly, defining the angular value at joint J_3 as a signal, we can consider joint J_2's movement triggered by joint J_3 as an error.

Table 2
Indicative factors

	Level		
Factor	1	2	3
A: arm's posture	Folded	Intermediate	Extended
B: acceleration	Low	Mid	High
C: velocity (constant)	6%	12%	18%

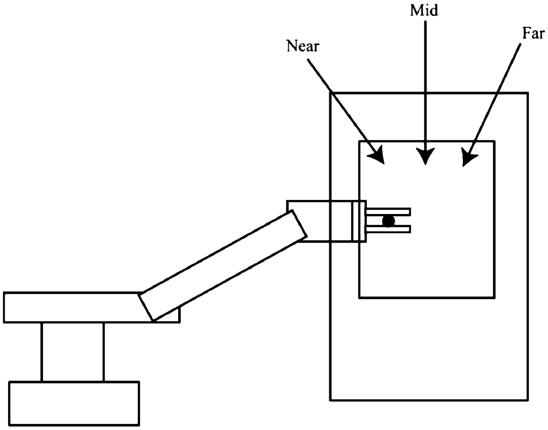


Figure 8
Position of origin for robot locating

Total variation:

$$S_T = (-4.98)^2 + (-9.83)^2 + \cdots + (-14.83)^2$$
$$= 51{,}030.1378 \qquad (f = 9) \qquad (9)$$

Effective divider:

$$r = (-5)^2 + (-10)^2 + (-15)^2 = 350 \qquad (10)$$

Linear equation:

$$L_1 = (-5)(-4.98) + (-10)(-9.83) + (-15)(-14.87)$$
$$= 346.250$$
$$L_2 = 348.950$$
$$L_3 = 344.800 \qquad (11)$$

Variation of proportional term:

$$S_\beta = \frac{(L_1 + L_2 + L_3)^2}{3r} = 1030.0952 \qquad (f = 1) \qquad (12)$$

Variation of proportional terms by joint J_3's movement:

$$S_{J_3\beta} = \frac{L_1^2 + L_2^2 + L_3^2}{r} - S_\beta = 0.0253 \qquad (f = 2) \qquad (13)$$

Error variation:

$$S_e = S_T - S_\beta - S_{J_3\beta} = 0.0172 \qquad (f = 6) \qquad (14)$$

Error variance:

$$V_e = \frac{S_e}{6} = 0.0029 \qquad (f = 6) \qquad (15)$$

Total error variance:

$$V_N = \frac{S_{J_3\beta} + S_e}{7} = 0.0061 \qquad (f = 7) \qquad (16)$$

SN ratio:

$$\eta = 10 \log \frac{(1/3r)(S_\beta - V_e)}{V_N} = 26.85 \text{ dB} \qquad (17)$$

Sensitivity:

$$S = 10 \log \frac{1}{3r}(S_\beta - V_e) = 4.69 \text{ dB} \qquad (18)$$

Analyzed Result

The response graphs of SN ratio and sensitivity regarding joint J_2 are shown in Figures 9 and 10, respectively, and those regarding joint J_3 are shown in Figures 11 and 12. Looking at the SN ratio factor effect plots, we can see that factor C (constant velocity) greatly affects the locating performance.

Table 3
Measurement data for $A_1B_1C_1$ (deg)

	M_1 (−5°)	M_2 (−10°)	M_3 (−15°)	Linear Equation
M_1' (−5°)	−4.98	−9.83	−14.87	L_1
M_2' (−10°)	−4.96	−9.96	−14.97	L_2
M_3' (−15°)	−4.85	−9.81	−14.83	L_3

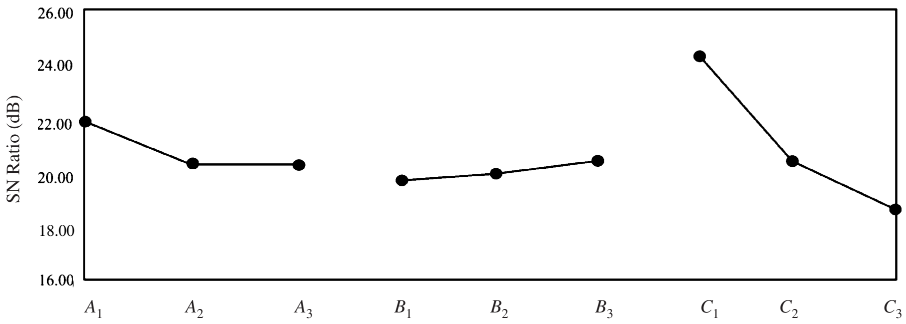


Figure 9
SN ratio for joint J_2

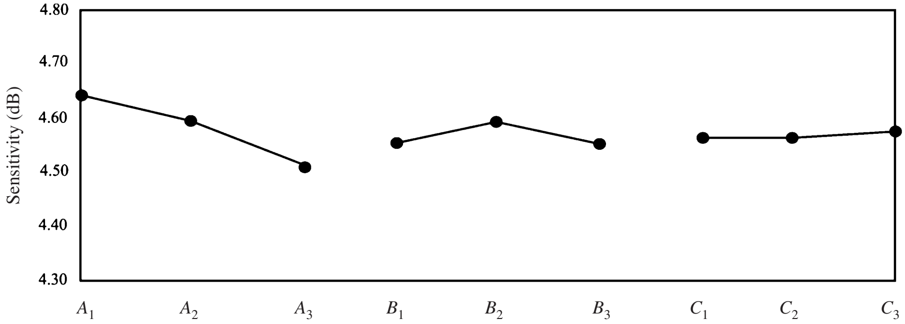


Figure 10
Sensitivity for joint J_2

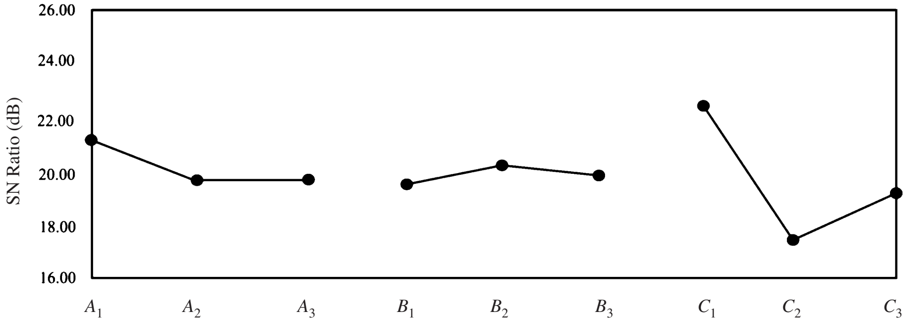


Figure 11
SN ratio for joint J_3

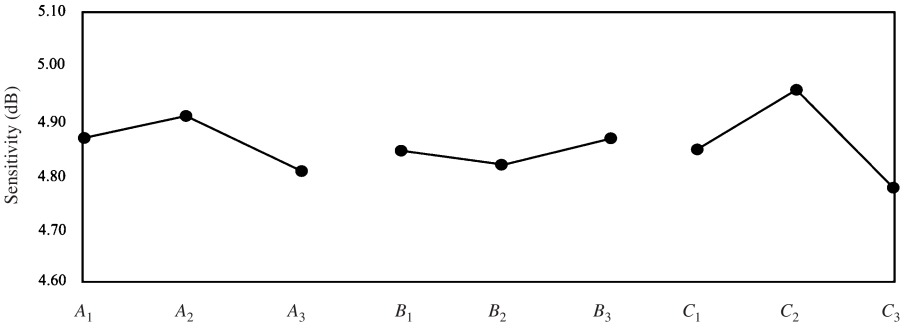


Figure 12
Sensitivity for joint J_3

According to the SN ratio factor effect plots, we notice that the optimal condition is $A_1B_2C_1$, whereas the initial condition is $A_2B_2C_2$. Table 4 shows the results in the confirmatory experiment, which reveals that we can obtain fairly good reproducibility.

4. Future Prospects in Robot Functionality Evaluation

In quality engineering, a variety of methods of evaluating different generic functions based on input/output of energy are proposed. As one application of the methods, we assessed robot functionality. Indeed, a number of problems remain to be solved before reaching a clear-cut conclusion; however, we may be able to evaluate robot functionality by measuring electricity consumption of an articulated robot.

At first, we considered the energy consumed by a robot. Many articulated robots move their arms by driving motors at joints with electric power. This mechanism enables a robot to work. Taking this fact into account, we wished to evaluate its functionality using robot arm's work and electricity consumption. However, work carried by a robot arm does not have the same weight all the time. Then we turned our attention to a free-of-load robot arm, as a robot is considered to consume energy due to the weight of its arm. Now, because of the constant weight of a robot arm, we evaluated its functionality based on a displacement element (i.e., angular value at each joint).

Considering all of the above, we should study its functionality by setting an instruction (angular) value at each joint to a signal factor and an amount of electricity consumed by a robot to a characteristic. In addition, to compare this evaluation method with the one based on "signal = instruction value

Table 4
Estimation of gains and results in confirmatory experiment (dB)

	Joint J_2		Joint J_3	
Condition	**Estimation**	**Confirmation**	**Estimation**	**Confirmation**
Optimal	25.13	25.33	24.25	23.81
Initial	20.69	23.17	18.44	19.28
Gain	4.44	2.16	5.81	4.53

Table 5
Indicative factors

Control Factor		Level 1	Level 2	Level 3
A:	teaching method	Controller	Digit	—
B:	arms used	J_2, J_3	J_2, J_4	J_3, J_4
C:	posture	Folded	Intermediate	Extended
D:	weight (kg)	None	1	3
E:	acceleration	Low	Mid	High
F:	velocity	Low	Mid	High
G:	deceleration	Low	Mid	High

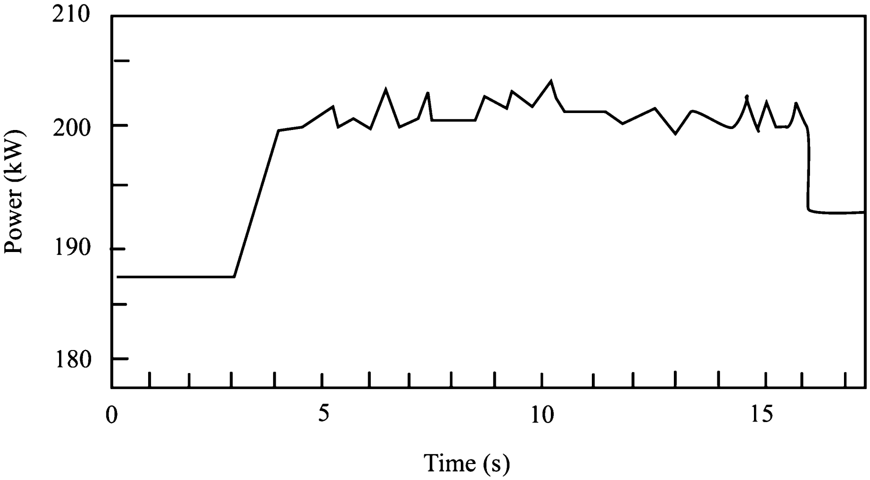


Figure 13
Electric power data

(angular change)" and "characteristic = angular change at a joint," we measured angular changes at joints as eventual movements as well as electricity consumption and defined them as characteristics.

The signal factor levels are as follows:

Level:	1	2	3
Joint instruction value (*deg*):	5	10	15

Allocating the indicative factors enumerated in Table 5, we performed an experiment. Figure 13 indicates the electricity data measured. For analysis of electricity consumption and locating values, we followed the functionality evaluation based on the joint angle discussed before.

Judging from the result of SN ratios measured in electric power, we found that factor *F* has a considerable effect on electric power. For locating, factors *A*, *D*, and *G* have a strong influence. Consequently, the fact that functionality evaluation method using electric power can be applied to an articulated robot demonstrates the validity of functionality evaluation method based on energy.

Reference

Takatoshi Imai, Naoki Kawada, Masayoshi Koike, Akira Sugiyama, and Hiroshi Yano, 1997. A study on the measurement of the generic function of articulated robots. *Quality Engineering*, Vol. 5, No. 6, pp. 30–37.

This case study is contributed by Naoki Kawada and Masayoshi Koike.