A Study of Adjustable Mechanisms with Multiple-Degree of Freedom*

(Number and Dimensional Syntheses of Mechanisms)

Hiroshi SHIMOJIMA**, Osamu SATOH***
and Masayuki KUWABARA****

Adjustable mechanisms with multiple-degree of freedom, whose adjustable inputs are part of redundant inputs which do not play a role in describing their output motion, can optimize characteristics other than the output motion, such as the size and shape of mechanism, operating time, and energy consumption of the actuator. In this paper, the above adjustable mechanisms are studied from the standpoints of both hardware and software, and the characteristics for application to path generators are clarified. Number and dimensional syntheses are carried out in section 1, with consideration given to such kinematic and kinetic characteristics as working space, input torques and joint forces under unit load.

Key Words: Link Mechanism, Multiple-Degree of Freedom, Working Space, Input Torque

1. Introduction

Mechanisms with multiple-degree of freedom are profitable for complicated and flexible applications, but, from the standpoint of responsibility and facility of control, a smaller number of inputs is better. An adjustable mechanism is a product of compromise between these requirements. It is obtained by replacing some time-variable inputs with adjustable inputs, that is, inputs varying by output patterns. When the number of time-variable inputs is less than that of the independent variables determining the state of the object, the adjustable input should be used to change the output of the mechanism, but when it is larger than the number of the independent variables, such

characteristics as the shape of mechanism, operating time, and consumption energy of the actuators may be optimized by the adjustable inputs.

A number of trials has been carried out for a planar adjustable mechanism with 1-degree of freedom which has one time-variable input and one input varying by the output patterns. These trials have aimed to change the shapes of coupler paths^{(1),(2)}, the positions of singular points on coupler curves⁽³⁾, the shapes of functions of input-output angular relationships^{(4),(5)}, and the dwell range of dwell mechanisms⁽⁶⁾. In a redundant mechanism with multiple-degree of freedom, the optimum redundant inputs of manlike articulated robot arms have been obtained⁽⁷⁾, and a method for obstacle avoidance through the use of redundancy has been suggested⁽⁸⁾.

Adjustable path generating mechanisms with multiple-degree of freedom are studied in this paper from the standpoints of both hardware and software. Optimum mechanisms are synthesized, and optimum operating conditions are determined. In section 1, type and dimensional syntheses of closed loop mechanisms are carried out.

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** Department of Mechanical Engineering, Tokyo Institute of Technology, 2-12-1 Ōokayama, Meguro-ku, Tokyo, 152, Japan

*** Miyakonojoh Technical College, 473-1 Yoshio-cho, Miyakonojoh, Miyazaki, 885, Japan

**** Matsushita Electric Industry Co., Ltd., 2-7 Matsubacho, Kadoma, Osaka, 571, Japan

2. Classification of Adjustable Mechanisms

In general manipulator mechanisms, let n be the number of independent variables which are necessary to determine such state variables as the position and velocity of an object, and let m be the number of inputs of the mechanism; then $m_r = m - n (> 0)$ is usually called the number of redundant inputs or freedom. As the human arm shows, mechanisms with redundant inputs can satisfy any condition other than the mechanism output, and therefore they are suitable to operations with various uses or those performed under a severe environment. In this paper, m_t denotes the number of inputs given as functions of time, and m_a represents those given as functions only of output pattern, not of time.

Manipulator mechanisms with multiple-degree of freedom are classified by the degree of freedom of the mechanism, the number of independent variables of the object, and the number of adjustable and redundant inputs, as shown in Table 1. In the table, the abscissas represent time and the vertical lines in the graphs represent the boundaries between outputs. The mechanisms in the first and second columns from the right need no kinematic synthesis for the purpose of satisfying the given output motions because they have redundant freedoms. But extra computing time is needed to determine the optimum redundant inputs, which can be shortened by replacing some parts of redundant inputs with adjustable ones, as in the second

column from the right.

3. Number and Type Syntheses

A synthesis of the mechanisms whose redundant inputs are adjustable ones, i.e., those classified in the second column from the right in Table 1, will be carried out. The kinematic conditions for synthesis are now given as follows.

(i) Mechanisms should be geometrically closed and all of the actuators should be placed on the frame in order to reduce the moving weights.

(ii) The method of adjustment should be such that the fixed joints can move along arcs in order to make adjustments continuously even in the operation of the mechanism.

(iii) Moving circuits should be eliminated from mechanisms in order to increase the rigidity.

The simplest point-path-generator which satisfies the above conditions is a planar mechanism with the number of time-variable inputs $m_t = 2$ and the number of adjustable inputs $m_a = 1$ (which is here called an adjustable mechanism with 2-degree of freedom). Such mechanisms with degree of freedom $m = m_t + m_a = 3$ may be synthesized according to the procedure shown in Fig.1, as follows.

(1) Since the frame has at least 3 pairing elements from the above conditions (i) and (ii), the number of k -nary arms should satisfy

$$N_{a,2} \geq 3$$

Then, we set $N_{a,2} = 3$ and go on to the next step.

Table 1 Classification of mechanisms with multiple-degree of freedom

n : Number of independent variables of body m : Number of inputs $m_r (=m-n)$: Number of redundant freedoms		m_a : Number of adjustable inputs $m_t (=m-m_a)$: Number of time-variable inputs		
Conditions	$m < n$	$m = n$	$m > n$	
	$m_t < n$	$m_a = 0$ $m_t = n$	$m_a > 0$ $m_t < n$	$m_a > 0$ $m_t \geq n$
Name of mechanisms	m -degree of freedom mechanism	m -degree of freedom mechanism with m_t -adjustable input	Redundant m -degree of freedom mechanism	
Pattern of input

(2) Since the number of moving circuits is

$$z \geq 1 + \frac{1}{2} \sum_{k=3} (k-3) N_{a,k} \quad (1)$$

we have

$$N_{a,k} = 0 \quad (k \geq 4)$$

from condition (iii).

(3) When $Z=0$ and a ternary arm exists, the mechanism absolutely degenerates to two or more simpler ones, and we may set

$$N_{a,3} = 0$$

(4) Since the number $N_{c,k}$ of k -nary links ($k > 3$) in a set of coupler links should satisfy

$$\sum_{k=3} (k-2) N_{c,k} = 2(z-1) - \sum_{k=2} (k-3) N_{a,k} \quad (2)$$

we have

$$N_{c,k} = \begin{cases} 1 & (k=3) \\ 0 & (k \geq 4) \end{cases}$$

(5) The total number of coupler links is

$$N_c = 2(z-1) + \sum N_{a,k} + m = 4 \quad (3)$$

(6) The total number of joints on the coupler links is

$$J_c = 3(z-1) + 2 \sum N_{a,k} + m = 6 \quad (4)$$

(7) The number of binary links in a set of coupler links is

$$N_{c,2} = \sum_{k=4} (k-3) N_{c,k} + \sum (k-2) N_{a,k} + m = 3 \quad (5)$$

Two types of 8-link kinematic chains are obtained from the above procedure, as shown in Fig. 2. In the figure, the circumscribed circle 1 denotes the fixed link. The arbitrary two among the three arms 2, 3, and 4 are the time-variable inputs, and the remaining arm is the adjustable input. The output link is an arbitrary member other than those links. Although no kinematic inversion is permissible, many types of adjustable mechanisms with 2-degree of freedom may be obtained by choosing the input and output links properly. These mechanisms are the 7 types derived from Fig. 2(a), and the 3 types from Fig. 2(b). The mechanisms with $N_{a,2}=4$ or 5 may be synthesized by the method described above; the results of this are shown in Fig. 3(a) or (b).

4. Characteristic Analysis and Dimensional Synthesis of Adjustable Mechanisms with 2-Degree of Freedom

Seven types of mechanisms obtained from Fig. 2(a) have simpler structures than the other types,

Fig. 1 Flow chart of number synthesis

Fig. 2 Mechanisms with 3-arms

Fig. 3 Mechanisms with 4 or more arms

and the motion analyses of these mechanisms result in the analysis of a 1-loop, 5-link mechanism. In order to facilitate the motion analysis, let the fixed joints of both adjustable input link 2 and time-variable input link 3 in Fig. 2(a) coincide, and further let the links 2, 3, 5, and 8 form a parallel quadrilateral, which will not cause a significant change in the displacement characteristics of the mechanism. Such a mechanism, as shown in Fig. 4, is optimally synthesized with consideration given to the kinematic and kinetic characteristics.

4.1 Characteristics of 5-link mechanisms

The parallel quadrilateral 2-3-5-8 has no influence on the output of the 8-link mechanism, and the parameters for synthesis are the link lengths $l_0, l_1, \dots, l_4$ of the 5-link loop ABCDE of Fig. 5. The characteristics may be evaluated quantitatively in terms of working space, input torque, and joint force under the restrictions of the maximum pressure angle and output continuity.

Fig. 4 Adjustable mechanism with 2-degree of freedom

Fig. 5 Working space of 5-link mechanism

(i) Working space

Adopting a cartesian coordinate system whose origin is the midpoint of AE, the outer boundary of the existing domain of the output point C is almost determined by two circles whose radii are $l_1 + l_2 (=r_1)$ and $l_3 + l_4 (=r_2)$ and whose centers are on the points A $(-l_0/2, 0)$ and E $(l_0/2, 0)$, respectively. The area S of the domain enclosed by these circles is given by $(l_0/2 = 1)$

$$S = r^2 \left\{ \left[\frac{1}{1+k} \right]^2 (\pi - \Theta) + \left[\frac{k}{1+k} \right]^2 \Phi \right\} - \frac{1}{2} \sqrt{(r^2 - 4)} \left\{ 4 - \left[\frac{1-k}{1+k} \right]^2 r^2 \right\} \quad (6)$$

where

$$\cos \Theta = -\frac{1}{r} \left[1 + k + \frac{1-k}{4} r^2 \right]$$

$$\cos \Phi = \frac{1}{kr} \left[1 + k - \frac{1-k}{4} r^2 \right]$$

$$r = r_1 + r_2, \quad k = \frac{r_1}{r_2}$$

The nondimensional areas $S/S_{\max}$ are shown in Fig. 6. Since the areas take the maximum values at $k=1$ for any r , and decrease to almost 90% of the maximum values at $k=1.4 \sim 1.8$ in the range of $r=4 \sim 12$, we set $k=1$, that is, $l_1 + l_2 = l_3 + l_4$. The ratios of link lengths $l_2/l_1, l_4/l_3$ may be determined as follows. Drawing circles whose centers are the origin and whose radii are $r_0 (=1, 2, \dots, 7)$, and lines which pass through the origin and incline at angles of $10^\circ \times i (i=0, 1, \dots, 9)$, we determine $7 \times 36 + 1 = 253$ points of intersection. The working space can be estimated approximately from the total number of such intersection points as satisfying the conditions for pressure angle and output continuity when the output point C exists on that point. The signature of $\angle BCD$ (that of $\overrightarrow{CB} \times \overrightarrow{CD}$) should not change in a working space. And if the maximum allowable pressure angle is 60° , $30^\circ < \angle BCD < 150^\circ$

Fig. 6 Area enclosed by two circles

should be satisfied.

(ii) Input torque and joint force

On a vertical moving plane of the mechanism, applying a unit pay load on the output point C, taking no account of any external force and mass of link, we obtain the static input torques M_1 , M_2 of the time-variable inputs and the static joint forces F_1 , F_2 at the moving joints B, D of the arms. The torques and forces may be estimated from the mean values ($\bar{M}$, $\bar{F}$) and their maximum values in a working space. These characteristics are investigated for three types of loops shown in Fig. 7.

4.2 Results of analyses and dimensional syntheses

The relationships between the link lengths $l_2/l_1 (= k_1)$, $l_4/l_3 (= k_2)$ and the working space of the mechanism

Fig. 7 Loop pattern of 5-link mechanisms

Fig. 8 Working space of mechanism I

I (loop I in Fig. 7) under $l_0 = 0.5 \times n (n=0, 1, \dots, 4)$ are shown in Fig. 8. The ordinates mean the ratios of the working spaces compared to the working spaces when $l_1 = l_2 = l_3 = l_4$, $l_0 = 0$. The torques and forces of the mechanism I and the characteristics of other types of mechanisms will all be represented by the ratios divided by those values of the basic mechanism I with $l_1 = l_2 = l_3 = l_4$, $l_0 = 0$, as above. Since the working spaces have the maximum values when $k_1 = 1.0 \sim 1.5$, $k_2 = 0.75 \sim 1.0$, we may set $k_1 k_2 = 1$; then we have

$$l_1 = l_4, \quad l_2 = l_3 \quad (7)$$

The input torques and joint forces under Eq. (7) are shown in Fig. 9. From the graph, we find that the working spaces have large values and the mean and maximum values of input torques and joint forces have small ones when

$$l_0 = 0.0 \sim 1.0, \quad k_1 \left[= \frac{1}{k_2} \right] = 1.0 \sim 1.5 \quad (8)$$

Figure 10 shows the results of mechanism II. The working spaces, Fig. 10(a), have large values when $k_1 = 0.4 \sim 0.6$, $k_2 = 0.4 \sim 0.75$ regardless of l_0 ; that is,

$$l_1 = l_3, \quad l_2 = l_4 \quad (9)$$

and they are about 60% of the values of the basic mechanism. The input torques, Fig. 10(b), also have large values under Eq. (9), the mean and maximum

Fig. 9 Input torque and joint force of mechanism I

Fig. 10 Characteristics of mechanism II

values of which are respectively 1.6~2.0 times and 2.6~2.8 times the values of the basic mechanism. The joint forces, Fig. 10(c), are almost constant, and their mean and maximum values approximately coincide with those of the basic mechanism. From the above analyses, it has become clear that although mechanism II may have less motion space (the space which can be swept by the moving parts of the robot arm), the working space is smaller and the input torque and joint force are larger than those of mechanism I.

Some results for mechanism III are shown in Fig. 11, which shows that the working space is at most one-half that of the basic mechanism.

5. Conclusions

This paper has analyzed and synthesized an adjustable path-generating mechanism with multiple-degree of freedom in relation to kinematic and kinetic characteristics. Redundant mechanisms, including adjustable ones, have been classified according to the numbers of time-variable inputs and path-pattern-variable inputs. Number and type syntheses have been carried out for planar adjustable path

Fig. 11 Characteristics of mechanism III

generators with 2 time-variable inputs and 1 adjustable input, and 10 types of 8-link mechanisms have been obtained. One of the above mechanisms has been synthesized dimensionally, with consideration given to the working space, input torques, and joint forces.

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