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Method for Determining the Power-saved Driving Motion of Manipulators by Heuristic Algorithms (In Case of CP Control)

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Abstract:
This study proposes a method for suppressing the torques of the manipulators, with considering the effect of inertial forces in order to achieve the power-saved drive. The present study generates the trajectories, which here reveal time profiles of positions, velocities and accelerations of the entire path of the output point of manipulators. The trajectories of manipulators are introduced by determining both the initial position and motion curves for the entire path. This study expresses the motion curve as a polynomial and determines its coefficients. The initial pose and unknown coefficients are decided by a heuristic algorithm to achieve power-saved drive. As such problems have non-linearity and multi-peak solutions, it is difficult to find out the optimum one. Thus, this study uses a heuristic algorithm "SHA" to determine the appropriate motions of manipulators, because the heuristic algorithm is, as well known, an effective solution for such complicated problem. This study determines the optimal motions of the PUMA560 comprising spatial 3 degrees-of-freedom by the proposed method, and verifies its availability.

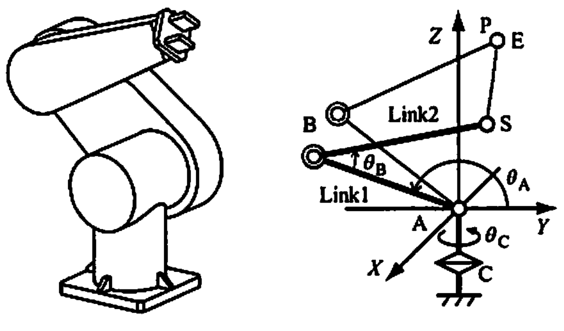
Keywords: Dynamic torque, Heuristic algorithm, Manipulator, Power-saved, CP control

1. Introduction

The determination for the motion of manipulators mainly depends on their kinematics; dimensions, works, environments, etc. However, although their dynamics strongly influence the driving torques, they are rarely considered due to the complicity and non-linearity. Also, the initial pose in the motion strongly influences the driving torques. Consequently, the motions that may cause excessive loads to manipulators are often used. Thus, this study presents a method for determining the optimum motion and the initial pose of a manipulator to suppress their driving torques by using a heuristic algorithm.

2. Power-saved Driving in Case of CP Control

Previously, we have proposed the method for determining the power-saved driving motion of manipulators that are driven by point to point (PTP) control [1]. The previous method determines the optimum motion of each input joint of a manipulator. However, manipulators are often driven by continuous path (CP) control, when they are employed for welding, painting and so on. Since the joint motions are dependent on the work path in such case, the previous method can not be applied directly. Thus, the study proposes the method for determining the power-saved driving motion of manipulators that are driven by CP control. The proposed method determines the trajectory that reveals time profiles of positions, velocities and accelerations of the output points of manipulators.



(a) Outline (b) Skeleton model

Figure 1: Articulated manipulator

3. Expression of the Motion

In this study, the trajectories of manipulators are provided by determining both the initial position and motion curves of the work path, which yield time profiles of displacements, velocities and accelerations of the driving joints. This study expresses the motion curve as a polynomial for ease of treatment. The motion curve of the work path displacement is expressed as follows:

$$S = C_0 + C_1 T + C_2 T^2 + \cdots + C_n T^n \qquad (1)$$

where C_i (i=0 ~ n) are unknown coefficients of the polynomial and T is a parameter obtained as operation time divided by the total work time. The velocity S' and acceleration S'' of the output points are obtained by differentiating S with respect to T.

Here, as motion curves expressed by Eq.(1) should be two-dwell motion, S' and S'' equal to zero at both T=0 and T=1. Further S becomes zero at T=0 and is set to the maximum value at T=1. Thereby C_i (i=0~2) become zero and C_i (i=3~5) are determined from the above conditions. C_i (i=6~n) are used as unknown parameters and varied to determine the appropriate motions.

4. Evaluation Function

Driving torques of an articulated manipulator such as shown in Fig.1 can be determined by the following equation;

$$T = H\ddot{\theta} + C(\theta,\dot{\theta}) + T_g \quad (2)$$

where T is a vector composed of torques needed for respective input joints. H is an inertia matrix; C is a vector that expresses influence of Coliolis force and centrifugal force; T_g is a vector that expresses torque at each joint caused by gravity. Although the above equation does not have terms that reveal frictions of joints and efficiency of reduction of gear and so on, these influences will be easily added to the above equation if they can be identified.

In this study, driving torques are suppressed by selecting the appropriate initial pose and motion curve of a work path. To suppress the input torques, the motion of a manipulator is determined so that maximum torque induced in all input joints during operation is minimized.

Here the study deals with the commercially available articulated manipulator "PUMA560" shown in Fig.1. The arm mechanism of the manipulator comprises spatial three-degrees of freedom mechanism. As shown Fig.1(b), θ_A, θ_B represents joint angle of point A and B which rotate link 1 and 2 respectively in a plane. θ_C denotes angle of swirling the link 1 and 2 around Z axis.

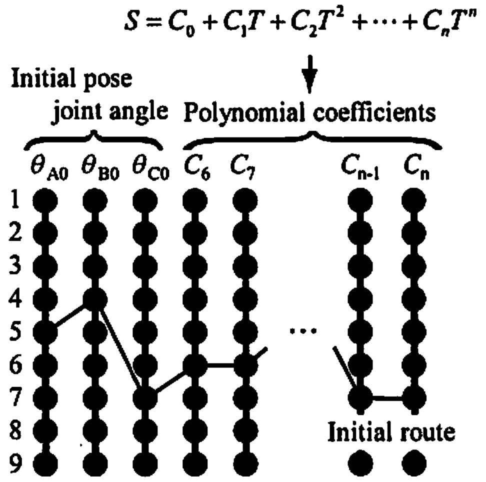


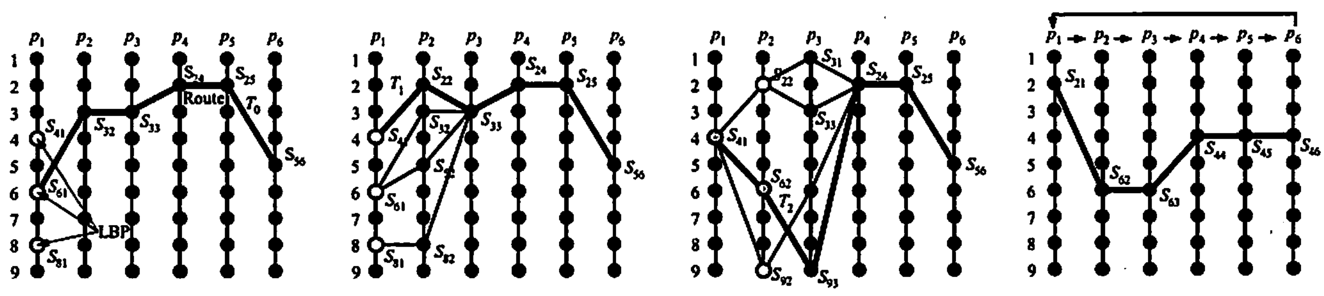
Figure 2: Parameter space matrix

5. Method for Determining Motion Curve

The dynamic and static characteristics of articulated manipulators change complicatedly with their own motion. The determination of the optimum motion is difficult since it becomes non-linearity and multi-peak problem. A heuristic algorithm is, as well known, an effective solution for such a complicated problem. Thus, the study uses a heuristic algorithm "SHA" to determine the appropriate motion of the manipulator. The SHA is an algorithm proposed by S. Lin[2] and applied to mechanical design by T. W. Lee[3], and modified for the design of robot mechanisms by H. Tachiya[4].

The SHA expresses design parameters in a matrix as shown Fig.2. The columns of the matrix denote the sort of the design parameters; the element of each column represents the discrete state of each parameter within its given scope. The above matrix is called as the parameter space matrix. The parameter space matrix on this problem is expressed as Fig.2. The element in the i-th row, the j-th column, S_{ij} (i=1~M : j=1~N), denotes the i-th discrete value of the j-th design parameter. The first, second and third columns of the matrix denote θ_{A0}, θ_{B0} and θ_{C0}, which are initial value of θ_{A0}, θ_{B0} and θ_{C0} respectively, for determining the initial pose. The forth to N-th columns denote unknown coefficients C_i (i=6~n) of a polynomial that reveals the motion curves. C_i denotes the coefficient of the motion curve of work path; i (i=6~n) denotes the coefficient of i-th degree term. The motion of the manipulators can be determined by selecting one element, which is one of the discrete values of each design parameter, at every column. The combination of such parameters, which is illustrated by a kinked line in Fig.3, is referred to as a "route." The SHA seeks a better combination of design parameters by operating the route. The following shows the concrete procedures by the example using a 9×6 parameter space matrix, which has 6 design parameters and 9 discrete values for each design parameter, as shown in Fig.3.

Step 1 : First, a certain number of initial routes are randomly determined. The SHA evaluates each route and find out the best route that has minimum evaluation value. The best route is referred as to a basic route T_0 as illustrated in Fig.3(a). Note that as the present problem imposes the motion curve to increase monotonically, a newly generated route always replaces the route that does not satisfy that condition.



(a) Steps 1~3 for the 1st column

(b) Step 4 for the 1st column

(c) Steps 2~4 for the 2nd column

(d) Step 7

Figure 3: Diagrams of the procedures by the SHA

Step 2 : The better element is searched from the first column in order by the SHA algorithm. The SHA finds out the better route (the better combination of the design parameters) by operating both elements in i-th and $(i+1)$-th column at the same time. Concretely, a specified number of elements are newly selected at i-th column as a candidate of the better element randomly. The newly selected element and the element originally involved in the basic route are collectively called as LBP (Look ahead Base Point[3].) Fig.3(a) shows the case in which a number of LBP is three; S_{41} and S_{81} are newly selected in addition to S_{61} involved in the initial basic route.

Step 3 : The SHA randomly selects elements of $(i+1)$-th column that should be connected to the respective LBPs selected at Step 2. Fig.3(a) shows the example that the elements S_{52}, S_{22} and S_{82} are selected to the LBPs S_{41}, S_{81} and S_{61} respectively. As a result, new three routes are generated as candidates for a new basic route.

Step 4 : Compare the evaluation values of those newly determined routes at Step 3 and the original basic route as shown in Fig.3(b), to set the best route as a new basic route. If plural routes reveal the same minimum evaluation value, the route originally generated is selected as a basic route. The element in the i-th column of the above-determined route is selected as the element of a new basic route "T_i" ; subscript "i " indicates the elements of i-th column of the basic route have been already determined. Note that the element in $(i+1)$-th column that simultaneously determined with the element in i-th column is reconsidered at the next stage. In the example shown in Fig.3(b) the route "T_1" is selected and S_{41}, the gray colored element of the first column, is determined as the value of the first design parameter.

The SHA repeats the above procedures to determine the elements in $(N-1)$-th column. The example shown in Fig.3(c) shows that the operation of second column, in which S_{22} (the elements involved in the basic route "T_1"), S_{62}, S_{92} are selected as LBPs, and the elements S_{13}, S_{93}, S_{63} are selected as the connected elements in fourth column to the LBPs respectively, while the first and fifth and later parameters are held fixed. The SHA compares T_1 and newly generated routes by the respective LBPs with regard to the evaluation function, and determines the best route that has the minimum evaluation value as the basic route "T_2."

Step 5 : In the N-th column, evaluate all elements (discrete values of a design parameter) as the candidate for the N-th design parameter and determine a basic route "T_N."

Step 6 : Return to Step 2 and repeat the procedures of Steps 2~6 by using the above-obtained route "T_N" as a basic route "T_0" again.

Step 7 : When there is no profit in the evaluation function by repeating the procedures of the Steps 2~6, the last column of the parameter space matrix is moved to the 1st column; the original first to $(N-1)$-th columns are shifted backward by one column as shown in Fig.3(d). After the transformation of the parameter space matrix, the procedures of Steps 2~6 are repeated. If the first column of the original parameter space matrix becomes first column again, go to Step 8.

Table 1: PUMA560 specification

	l (m)	lm (m)	m (kg)	I (kgm^2)
Link 1	0.432	0.068	17.4	5.25
Link 2	0.433	0.070	4.8	0.92

Table 2: Work path configuration

Displacement (m)	X-axis	-0.3
	Y-axis	0.3
	Z-axis	0.3
Work time (s)	1.0	

Table 3: Ranges and step size of the design parameters

(a) Preliminary search

Parameter	Range	Step
C_6~C_{11}	-20 ~ +20	0.4
θ_A(deg)	-90 ~ +90	1.8
θ_B(deg)	0 ~ +90	3.6
θ_C(deg)	+30 ~ +120	0.9

(b) Refinement search

Parameter	Step
C_6~C_{11}	0.02
θ_A(deg)	0.2
θ_B(deg)	0.2
θ_C(deg)	0.2

Table 4: Evaluation value and initial pose

Motion curve		Tmax (Nm)	θ_A (deg)	θ_B (deg)	θ_C (deg)
SHA	1	27.63	68.2	88.6	13.8
11th polynomial	2	52.54	62.6 *	55.1 *	0.0 *
Modified trapezoid	3	28.52	79.2	74.9	26.6
	4	88.49	62.6 *	55.1 *	0.0 *

(*) Initial pose given

Table 5: Polynomial coefficients

Coefficients	C_3	C_4	C_5
	5.34	-11.24	9.84

C_6	C_7	C_8	C_9	C_{10}	C_{11}
8.30	-16.98	9.70	-16.30	17.84	-5.50

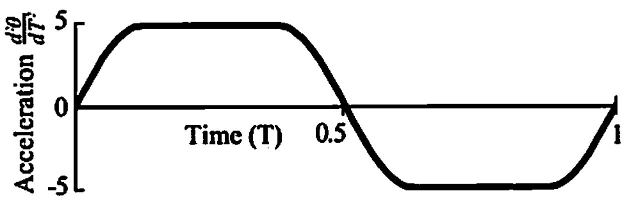


Figure 4: Normalized acceleration of modified trapezoid

Step 8 : As well known, heuristic algorithms may not always find out the optimum solution but yield satisfying ones that are probability near to the optimum value. Thus, in order to improve the optimally of the above-obtained solution, the step size of each design parameter is subdivided with the above-determined value as the center value. With the reconstructed parameter space matrix, the operations of the Steps 2~7 are performed again.

As above mentioned, the SHA performs the operation of a parameter space matrix by two stages; the first stage is

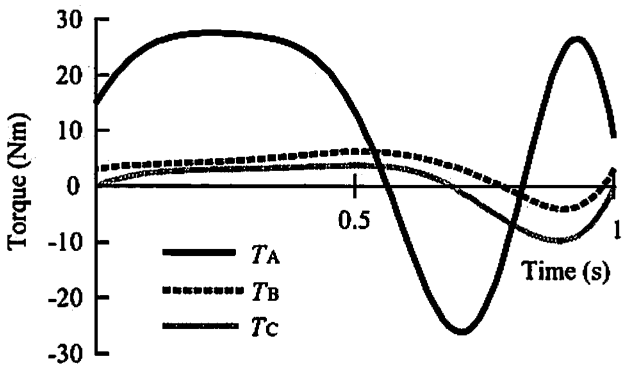
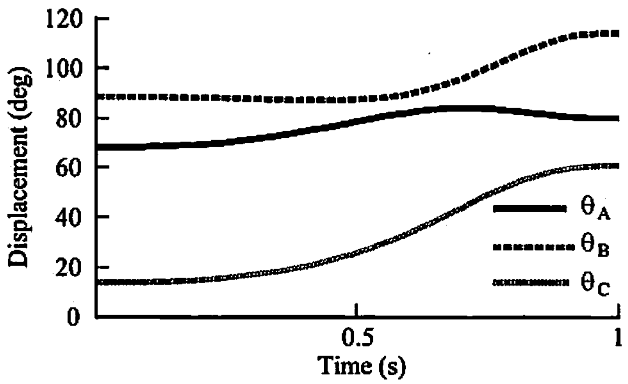
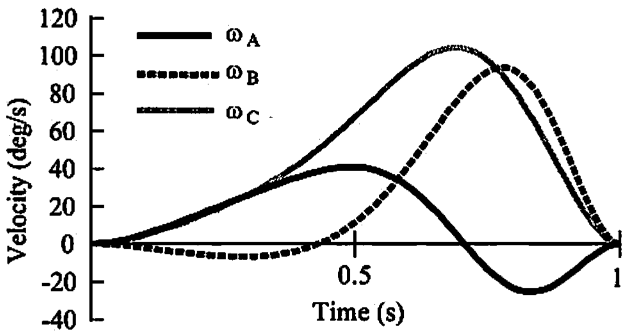


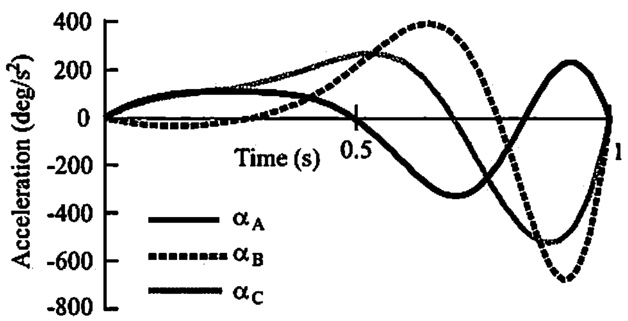
Figure 5: Changes in torques (11th polynomial)



(a) Changes in angular displacement



(b) Changes in angular velocity



(c) Changes in angular acceleration

Figure 6: Changes in angular displacement and velocity and acceleration of evaluation function maximum torque

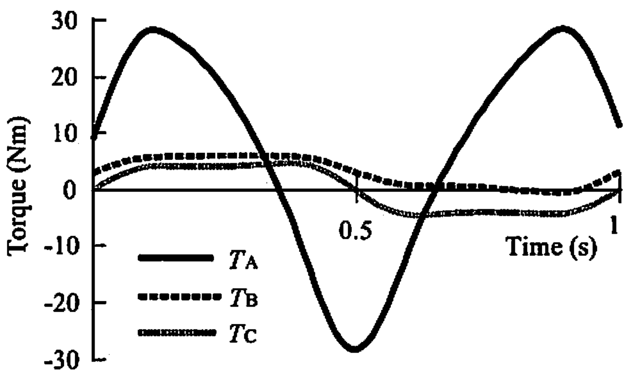


Figure 7: Changes in torques (modified trapezoid)

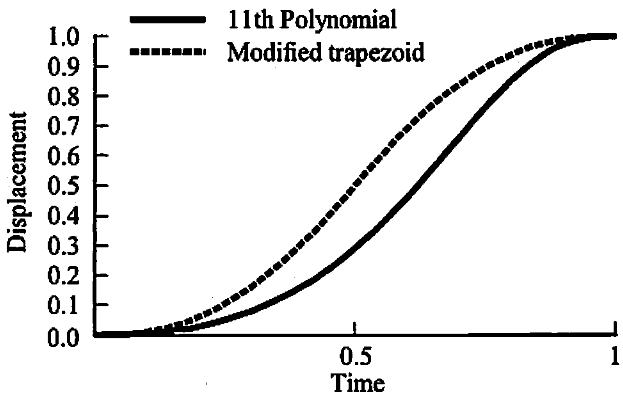


Figure 8: Normalized displacement of motion curve

referred as to preliminary search, the next stage that uses a subdivided parameter space matrix is referred as to refinement search.

6. Determination of the Motion for PUMA560

6.1 Conditions for the Determination

The specification of the manipulator is shown in Table 1[5]. This study uses 11th-degree polynomials to express the motion curve of the output point P of the manipulator. We had performed trial determination of the motion curve by changing degree of polynomials with regards of computational time and quality of the result to determine appropriate one. The investigated work path is straight line and the displacements for X, Y and Z directions are shown in Table 2 with the operation time. The motions of the input joints of the manipulator can be easily determined by inverse kinematics, since it is a spatial 3 degrees-of-freedom mechanism without redundancy. Table 3(a) and (b) indicate the range and step size of each design parameter at the preliminary and the refinement searches respectively.

Since the SHA, like other heuristic algorithms, uses random number, the yield solution varies with every search for the same problem and is not always the optimum. Thus, the proposed method repeats the search of a motion curve one hundred times for the same problem, and selects the best solution among the obtained results.

Obtained motions for the manipulator are compared with the motion using the modified trapezoid, which is two-dwell motion curve and often used for the work path motion of

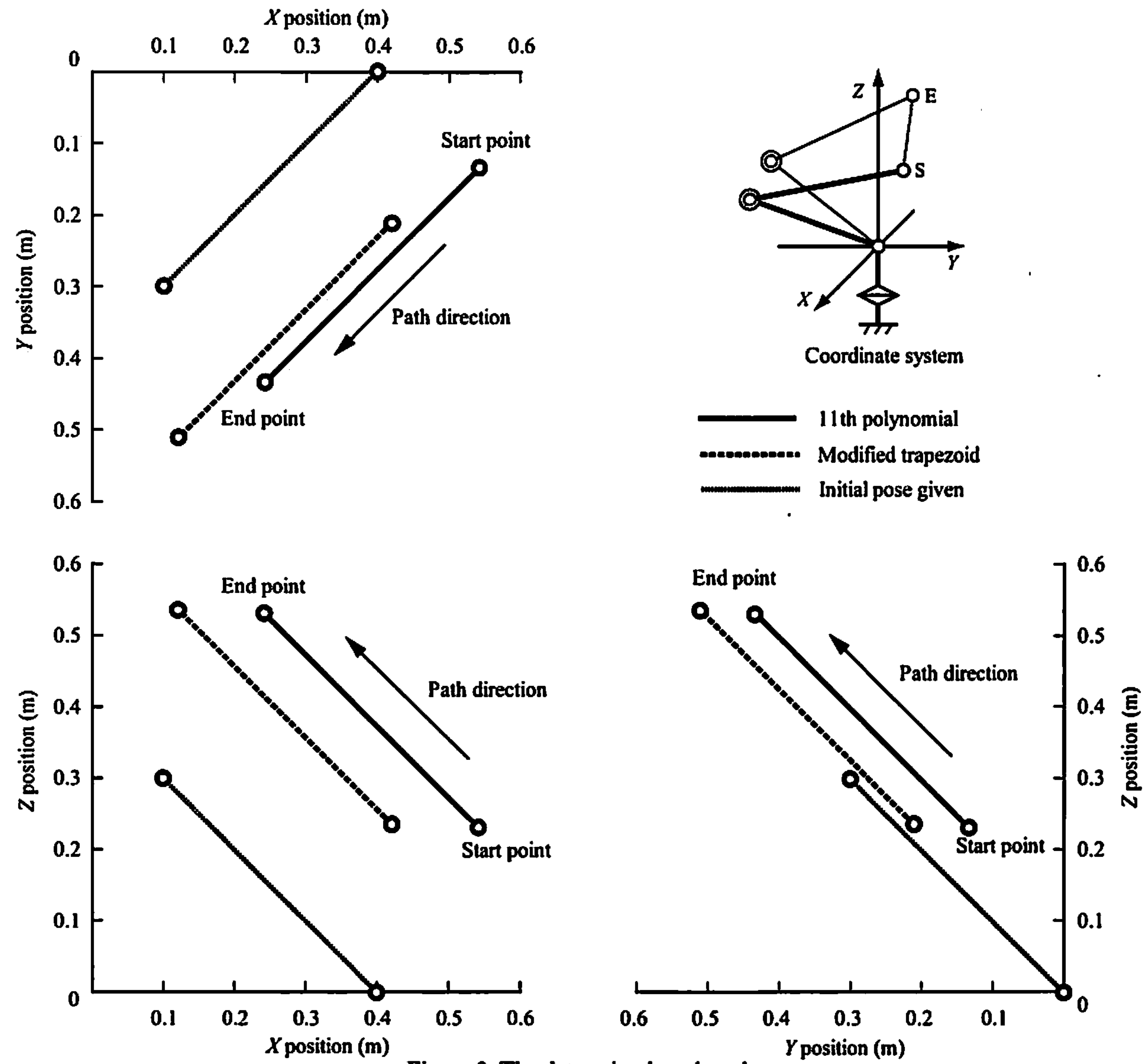


Figure 9: The determined work path

robots. The normalized acceleration of the modified trapezoid motion curve is shown in Fig.4.

This study determines the motion of the manipulator with the driving torque expressed by Eq.2 as the evaluation function by the proposed method. The motion is determined so that the maximum value among the driving torques generated at all input joints during the total motion may be minimized. While the proposed method also can use RMS, consumption energy and so on easily, the maximum torque was used as the evaluation value, since the RMS and consumption energy have some tendency with the driving torque.

6.2 Results and discussions

Firstly, the study determined the only motion curve of the output point, assuming that the initial pose was given as described in Table 4(2), (4). The initial pose was set near the center of the total work space of the manipulator. Table 5 shows the determined coefficients of the motion curve that express motion of the output point, and the maximum driving torque generated by the determined motion is shown in Table 4. For comparison, Table 4(2), (4) show the maximum driving torque that is generated when the modified trapezoid is used with the same initial pose. The obtained motion curve reduce the maximum driving torque by 41% (from 88.5Nm to 52.5Nm) comparing with the modified trapezoid. Namely, even if the initial pose is given, the proposed method can improve the maximum driving torque by determining an appropriate motion curve.

Next, the initial pose was only determined with the proposed method by using the modified trapezoid as the motion curve. Figure7 shows the changes in torques of the input joints. Table 4 shows the determined initial pose and the value of the maximum driving torque. Comparing with the case that the initial pose is given as shown in Table 4(3), (4), the maximum driving torque is reduced by 68% (from 88.5Nm to 28.5Nm). Namely, the determination of the initial pose significantly affects the optimization of the motion of the manipulator.

Furthermore, both the initial pose and the motion curves expressed by 11th-degree polynomial were simultaneously determined with the proposed method. Figure 5 shows changes in torques of the input joints, those angular displacements, velocities and accelerations are shown in Fig.6. Table 4(1) and 5 show the determined initial pose, coefficients of the motion curve, and the maximum torque. The motion curve is drawn in Fig.8. The comparison of resultant paths is shown in Fig.9. As known from the result, the maximum torque is reduced by 47% (from 52.5Nm to 27.6Nm) comparing with the one in the case that the initial pose is given as shown in Table 4(1), (2). Thus, the determination of both the initial pose and the motion curve with the proposed method is significantly available to achieve the power-saved driving motion of manipulators.

From the above results, the proposed method that based on the heuristic algorithm SHA is effective to optimize the motion of the manipulator that is driven by CP control.

As well known, the GA (Genetic Algorithm) is a representative heuristic algorithm and applied to various fields [6]. Thus, we have tried to use with GA as search engine as well as the SHA. The SHA does not need to convert design parameters into special expressions, while the GA needs a genotype model. Additionally, the GA has to be tuned many parameters; individual number, crossover ration and mutation ration, etc. Thus, the proposed method based on the SHA is very effective to determine the optimum motions of manipulators.

7. Conclusions

(1) This study proposed the method for determining of the motion of manipulators driven with CP control, which determines the optimum motion curves of the work path and the initial pose of a manipulator by heuristic algorithm SHA so as to suppress the driving torques.
(2) The motion curves of the output point and the initial pose of the articulated manipulator "PUMA560" were determined by the proposed method. Comparison of the obtained motion curves with a conventional one shows that the presented method can reduce the torques effectively. In addition, the determination of the initial poses of a manipulator significantly affects the suppression of the driving torques.
(3) The proposed method does not need complicated tuning of the parameters for searching of solutions and conversion of the design parameters to special expression such as the GA, which is representative heuristic algorithms, needs. Thus the proposed method is available to determine the power-saved driving motion of a manipulator.

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