Analysis and Classification by Geometric Characteristics of Robot Wrist Configuration*

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The purpose of this paper is the analysis and classification of robot wrist configurations by geometric characteristics of orientation and canceling. The relationships between wrist configurations and these characteristics must be specified for designing the kinematic mechanisms of a robot. The analysis and classification are performed, dealing with a list of useful wrist configurations. The process of establishing the list is as follows : 1) exhaustively enumerating types of wrist combinations, 2) forming rules to exclude duplicate or ineffective combinations among enumerated wrist configurations, 3) listing the useful wrist configurations without duplicate or ineffective configurations. Each wrist combination in the list is analyzed in view of the geometric characteristics consisting of the orientation and canceling characteristics. From the result of the analysis, the respective wrist configurations are classified according to their orientation and canceling characteristics.

Key Words : Precision Machine, Industrial Robot, Wrist Configuration, Geometric Characteristics, Orientation Characteristic, Canceling Characteristic, Analysis and Classification of Wrists

1. Introduction

A robot arm configuration controls the position of the manipulator in order to reach a point in workspace, while a wrist configuration controls the orientation to get to a target point. This thesis deals with the wrist configurations which have two or three degrees of freedom, and establishes a list of useful configurations. To establish the list of wrist configurations, first, the possible types of wrist joint combinations are exhaustively enumerated. Next, the duplicate or ineffective combinations among these enumerated wrists are eliminated.

The useful wrist configurations involved in the above-mentioned list are analyzed in view of their geometric characteristics. The geometric characteristics of the wrist configurations consist of orientation and canceling characteristics. As a result of the analy-

sis, each wrist configuration is classified by their orientation and canceling characteristics.

The significance of the list is to provide an effective database for selecting the wrist configuration suitable to the orientation motions required for completing a given task.

2. Orientation Control Parameters of Wrist Configuration

A unit sphere centered at a point "O" is illustrated in Fig. 1⁽¹⁾. When the end point "P" of an arm is set to an arbitrary point on the sphere, the values of the "P"

Fig. 1 Parameters for orientation control of wrist configuration⁽¹⁾

*Received 22nd March, 1990. Papar No. 88-0986B

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coordinates are determined by each independent angle θ and ϕ . Since a line between points "P" and "O" signifies an orientation direction from points "P" to "O", the wrist configuration can specify the orientation to reach point "O" by two degrees of freedom, θ and ϕ . When orientation control around the axis along the direction of the line is needed, further degree of freedom is required (ω). Here a vector which consists of the orientation direction (θ and ϕ) and the extra orientation (ω) around the line axis is designated as an "orientation-indicating" vector⁽²⁾. Therefore, the wrist requires three degrees of freedom in order to control arbitrary orientations in the workspace. The θ , ϕ , and ω parameters are designated as the orientation control of the wrist.

In Fig. 2, several terms in relation to the wrist configurations are defined. The vectors on the link between the arm and wrist, and the third link of the wrist (or the second link of the wrist, in the case of the wrist possessing two degrees of freedom) are the unit "orientation-indicating" vectors " a^* " and " e^* ". At the original posture of the arm and wrist configurations, the third link of the arm connects the link between the arm and wrist with the same directions about their link axes. The original posture of the wrist configuration is such that the directions of all the links involved in the wrist configuration in Fig. 2 are identical to the positive direction about the Z axis.

3. Establishment of Wrist Configuration List

To establish the list of useful wrist configurations, preconditions are made. Based on the established preconditions, alternative types of wrist joint combinations which have two or three degrees of freedom are exhaustively enumerated. The useless combinations of the wrists, which have redundant degrees of freedom and duplicated expressions in spite of the

Fig. 2 Terms and original posture of wrist configuration (i , j , and k are the unit vectors about the X, Y, and Z axes, respectively)

same configurations, exist in the enumerated combinations. To remove the ineffective and duplicate combinations, the rules to exclude such configurations are set.

3.1 Preconditions for establishing the wrist configuration list

Three preconditions are prepared for the list of useful wrist configurations. First, the arm configuration has the function of position control, while the wrist has the function of orientation control. The arm configuration consists of combinations of rotational, pivotal, and prismatic joints. The wrist configuration is composed of rotational and pivotal joints except the prismatic joint. The reason why the wrist must not involve the prismatic joint is that this joint has a disadvantage in controlling the orientation with regard to the manipulability of the joint movements.

Second, the alternative combinations of the wrist are composed of the following joints of one degree of freedom: the rotational joint (R_0 : $\diamond$) and the pivot joints (T_1 : $\odot$, T_2 : $\oplus$). Third, the subject of the wrist in the list is the only configuration without off-set connection between each link involved in the wrist.

3.2 Elimination rule of duplicate or ineffective wrist configurations

The rules in Fig. 3 are defined so as to eliminate the duplicated or ineffective wrist configurations from comprehensively enumerated types of wrist joint combinations^{(3),(4)}. Now, case 1 and case 2 in Fig. 3 are explained as follows.

Case 1: Duplicate combinations

In the enumerated types of wrist joint configurations, there are duplicate types of joint combinations in spite of an identical wrist type. The

CASE	ELIMINATION RULE	EXAMPLE
Case 1: DUPLICATE COMBINATIONS of Wrist Joint Configurations	Wrist Rule 1: DUPLICATE COMBINATIONS --When a point of view is turned by 90 degrees, the representation of one joint configuration becomes the same as that of another.	
Case 2: INEFFECTIVE COMBINATIONS of Wrist Joint Configurations	Wrist Rule 2: INEFFECTIVE COMBINATIONS which degenerate degrees of freedom.	
	Wrist Rule 3: INEFFECTIVE COMBINATIONS which lack three (or two) degrees of freedom for orientation control.	

Fig. 3 Elimination rule of duplicate or ineffective wrist configurations^{(3),(4)}

uplicated combinations must be consolidated with a single wrist type. In this case, a wrist configuration which has the pivot joint ($T_1: \odot$) around the X axis existing in a position closer to the first wrist joint is selected from the duplicate joint combinations (see "Example" of "Wrist Rule 1" in Fig. 3).

Case 2 : Ineffective combinations

The ineffective wrist joint combinations are those in which the three motion-degrees of freedom (or two motion-degrees in the case of two-joint combinations) required for orientation control in workspace are lacking.

3.3 List of useful wrist configurations

When wrists of two or three degrees of freedom are enumerated, the total number of combinations is $36 (= (3 \times 3) + (3 \times 3 \times 3))$. As a result of eliminating the duplicated or ineffective configurations from the total combinations based on the elimination rules, the list comprises 13 useful types of wrist configurations shown in Fig. 4.

4. Analysis of Geometric Characteristics of Wrist Configurations

The geometric characteristics of the 13 wrist configurations in the list are analyzed in terms of the next two points.

(a) Orientation characteristic: the wrist's manipulability to control the orientation of an object by an end effector connected to the end point of the wrist⁽⁵⁾(see section 4.1).

(b) Canceling characteristic: in the case of movements of an object maintaining its posture, the wrist's manipulability to cancel the undesired change of object orientation generated by motions of the arm⁽²⁾(see section 4.2).

4.1 Orientation characteristic of wrist configuration

The orientation of the third link on the wrist directly influences the orientation of the object. In terms of two degrees of freedom, the direction of the second link on the wrist corresponds to the above-mentioned orientation of the object. As shown in Fig. 5, to analyze the orientation characteristic, the behavior of the "orientation-indicating" vector " e^* " is examined by fixing vector " a^* " on the link between the arm and wrist (see Fig. 2).

Before the analysis of the orientation characteris-

NO.	W-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	-12	-13
Wrist Joint Configuration													

Fig. 4 List of useful wrist configurations

tic in Fig. 6, the four preconditions are determined. First, the movement range of the rotational and pivotal joint is from zero to 180 degrees. Second, trajectories about the end point of the second link are illustrated with graphic wire-frame representation. Third, the behavior of " e^* " is represented by an arrow. Fourth, the parameters, in terms of controlling the orientation about " e^* ", correspond to each movement around the axes of unit vectors i, j , and k about the X, Y , and Z axes, respectively.

Therefore, the orientation characteristic of " e^* " can be represented by the following three parameters about vectors i, j , and k , respectively (see Fig. 6).

"A": the parameter to control the orientation about an object axis without the influence of the

Fig. 5 Behavior of "orientation-indicating" vector " e^* "

NO.	Orientation Characteristic	i	j	k
W-7 		B (A)	A (B)	C (C)
W-8 		A	A	C
W-9 		B	A	A

Fig. 6 Example of orientation characteristic analysis

orientation about the other axes. It is designated as an "independent-orientation-control" parameter.

"B": the parameter to control the orientation about an object axis, accompanied by the influence of the orientation about the other axes. It is called a "dependent-orientation-control" parameter.

"C": the parameter which cannot change the orientation around an object axis.

As for "W-7" in Fig. 6, the value of the parameters in the parentheses is that when its first joint is rotated 90 degrees.

4.2 Canceling characteristic of wrist configuration

As previously mentioned, with regard to the connection between the arm and wrist configuration, the third link of the arm connects the link between the arm and wrist in the same direction about their link axes. Therefore, the canceling characteristic related to the orientation of the third link in the arm is concerned with " a^* " on the link between the arm and wrist.

As shown in Fig. 7, to analyze the canceling characteristic, the behavior of " a^* " is examined by fixing " e^* ". In a similar manner as the analysis of the orientation characteristic, the movement range of each rotational and pivotal joint is from zero to 180 degrees. In the case of three degrees of freedom, trajectories about the lowest point of the first link are expressed in graphic wire-frame representation. With two degrees of freedom, trajectories about the lowest point of the link between the arm and wrist are also expressed.

The parameters in terms of controlling the orientation about " a^* " correspond to movements around vectors i , j , and k . Therefore, the canceling characteristic about " a^* " is examined by the following three parameters (see Fig. 8).

"F": the parameter which can cancel undesired orientation about an object axis in the range from zero to 360 degrees.

"H": the parameter which can cancel undesired

orientation about an object axis in the range from zero to 180 degrees.

"N": the parameter which cannot cancel undesired orientation about an object axis.

With regard to "W-9" in Fig. 8, the value of the parameters in parentheses is that when its third joint is rotated 90 degrees.

5. Conclusions

The rotation and canceling characteristics, are analyzed for the 13 listed wrist configurations with two or three degrees of freedom, and the results of the classification based on the analysis are illustrated in Fig. 9. The combinations of the parameters of the orientation characteristic to the vertical axis and those of the parameters of canceling to the horizontal

NO.	Canceling Characteristic	i	j	k
W-7 		H	H	F
W-8 		F	H	N
W-9 		F (H)	H (F)	N (N)

Fig. 8 Example of canceling characteristic analysis

Fig. 7 Behavior of "orientation-indicating" vector " a^* "

		← Canceling Characteristic			
		F-H-H	F-H-N	F-N-H	H-H-N
Orientation Characteristic ↑	A-A-A	Three Degrees of Freedom W-6			
	A-A-B		W-12 W-9	Two Degrees of Freedom	
	A-A-C		W-8 W-11	W-1	W-2 W-5
	A-B-C	W-7	W-10 W-13		W-3 W-4

Fig. 9 Wrist classification in view of orientation and canceling characteristic

axis are shown in Fig. 9. Consequently, the positions of geometric characteristics to each wrist joint in the list are represented. The "W-6" configuration for three and the "W-1" configuration for two degrees of freedom have the advantage of both characteristics.

However, wrist configurations "W-6" and "W-1" do not always maintain superiority in all tasks. Namely, the appropriate wrist which satisfies the orientation characteristic required for completing a given task must be selected. Moreover, the wrist to meet the needs of the canceling characteristic required in view of the structural joint combination of the arm must also be chosen.

Acknowledgements

This research was a part of the WASCOR(WASeda COnstruction Robot) Recsearch Project, a multiclient research project for developing building construction robots by the System Science Institute of Waseda University, all 11 Japanese construction and machinery companies. This research was also supported in part by the Kajima Foundation.

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