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Dexterity Modulation of Parallel Manipulators Using Joint Freezing/Releasing and Joint Unactuation/Actuation

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Abstract This paper presents the modulation of the dexterity of a parallel manipulator using joint freezing/releasing and joint unactuation/actuation. In this paper, individual limbs have redundant number of joints, and each joint can be frozen/released and unactuated/actuated, as needed. First, given a task, the restrictions on joint freezing and joint unactuation of a parallel manipulator are derived. Next, with/without joint freezing and/or joint unactuation, the kinematics of a parallel manipulator is formulated, based on which the manipulability ellipsoid is defined. The effects of joint freezing and joint unactuation on the manipulability are analyzed and compared. Finally, simulation results for a planar parallel manipulator are given. Joint mechanisms, such as joint freezing and joint unactuation, are rather simple to adopt into a parallel manipulator, but is quite effective to improve the task adaptability of the system.

Keywords Parallel Manipulator, Joint Freezing, Joint Unactuation, Redundancy, Manipulability

1. Introduction

Parallel manipulators are the closed-chain mechanisms of active/passive joints, whereas serial manipulators are open-chain mechanisms of active joints only. One extreme of parallel manipulators is a Stewart-platform based parallel manipulator [1], in which a single joint of individual limbs is active with the others passive. The other extreme is a multiple cooperative robot system, in which all joints of individual robots are active.

Two types of redundancies can be considered in a parallel manipulator: the redundancy in serial-chain and the redundancy in joint actuation. The former is introduced by putting additional joints to the system [4], and the latter is introduced by actuating more joints than necessary [2-4]. The former is expected to improve the dexterity of a parallel manipulator at the expense of the force applicability, and the reverse is true for the latter [3].

Suppose that individual limbs of a parallel manipulator have redundant number of joints, all of which are actuated. Some joints of such a system may be enforced to be locked using joint freezing, and some of the released joints after joint freezing, may be left to be passive using joint unactuation. However, certain restrictions should be placed on joint freezing and joint unactuation to maintain the mobility and controllability of the system.

The dexterity of a parallel manipulator can be represented by the manipulability ellipsoid [4,5], which is defined as the range of Cartesian velocities mapped from the unit sphere velocities of the active joints. An appropriate metric may be employed, to overcome the physical inconsistency caused by the mixed usage of different types of joints [6]. Notice that the reciprocal of the manipulability ellipsoid can represent the force applicability of the system.

The desirable operational characteristics of a parallel manipulator may vary depending on the requirements of a given task. For instance, higher dexterity (lower force applicability) is recommended for some tasks, and higher force applicability (lower dexterity) is recommended for others. The manipulability of a parallel manipulator can be changed using joint freezing, joint unactuation, and their combination. The adjustable manipulability may play an important role to enhance the task adaptability of the system.

It is a concern of this paper to demonstrate the potentials of joint freezing and joint unactuation for modulating the kinematic property of a parallel manipulator. This paper is organized as follows: Section 2 derives the restrictions on the joint freezing and the joint unactuation for a given task. Section 3 represents and compares the manipulability ellipsoids of a parallel manipulators with/without joint freezing and/or joint unactuation. Section 4 gives the simulation results of a 2 d.o.f. planar parallel manipulator. Finally, conclusions are made in Section 5.

In what follows, it is assumed that a parallel manipulator consists of two redundant limbs, denoted by limb 1 and limb 2, and all joints of individual limbs are of the same type and are identical in contributing to d.o.f. However, the results of this paper can be easily extended to a parallel manipulator with more than two limbs having mixed types of joints.

2. Restrictions on Joint Mechanisms

Joint freezing and joint unactuation can be attempted on a parallel manipulator in several ways, however, they are restricted by the dimension of a given task.

Let m is the dimension of a task assigned to a parallel manipulator. For limb i, $i=1,2$, let n_i ($\geq m$) be the number of whole joints, and n_{ir} and n_{if} be the numbers of joints to be released and to be frozen, such that

$$n_i = n_{ir} + n_{if}, \quad i=1,2 \tag{1}$$

To maintain the d.o.f. of individual limbs,

$$n_{ir} \geq m, \quad i=1,2 \tag{2}$$

and, to maintain the mobility of a parallel manipulator,

$$n_{1r} + n_{2r} - K \geq r \tag{3}$$

where K ($\geq m$) is equal to 3 for planar ones and 6 for spatial ones.

Using (1), from (2), and (3), we have

$$n_{if} \leq n_i - m, \quad i=1,2 \tag{4}$$

$$n_{1f} + n_{2f} \le (n_1 + n_2) - (m + K) \quad (5)$$

which restrict joint freezing for a parallel manipulator. The number of frozen joints of individual limbs is limited by (4), and the total number of frozen joints of a parallel manipulator is limited by (5). Note that (4) implies (5), if $K = m$.

For limb i, $i=1,2$, let $n_{ip}\ (\le n_{ir})$ be the number of joints to be unactuated. To maintain the controllability of a parallel manipulator,

$$n_{1p} + n_{2p} \le K \quad (6)$$

which restricts joint unactuation for a parallel manipulator. The limit on the number of unactuated joints is placed on a parallel manipulator as a whole. Note that (6) implies $n_{ip} \le K$, $i=1,2$.

There may be multiple choices in selecting the joints to be frozen, as far as both (4) and (5) are satisfied. Also, there may be multiple choices in selecting the joints to be unactuated, as far as (6) is satisfied. Under such restrictions, joint freezing and/or joint unactuation can be attempted to modulate the dexterity of a parallel manipulator, which would enhance the task adaptability of the system.

3. Dexterity Modulation

Joint freezing and joint unactuation affect the kinematics of a parallel manipulator, and as a result, the manipulability of the system. It is assumed that individual limbs may have redundant number of joints, before/after joint freezing.

3.1 Neither Joint Freezing Nor Joint Unactuation

Here, we assume that all joints of a parallel manipulator are both released and actuated.

Let θ_i, $i=1,2$ be the joints of limb i. The Cartesian velocity at a task point, $\dot{\mathbf{x}}_i$, of limb i, is given by

$$\dot{\mathbf{x}}_i = \mathbf{J}_i\ \dot{\theta}_i, \quad i=1,2 \quad (7)$$

where $\mathbf{J}_i$, $i=1,2$, represents the Jacobian of limb i. Subject to min $\dot{\theta}_i^t\ \dot{\theta}_i$, $i=1,2$, the solution to (7) is given by

$$\dot{\theta}_i = \mathbf{J}_i^{+}\ \dot{\mathbf{x}}_i, \quad i=1,2 \quad (8)$$

where

$$\mathbf{J}_i^{+} = \mathbf{J}_i^t\ (\mathbf{J}_i\ \mathbf{J}_i^t)^{-1}, \quad i=1,2 \quad (9)$$

Note that $\mathbf{J}_i^{+} = \mathbf{J}_i^{-1}$, $i=1,2$, if limb i is non-redundant. (7) and (8) represent the forward and inverse kinematics of individual limbs with all joints released and actuated.

The Cartesian velocity of a parallel manipulator, $\dot{\mathbf{x}}_o$, is determined under the kinematic constraint between two limbs:

$$\dot{\mathbf{x}}_o = \dot{\mathbf{x}}_1 = \dot{\mathbf{x}}_2 \quad (10)$$

From (8) and (10), we have

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{J}_1^{+} \\ \mathbf{J}_2^{+} \end{bmatrix} \dot{\mathbf{x}}_o \quad (11)$$

(11) represents the inverse kinematics of a parallel manipulator without joint freezing and joint unactuation.

Based on (11), the manipulability ellipsoid of a parallel manipulator without freezing and joint unactuation, $R_{\dot{x}_o}(\bar{F}\ \bar{U})$, is obtained, from $\|\dot{\theta}_1\|^2 + \|\dot{\theta}_2\|^2 \le 1$, as

$R_{\dot{x}_o}(\bar{F}\ \bar{U})$:

$$\dot{\mathbf{x}}_o^t\ [\ (\mathbf{J}_1\ \mathbf{J}_1^t)^{-1} + (\mathbf{J}_2\ \mathbf{J}_2^t)^{-1}\ ]\ \dot{\mathbf{x}}_o \le 1 \quad (12)$$

Note that the manipulability of a parallel manipulator is dominated by the limb with worse manipulability.

3.2 Joint Freezing Only

Here, we assume that some joints of a parallel manipulator are frozen, but all of the released joints are actuated.

Let θ_{ir} and θ_{if}, $i=1,2$, be the joints to be released and to be frozen. Since the motions of the frozen joints are kept zero, that is, $\dot{\theta}_{if} = 0$, $i=1,2$, (7) becomes

$$\dot{\mathbf{x}}_i = \mathbf{J}_{ir}\ \dot{\theta}_{ir} + \mathbf{J}_{if}\ \dot{\theta}_{if} = \mathbf{J}_{ir}\ \dot{\theta}_{ir}, \quad i=1,2 \quad (13)$$

where $\mathbf{J}_{i\alpha}$, $i=1,2$, $\alpha=r,f$, represents the submatrix of $\mathbf{J}_i$ corresponding to $\theta_{i\alpha}$. Note that $\mathbf{J}_{ir}$, $i=1,2$, is constructed from $\mathbf{J}_i$ by deleting the columns corresponding to the frozen joints.

Subject to min $\dot{\theta}_{ir}^t\ \dot{\theta}_{ir}$, $i=1,2$, the solution to (13) is given by

$$\dot{\theta}_{ir} = \mathbf{J}_{ir}^{+}\ \dot{\mathbf{x}}_i, \quad i=1,2 \quad (14)$$

where

$$\mathbf{J}_{ir}^{+} = \mathbf{J}_{ir}^t\ (\mathbf{J}_{ir}\ \mathbf{J}_{ir}^t)^{-1}, \quad i=1,2 \quad (15)$$

(13) and (14) represent the forward and inverse kinematics of individual limbs with some joints frozen but all released joints actuated. From (14) and (10), we have

$$\begin{bmatrix} \dot{\theta}_{1r} \\ \dot{\theta}_{2r} \end{bmatrix} = \begin{bmatrix} \mathbf{J}_{1r}^{+} \\ \mathbf{J}_{2r}^{+} \end{bmatrix} \dot{\mathbf{x}}_o \quad (16)$$

(16) represents the inverse kinematics of a parallel manipulator with joint freezing only.

Based on (16), the manipulability ellipsoid of a parallel manipulator with joint freezing only, $R_{\dot{x}_o}(F\bar{U})$, is obtained, from $\dot{\theta}_{1r}^t\ \dot{\theta}_{1r} + \dot{\theta}_{2r}^t\ \dot{\theta}_{2r} \le 1$, as

$R_{\dot{x}_o}(F\bar{U})$:

$$\dot{\mathbf{x}}_o^t\ [\ (\mathbf{J}_{1r}\ \mathbf{J}_{1r}^t)^{-1} + (\mathbf{J}_{2r}\ \mathbf{J}_{2r}^t)^{-1}\ ]\ \dot{\mathbf{x}}_o \le 1 \quad (17)$$

Since

$$\mathbf{J}_i^t\ \mathbf{J}_i = \mathbf{J}_{ir}^t\ \mathbf{J}_{ir} + \mathbf{J}_{if}^t\ \mathbf{J}_{if}, \quad i=1,2 \quad (18)$$

from (12) and (17), it can be seen that

$$R_{\dot{x}_o}(F\bar{U}) \subset R_{\dot{x}_o}(\bar{F}\ \bar{U}) \quad (19)$$

(19) tells that the manipulability of a parallel manipulator is decreased due to joint freezing, which agrees to our intuition.

3.3 Joint Unactuation Only

Here, we assume that all joints of a parallel manipulator are released, but some of them are unactuated.

Joint unactuation does not affect the forward kinematics of individual limbs, but may affect the inverse kinematics. It would be reasonable to promote the efforts of unactuated joints, while suppressing the efforts of actuated joints. To this end, one may define a weighting matrix, $\mathbf{W}_i$, $i=1,2$, which is diagonal and consists of weights that are set larger for actuated joints and smaller for unactuated joints.

Subject to min $\dot{\theta}_i^t\ \mathbf{W}_i\ \dot{\theta}_i$, $i=1,2$, the solution to (7) is obtained by

$$\dot{\theta}_i = J_i^{\#} \dot{x}_i = Q_i \dot{x}_i, \quad i=1,2 \tag{20}$$

where

$$J_i^{\#} = W_i^{-1} J_i^t (J_i W_i^{-1} J_i^t)^{-1} = Q_i, \quad i=1,2 \tag{21}$$

and Note that $J_i^{\#} = J_i^{-1}$, $i=1,2$, if limb i is non-redundant. (20) represents the inverse kinematics of individual limbs with all joints released but some of them unactuated.

For limb i, $i=1,2$, let $\dot{\theta}_{ia}$ and $\dot{\theta}_{ip}$ be the joints to be actuated and to be unactuated. From (20) and (10), the inverse kinematics of a parallel manipulator with joint unactuation only is obtained by

$$\begin{bmatrix} \dot{\theta}_{1a} \\ \dot{\theta}_{2a} \end{bmatrix} = \begin{bmatrix} Q_{1a} \\ Q_{2a} \end{bmatrix} \dot{x}_o \tag{22}$$

where Q_{ia}, $i=1,2$, $a=a,p$, is the submatrix of Q_i, corresponding to $\dot{\theta}_{ia}$. Note that Q_{ia}, $i=1,2$, is constructed from Q_i by deleting the rows corresponding to the unactuated joints.

Based on (22), the weighted manipulability ellipsoid of a parallel manipulator with joint unactuation only, $\hat{R}_{\dot{x}_o}(\bar{F}U)$, is obtained, from $\dot{\theta}_{1a}^t \dot{\theta}_{1a} + \dot{\theta}_{2a}^t \dot{\theta}_{2a} \leq 1$, as

$$\hat{R}_{\dot{x}_o}(\bar{F}U) : \quad \dot{x}_o^t [Q_{1a}^t Q_{1a} + Q_{2a}^t Q_{2a}] \dot{x}_o \leq 1 \tag{23}$$

On the other hand, the weighted manipulability ellipsoid of a parallel manipulator without joint unactuation and joint freezing, $\hat{R}_{\dot{x}_o}(\bar{F}\bar{U})$, can be expressed as

$$\hat{R}_{\dot{x}_o}(\bar{F}\bar{U}) : \quad \dot{x}_o^t [Q_1^t Q_1 + Q_2^t Q_2] \dot{x}_o \leq 1 \tag{24}$$

Since

$$Q_i^t Q_i = Q_{ia}^t Q_{ia} + Q_{ip}^t Q_{ip}, \quad i=1,2 \tag{25}$$

from (23) and (24),

$$\hat{R}_{\dot{x}_o}(\bar{F}U) \supset \hat{R}_{\dot{x}_o}(\bar{F}\bar{U}) \tag{26}$$

(26) tells that the manipulability of a parallel manipulator is decreased due to joint unactuation. This is because the dexterity of unactuated joints is infinite, while the dexterity of actuated joints is finite within their velocity limits.

3.4 Both Joint Freezing and Joint Unactuation

Here, we assume that some joints of a parallel manipulator are frozen, and some of the released joints are unactuated.

With joint freezing and joint unactuation, the forward kinematics of individual limbs is obtained as in Section 3.2, and the inverse kinematics can be obtained as in Section 3.3. Subject to min $\dot{\theta}_{ir}^t W_{ir} \dot{\theta}_{ir}$, $i=1,2$, the solution to (13) is obtained by

$$\dot{\theta}_{ir} = J_{ir}^{\#} \dot{x}_i, \quad i=1,2 \tag{27}$$

where

$$J_{ir}^{\#} = W_{ir}^{-1} J_{ir}^t (J_{ir} W_{ir}^{-1} J_{ir}^t)^{-1}, \quad i=1,2 \tag{28}$$

where W_{ir}, $i=1,2$, is the weighting matrix for $\dot{\theta}_{ir}$.

For limb i, $i=1,2$, let $\dot{\theta}_{ira}$ and $\dot{\theta}_{irp}$ be the joints to be actuated and to be unactuated, taken out of the released joint $\dot{\theta}_{ir}$. From (27) and (10), the inverse kinematics of a parallel manipulator with joint freezing and joint unactuation is obtained by

$$\begin{bmatrix} \dot{\theta}_{1ra} \\ \dot{\theta}_{2ra} \end{bmatrix} = \begin{bmatrix} Q_{1ra} \\ Q_{2ra} \end{bmatrix} \dot{x}_o \tag{29}$$

where Q_{1ra}, $i=1,2$, is the submatrix of $J_{ir}^{\#}$, corresponding to $\dot{\theta}_{ira}$.

Based on (29), the weighted manipulability ellipsoid of a parallel manipulator with joint freezing and joint unactuation, $\hat{R}_{\dot{x}_o}(FU)$, is obtained, from $\dot{\theta}_{1ra}^t \dot{\theta}_{1ra} + \dot{\theta}_{2ra}^t \dot{\theta}_{2ra} \leq 1$, as

$$\hat{R}_{\dot{x}_o}(FU) : \quad \dot{x}_o^t [Q_{1ra}^t Q_{1ra} + Q_{2ra}^t Q_{2ra}] \dot{x}_o \leq 1 \tag{30}$$

As discussed, joint freezing alone decreases the manipulability (Refer to (19)), while joint unactuation alone increases the manipulability (Refer to (26)). However, the combined effect of joint freezing and joint unactuation is highly complicated and varies depending on which joints to freeze and which joints to unactuate. More precisly, the numbers and the locations of the frozen and the unactuated joints affect the manipulability of the system.

4. Simulation

This section gives the simulation results for a 2 d.o.f. planar parallel manipulator shown in Fig. 1, which consists of two redundant limbs having three revolute joints. For convenience, two linear velocities are taken as task components, and no weighting is assumed between the actuated and the unactuated joints.

Since $n_1 = n_2 = 3$, $m = 2$, and $K = 3$, from (4) and (5), we have $n_{1f} \leq 1$, $n_{2f} \leq 1$, and $n_{if} + n_{2f} \leq 1$, which tells that only a single joint out of either limb 1 or 2 can be frozen. On the other hand, from (6), we have $n_{ip} + n_{2p} \leq 3$, which tells that at most three joints of a parallel manipulator can be unactuated, in other words, at least three joints should be actuated. Note that the frozen joint is treated as an actuated joint.

With no joint frozen, the number of possible joint actuations amounts to

$$_6C_3 + {_6C_4} + {_6C_5} + {_6C_6} = 42 \tag{31}$$

With a single joint frozen, the number of possible joint actuations amounts to

$$6 \times ({_5C_2} + {_5C_3} + {_5C_4} + {_5C_5}) = 156 \tag{32}$$

With joint freezing and joint unactuation, there are 198 combinations even for a simple form of parallel manipulators. Such variety in joint freezing and joint unactuation seems to be enough to ensure the improvement of the task adaptability of the system.

For simplicity, two limbs of the parallel manipulator are of symmetric configurations, to reduce the number of different joint actuations to consider. With no joint frozen, Fig. 2a) shows that the variation of the volume of the manipulability ellipsoid with respect to 23 different joint actuations. Fig. 2b) and 2c) show the variations of manipulability with respect to 26 joint actuations when the 1st joint (from the base) of limb 1 is frozen and when the 3rd joint of limb 1 is frozen, respectively. In Fig. 2, the combinations with three, two, one, and zero unactuated joints are marked as 'o', 'x', '+', and '*', respectively.

From Fig. 2, the following observations can be made:

1) First of all, the span of the manipulability is remarkably

extended due to joint freezing and joint unactuation, which contributes to improving the task adaptability.
2) Regardless of joint freezing, the level of the manipulability drops as the number of the actuated joints increases. The manipulability also changes considerably depending on the location of the actuated joints.
3) The manipulability may increase even after joint freezing when combined with joint unactuation, and it also changes considerably depending on the location of the frozen joint.
Note that joint freezing does not always decrease the manipulability of the system. For instance, more joint freezing and less joint actuation may increase the manipulability compared to less joint freezing and more joint actuation.

5. Conclusions

This paper demonstrated the effectiveness of joint freezing and joint unactuation to modulate the manipulability of a parallel manipulator consisting of multiple redundant limbs. First, the restrictions on the numbers of the frozen and the unactuated joints were derived for a given task. Next, the manipulabilites of a parallel manipulator with/without joint freezing and/or joint unactuation were analyzed and compared. Simulation results were given for a 2 d.o.f. planar parallel manipulator. Currently, the optimization associated with joint freezing and joint unactuation is under study.

References

[1] E. F. Fichter, "A Stewart Platform-Based Manipulator: General Theory and Practical Consideration," Int. Jour. Robotics and Research, Vol. 5, pp. 157-182, 1986.
[2] Y. Nakamura and M. Ghdoussi, "Dynamics Computation of Closed-Link Robot Mechanisms with Nonredundant and Redundant Actuators," IEEE Trans. Robotics and Automation, Vol. 5, pp. 294-302, 1989.
[3] V. Kumar and J. F. Gardner, "Kinematics of Redundantly Actuated Closed Chains," IEEE Trans. Robotics and Automation, Vol. 6, pp. 269-274, 1990.
[4] S. Lee and S. Kim, "Kinematic Feature Analysis of Parallel Manipulator Systems," Proc. IEEE Int. Conf. Robotics and Automation, pp. 77-82, 1994.
[5] T. Yoshikawa, "Analysis and Control of Robot Manipulator with Redundancy," Proc. 1st Int. Symp. Robotics Research, MIT Press, pp. 735-748, 1984.
[6] K. L. Doty, C. Melchiorri, E. M. Schwartz, and C. Bonivento, "Robot Manipulability," IEEE Trans. Robotics and Automation, Vol. 11, pp. 462-468, 1995.

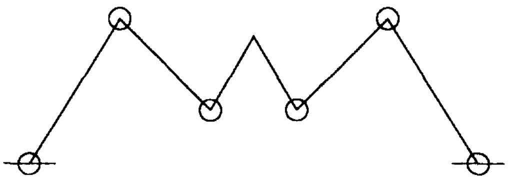

Fig. 1 A 2 d.o.f. planar parallel manipulator with two redundant limbs.

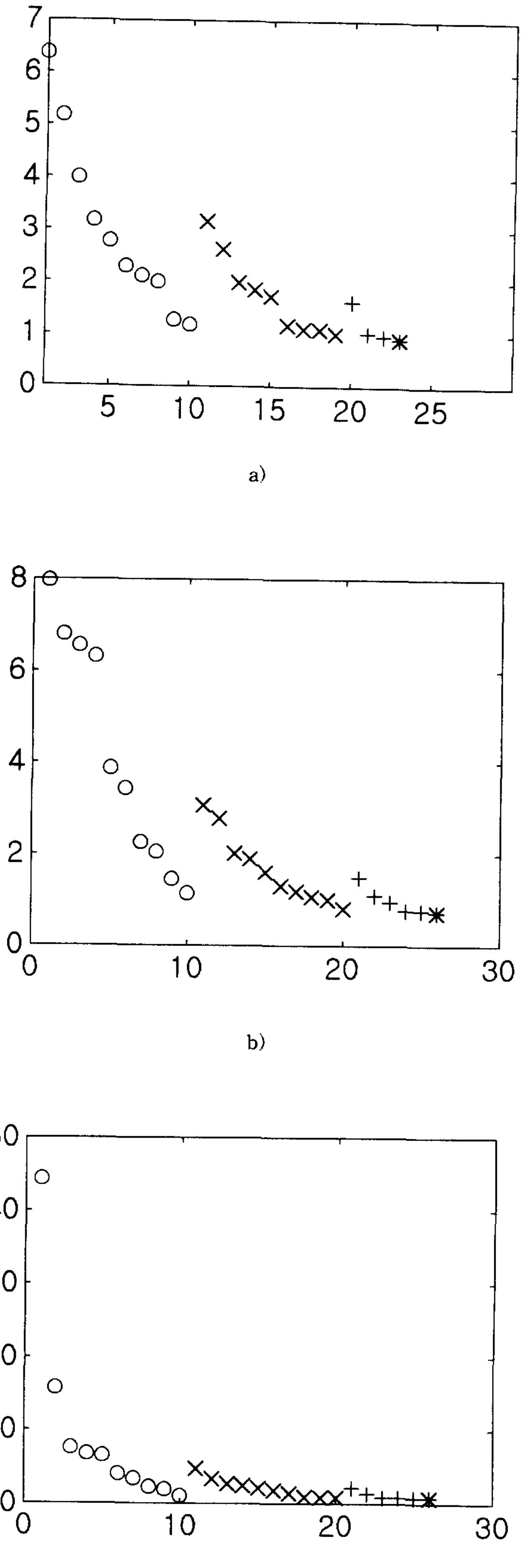

Fig. 2 The variations of the volume of the manipulability with respect to different joint actuations: a) with no joint frozen, b) with the 1st joint of limb 1 frozen, and c) with the 3rd joint of limb 1 frozen.