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A Study on Motion Adaptation against Robot Structure Changes

Yuki Funabora, Shinji Doki and Shigeru Okuma
Department of Electrical Engineering
Nagoya University
Nagoya City, Japan
(funabora,doki,okuma)@okuma.nuee.nagoya-u.ac.jp

Yoshikazu Yano
Department of Electrical and Electronics Engineering
Aichi Institute of Technology
Toyota City, Japan
yoshiyano@aitech.ac.jp

***Abstract*—Robot motions are designed according to the properties such as the number of joints, the range of each joint, the length of each frame and so on. Structure changes such as joint failures or frame distortion make the tasks of prepared motions unaccomplished. Identification of structure changes on multi degree-of-freedom (DOF) robots like humanoid is so difficult that the traditional approaches based on inverse kinematics would not be applied. We propose a motion adaptation method to generate new proper motions accomplishing the tasks on changed structure without identification of the structure changes. All the motions can be expressed with the time-series data of postures. Each proper posture as an element of motions for changed structure is estimated by Kriging with joint angle data of several original postures sorted by Vector Quantization (VQ) and the corresponding postures explored on changed structure by Simulated Annealing (SA). At the case the tasks couldn't be accomplished with the generated motions in designed DOF, new motions are generated in expanded DOF adding redundancy joints. Experimental results show that the generated motion by proposed method is accomplished 96.6% similarity with the original task referenced failure motion's task to 0% on changed structure by single joint locking.**

***Index Terms*—Motion Adaptation, Structure Changes, Vector Quantization, Kriging.**

I. INTRODUCTION

Recently the technologies for multi degree-of-freedom (DOF) robots have been progressed, and an increasing number of service robots has been developing for an assist on human life, disaster relief and so on [1] [2] [3]. These service robots have to accomplish their tasks under not only well known circumstances but also unseen environments because of the unpredictable circumstance condition such as disaster relief. Under unseen environments, robots cannot work as designed, so that they may fall or collide with debris. These impacts will cause several structure changes to the robot, such as gear cracks, joint fixations and frame distortions. These failures prevent the robot from accomplishing their tasks with the prepared motions designed on original structure. In the case when the robots cannot get rapid repair service, they have to work for the tasks with their body broken. Therefore, it is necessary for them to obtain the new proper motions accomplishing the tasks on changed structure.

In this paper, we focus on the tasks based on position control; the tasks are accomplished by achieving the designed trajectories. When the structure of the robot has changed which causes the designed original motions incomplete, the new proper motions achieving the designed original trajectories would be obtained on changed structure. There are two typical approaches. One is identification of the structure changes to apply inverse kinematics. Once changed structure is identified, inverse kinematics leads the proper motions for new properties of changed structure. It is however so difficult to identify the complex structure changes such as frame distortion, gear cracking and backlash on multi DOF robot. Another approach is to explore the motions achieving the designed trajectories according to motion evaluation function on changed structure. The robot can obtain the proper motions without identification of structure changes, but this approach needs huge costs of exploring. The proper motions achieving the designed trajectories would be needed on changed structure, with low-cost of exploring and without failure identification.

We propose a motion adaptation method based on exploratory to accomplish the tasks on changed structure without identification. Using an estimation method based on the relations of the postures which are elements of motions saves costs of exploring. Under the condition that the robot can observe a current posture using sensors such as a camera, the robot generates the new motions achieving the designed trajectories with low-cost exploring.

II. PROPOSED METHOD

In this section, we describe an outline of proposed motion adaptation method. All the motions are expressed with the time-series data of postures. All the proper postures indicating the designed target points on changed structure are obtained by exploring and estimation. Each proper posture is estimated by Kriging with joint angle data of several original postures sorted by Vector Quantization (VQ) and the corresponding postures explored by Simulated Annealing (SA) on changed structure.

See Fig.1, a task "draw a circle" with robot's right hand is achieved by the motion consisted of time-series postures. Each posture has a label which is corresponded with certain target point. A posture $\boldsymbol{p}(l_n)$ indicated a target point which is corresponded with the label l_n is expressed with N_J joints $j_1,\ j_2,\ ...,\ j_{N_J}$ as (1).

$$\boldsymbol{p}(l_n) = (j_1(l_n),\ j_2(l_n),\ ...,\ j_{N_J}(l_n)\ ) \tag{1}$$

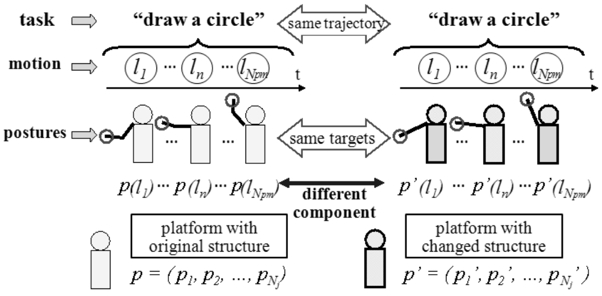


Fig. 1. Motion description with postures

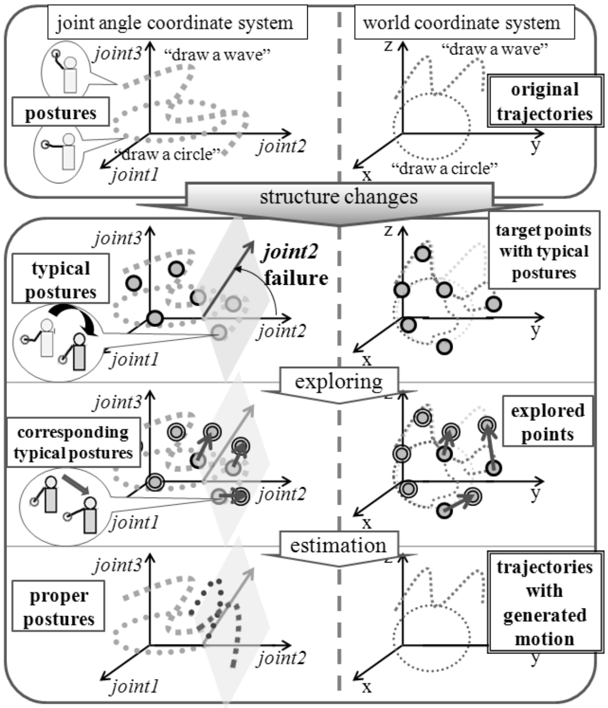


Fig. 2. Motion adaptation in consideration of posture modification

The proper posture $\boldsymbol{p}'(l_n)$ indicated the same target point as the posture $\boldsymbol{p}(l_n)$ on changed structure is expressed with N'_J joints $j'_1,\ j'_2,\ \dots,\ j'_{N'_J}$ as (2).

$$\boldsymbol{p}'(l_n) = (j'_1(l_n),\ j'_2(l_n),\ \dots,\ j'_{N'_J}(l_n)\ ) \tag{2}$$

The proper posture $\boldsymbol{p}'(l_n)$ is generated by posture modification method described at chapter III. A motion "draw a circle" is described with N_{pm} labels $l_1,\ \dots,\ l_n,\ \dots,\ l_{N_{pm}}$ on both original and changed structure.

All the proper postures are generated by modification of the designed postures. The concept of a motion adaptation in consideration of the posture modification is shown as Fig.2. A designed posture $\boldsymbol{p}$ is plotted on joint angle coordinate system with axes consisted of N_J joints $j_1,\ j_2,\ \dots,\ j_{N_J}$. All the designed postures $P = \{\boldsymbol{p}(l_n)|\ {}^{\exists}l_n\}$ are distributed on joint angle coordinate system. Each posture can indicate each target point on world coordinate system, and an expected trajectory will be obtained by expressing certain postures to follow the target points. When the robot structure has changed by failure of $joint2$, it is assumed that the designed trajectories could not be achieved with the designed motions because of changes some target points in accordance with changes of some postures based on failure. By exploring the adequate postures indicating the same target points on several sorted postures and estimation all the proper postures, the new proper postures for changed structure would be generated with low-cost of exploring. In Fig.2, 6 typical postures are sorted from all the designed postures, where the explored adequate postures are shown as double circle symbols. All the proper postures are estimated according to joint angle data of adjusted 6 typical postures.

The reachable area where the robot can indicate as a target point depends on the robot structure such as frame length, joint range of motion and so on. So structure changes cause the reachable area deteriorated. Also it has possibilities that the robot cannot indicate some target points in designed joint DOF. In that case, expansion of joint DOF adding redundancy joints resolve to extend reachable area encompassing all the target points.

III. POSTURE MODIFICATION

The proposed posture modification is consisted of three phases. The first phase is to sort some typical postures for exploring the adequate one on failure. The second is to explore the corresponding postures to designed ones which could indicate the points. The last is to estimate all the proper postures by Kriging based on unification of typical postures.

A. Sort typical postures

For cutting costs of exploration, the number of the exploring postures should be reduced. It is necessary to sort some postures for exploring which are represented distribution of all postures on joint angle coordinate system. Several typical postures to explore the target points are sorted by Vector Quantization (VQ) [4]. VQ is used in many applications such as image compression, voice compression, voice recognition and so on. Some codewords represent a given set of input vectors on coordinate system. The typical postures as codewords resulting from VQ represent all postures.

A set of K typical postures $Q = \{\boldsymbol{q}(k)|1 \leq k \leq K\}$ are sorted from all the designed postures P. VQ is calculated based on the LBG algorithm. A typical posture $\boldsymbol{q}(k)$ is represented with the joint angles $j_1(k),\ j_2(k),\ \dots,\ j_{N_j}(k)$ as (3).

$$\boldsymbol{q}(k) = (j_1(k),\ j_2(k),\ \dots,\ j_{N_j}(k)\ ) \tag{3}$$

The brand-new postures indicated the same target points on changed structure are explored for corresponding designed postures under the sorted K typical postures as base postures.

As all the motions are described with the labels and the posture with same label indicates the same target point in each structure, the motions represented with labels don't have to be modified on changed structure.

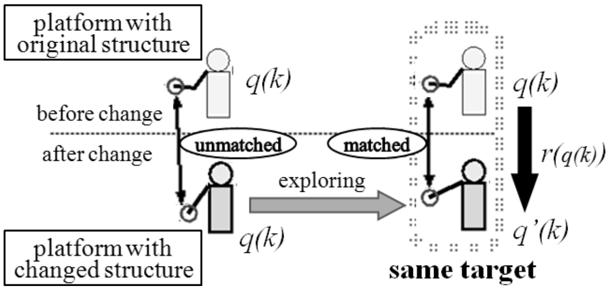


Fig. 3. Acquired transformation vector by exploring at a sorted typical posture

B. Exploration on the typical postures

The adequate postures on changed structure which are corresponding to typical postures are acquired by exploration. The adequate postures Q' are acquired by exploring the same target points under the sorted typical postures Q as starting points on changed structure, and transformation vectors are calculated with Q and Q'.

Under the condition that the robot can acquire the current position of target point using sensors such as a camera, the robot explores the adequate typical postures indicating the same target points on changed structure. The adequate posture $\boldsymbol{q}'(k)$ is explored under the typical posture $\boldsymbol{q}(k)$ as starting point on changed structure. The concept of acquiring the transformation vector $\boldsymbol{r}(\boldsymbol{q}(k))$ on the typical posture $\boldsymbol{q}(k)$ is shown in Fig.3. The transformation vector $\boldsymbol{r}(\boldsymbol{q}(k))$ is acquired by difference of joint angles between the explored adequate posture $\boldsymbol{q}'(k)$ and the typical posture $\boldsymbol{q}(k)$ as (4).

$$\boldsymbol{r}(\boldsymbol{q}(k)) = \boldsymbol{q}'(k) - \boldsymbol{q}(k) \tag{4}$$

Each transformation vector is acquired on each typical posture.

In this paper, the adequate postures consisted of the combination of joint angles are explored by Simulated Annealing (SA). SA is one of the famous global optimization method and often used when the search space is discrete. It is considered that the structure changes cause the joint angle coordinate system to go into some discrete changes. The evaluation function is decided on position difference between the current target point and the original target point. By minimizing the evaluation function, the adequate postures indicating the same target points are explored on changed structure.

C. Generation of all the proper postures with estimation

All the proper postures indicating the same target points on changed structure are generated by Kriging [5]; one of the spatial estimation method in geostatistics. Each estimation transformation vector which transforms the designed posture into the proper posture is estimated by Kriging based on acquired transformation vectors on the typical postures.

1) Estimation by Kriging: Kriging is a group of geostatistical method to interpolate the value of a random field at an unobserved location from observations of its value at nearby locations. Mukai [6] achieved creating a lot of similar CG motions from limited sample motions by Kriging.

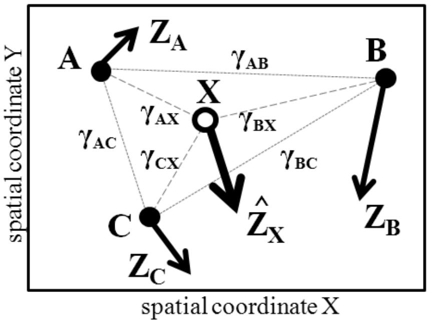


Fig. 4. Estimation by Kriging

The estimation value $\hat{\boldsymbol{Z}}(\boldsymbol{x})$ at an estimation point $\boldsymbol{x}$ is estimated from the N_{sa} sample values $\boldsymbol{Z}(\boldsymbol{x}_\alpha)$ at the observation points $\boldsymbol{x}_\alpha(\alpha = 1, \ ..., \ N_{sa})$. The estimation value $\hat{\boldsymbol{Z}}(\boldsymbol{x})$ is calculated with the sample values $\boldsymbol{Z}(\boldsymbol{x}_\alpha)$ at the nearby observation points as (5).

$$\hat{\boldsymbol{Z}}(\boldsymbol{x}) \ = \ \sum_{\alpha=1}^{N_{sa}} w_\alpha \boldsymbol{Z}(\boldsymbol{x}_\alpha), \ \ \sum_{\alpha=1}^{N_{sa}} w_\alpha = 1 \tag{5}$$

Each weight w_α is determined on the formulated variogram γ acquired from samples. The variogram is an index of relevance between spacial autocorrelation and distance of spacial position. A variogram $\gamma_{x_i x_j}$ showing the relevance of two samples $x_i, x_j (i, j \in \alpha)$ is calculated as (6).

$$\gamma_{x_i x_j} = \frac{1}{2} Var[\boldsymbol{Z}(x_i) - \boldsymbol{Z}(x_j)] \tag{6}$$

The formulated variogram based on a variogram with sample data is involved with model error. So the prediction error ϵ on Kriging are obtained as (7).

$$\epsilon \ = \ \hat{\boldsymbol{Z}}(\boldsymbol{x}) - \sum_{\alpha=1}^{N_{sa}} w_\alpha \boldsymbol{Z}(\boldsymbol{x}_\alpha) \tag{7}$$

As minimizing the prediction error ϵ on sample points, the combination of weights w_α is calculated. The estimation value $\hat{\boldsymbol{Z}}(\boldsymbol{x})$ is calculated from both calculated weights w_α and (5).

The flow of estimation of an estimation value $\hat{\boldsymbol{Z}}_X$ at unknown point $\boldsymbol{X}$ from three sample values $\boldsymbol{Z}_A, \boldsymbol{Z}_B, \boldsymbol{Z}_C$ at three sample points $\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}$ is shown as Fig.4.

$$\begin{cases} w_A \gamma_{AA} + w_B \gamma_{AB} + w_C \gamma_{AC} = \gamma_{AX} \\ w_A \gamma_{BA} + w_B \gamma_{BB} + w_C \gamma_{BC} = \gamma_{BX} \\ w_A \gamma_{CA} + w_B \gamma_{CB} + w_C \gamma_{CC} = \gamma_{CX} \\ w_A + w_B + w_C = 1 \end{cases}$$

Each value of $\gamma_{AA}, \gamma_{BB}, \gamma_{CC}$ shows zero. The estimation value $\hat{\boldsymbol{Z}}_X$ is calculated with each weight w_A, w_B, w_C resulting from the Lagrange's method of undetermined multipliers as (8).

$$\hat{\boldsymbol{Z}}_X = w_A \boldsymbol{Z}_A + w_B \boldsymbol{Z}_B + w_C \boldsymbol{Z}_C \tag{8}$$

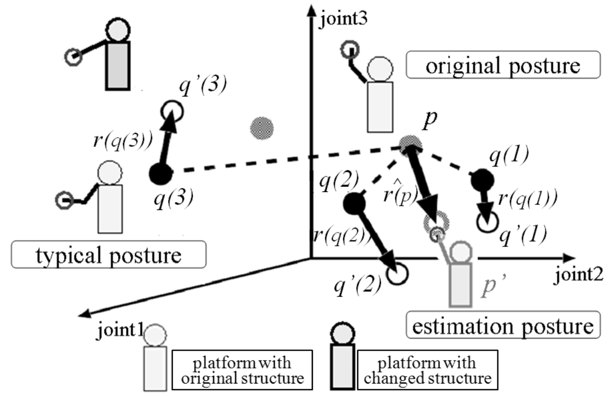


Fig. 5. Generation of the estimation proper posture with the acquired estimation transformation vector

2) Estimation all the proper postures: The flow of generation of the estimation proper posture $\boldsymbol{p}'$ with acquiring the estimation transformation vector $\hat{\boldsymbol{r}}(\boldsymbol{p})$ at an unexplored posture $\boldsymbol{p}$ from the three nearby typical postures $\boldsymbol{q}(1), \boldsymbol{q}(2), \boldsymbol{q}(3)$ is shown in Fig.5. The estimation transformation vector $\hat{\boldsymbol{r}}(\boldsymbol{p})$ is acquired by weighted summation of the explored transformation vectors $\boldsymbol{r}(\boldsymbol{q}(1))$, $\boldsymbol{r}(\boldsymbol{q}(2))$, $\boldsymbol{r}(\boldsymbol{q}(3))$. Each weight is determined from distance between a designed posture $\boldsymbol{p}$ and each typical postures $\boldsymbol{q}(1), \boldsymbol{q}(2), \boldsymbol{q}(3))$ on joint angle coordinate system. The further the designed posture is from the typical posture, the less weight is got. The nearer the designed posture is, the heavier weight is got.

The estimation proper posture $\hat{\boldsymbol{p}}'$ is generated as (9) with the estimation transformation vector $\hat{\boldsymbol{r}}(\boldsymbol{p})$ estimated from the explored transformation vectors.

$$\hat{\boldsymbol{p}}' \quad = \quad \boldsymbol{p} + \hat{\boldsymbol{r}}(\boldsymbol{p}) \tag{9}$$

All the estimation proper postures P' are generated to transform from P based on the estimation transformation vectors.

IV. EXPANSION OF JOINT DOF

To achieve the designed trajectories on changed structure, the joint DOF is expanded adding redundancy joints if necessary. When the generated postures could not achieve the designed trajectories in designed joint DOF, the new postures are explored in expanded joint DOF adding redundancy joints.

The concept of deterioration of the reachable area and expansion of joint DOF is shown as Fig.6. A motion "draw a circle" is designed in 3 DOF consisted of shoulder yaw joint, shoulder pitch joint and elbow yaw joint. The designed trajectory is achieved in designed 3 DOF on original structure. When the robot structure was changed by frame distortion, the designed trajectory could not be achieved in designed DOF because of deterioration of the reachable area. The reachable area will be expanded according to addition of redundancy waist yaw joint, making the robot achieve the designed trajectory "draw a circle" on changed structure.

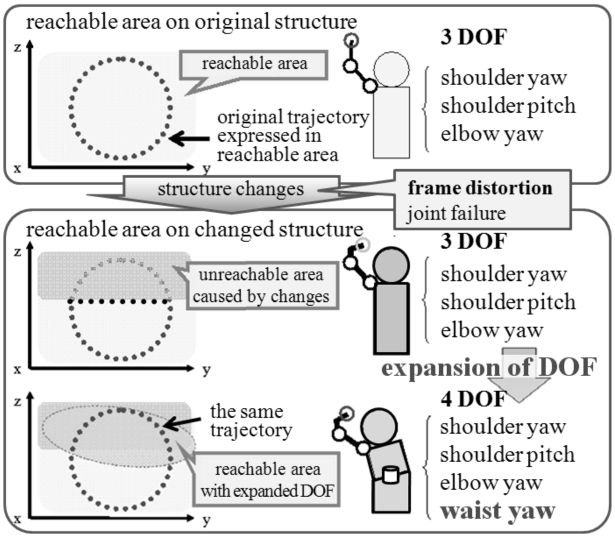


Fig. 6. Deterioration of the reachable area in each joint DOF

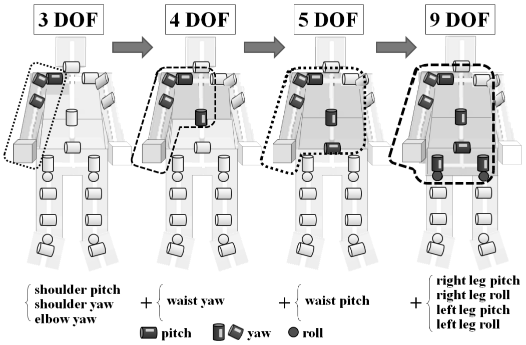


Fig. 7. Expansion of joint DOF in stages on a robot

The fewer the joint DOF in which the robot can indicate all the target points is, the lower exploration costs are. It is difficult to find the combination of joints in which the robot can indicate all the target points autonomously. Human selects beforehand the right combination of joints to reach the target point based on their experimental rule. The prioritization of the joints in response to each motions is designed in advance. Exploring joint DOF is expanded in stages based on the prioritization. An example of expansion of joint DOF in response to right hand point control on a humanoid is shown as Fig.7. If a motion "draw a circle" designed in 3 DOF consisted of shoulder yaw joint, shoulder pitch joint and elbow yaw joint wouldn't have achieved the designed trajectory by structure changes, the adequate postures are explored from the typical postures in 4 DOF adding waist yaw joint based on the designed prioritization of the joints. Even if one adequate posture isn't explored in 4 DOF, the adequate postures are explored on typical postures in 5 joints adding waist pitch joint. If the adequate postures are not enough to achieve the designed trajectory in 5 DOF, these postures are explored in expanded 9 DOF. As adding the redundancy joints in stages, the adequate

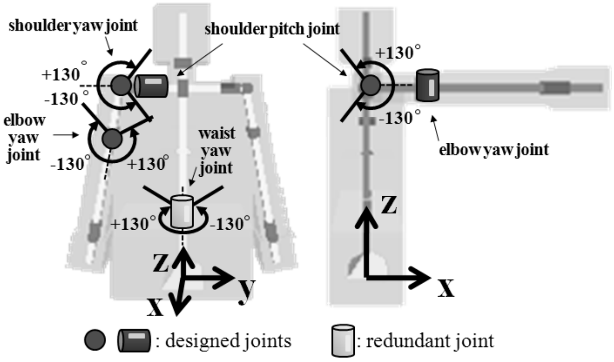


Fig. 8. Structure of the intended humanoid robot

postures are acquired through low-costs exploring. Proposed posture modification method consisted of VQ and Kriging is independent of joint DOF. When the generated postures can't indicate the same target points in designed joint DOF, the new adequate postures in expanded joint DOF are generated only to explore the corresponding typical postures in expanded joint DOF. There is a typical posture $\boldsymbol{q}$ in designed N_j joint DOF. The expanded typical posture $\boldsymbol{q}_e$ in expanded $N_j + N_r$ joint DOF adding N_r redundancy joints is shown as (10).

$$\boldsymbol{q}_e = (q_1, q_2, ..., q_{N_j}, q_{N_j+1}, ..., q_{N_j+N_r}) \quad (10)$$

The transformation vectors are acquired in expanded joint DOF by SA. The estimation transformation vectors are acquired in expanded joint DOF by Kriging. So the estimation proper postures are generated in expanded joint DOF.

V. EXPERIMENTAL RESULTS

The proposed motion adaptation method is evaluated with simulation. The structure of the intended humanoid robot and world coordinate system are shown in Fig.8. A motion "draw a circle" achieved with right hand point is designed with 100 postures in 3 DOF consisted of the joints on shoulder yaw, shoulder pitch and elbow yaw. A redundancy waist yaw joint is prepared based on the prioritization against the right hand point. Here, the changes of the structure are defined as elbow yaw joint locking to 0 degree.

The adequate postures are explored by SA at 8 typical postures sorted by VQ. All the proper postures are estimated by Kriging. If the generated motion in designed 3 DOF cannot achieve the designed trajectory, the new motion is generated according to proposed method in expanded 4 DOF adding waist yaw joint.

The new trajectory achieved with the generated motion in designed 3 DOF is shown as Fig.9. The solid line shows the designed trajectory, the dotted line shows the failure trajectory achieved with the designed motion on changed structure and the broken line shows the new trajectory achieved with the generated motion on changed structure. Indexes of circle show the explored points at typical postures. It is to be sure that the generated trajectory represents nearer by the designed trajectory than the failure one, but the generated trajectory is not matched the designed one. The generated trajectory is matched the optimum trajectory acquired from exploration at all the 100 postures. It should be considered that the reachable area has deteriorated by joint failure and the designed trajectory cannot be achieved in designed 3 DOF on changed structure. Even in that case, the results show that the generated trajectory is achieved to the nearest extent possible from the designed one. Then, the robot generates a new motion by exploring in 4 DOF adding redundancy waist yaw joint.

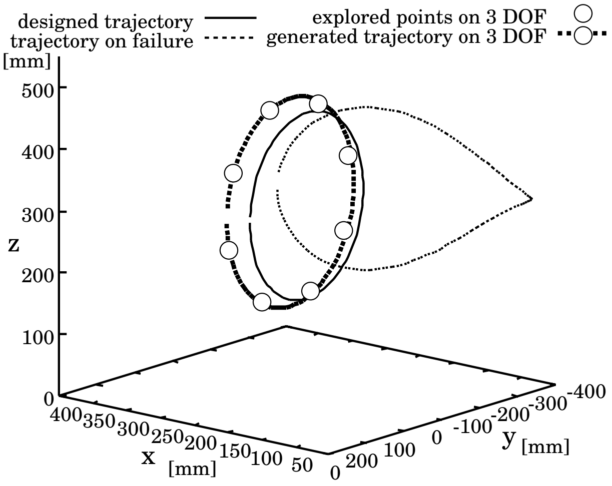


Fig. 9. The generated motion trajectory in 3 DOF

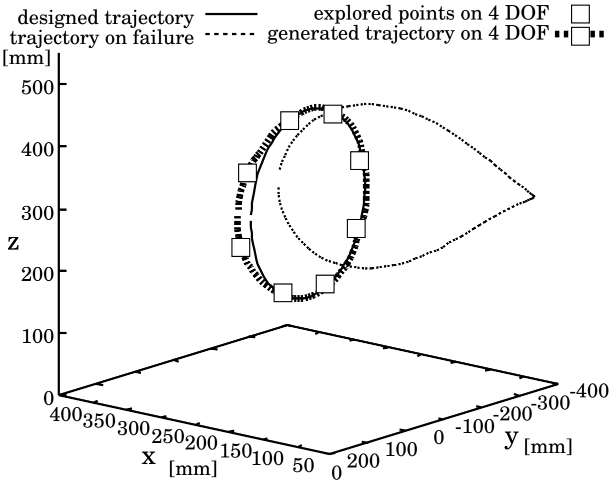


Fig. 10. The generated motion trajectory in 4 DOF

The new trajectory achieved with the generated motion in expanded 4 DOF is shown as Fig.10. Each line shows each trajectory along with Fig.9. Indexes of square show the explored points at typical postures in expanded DOF. The new trajectory in expanded DOF is very nearer by the designed trajectory than the trajectory generated in designed DOF. Some of the target points cannot be indicated absolutely even if

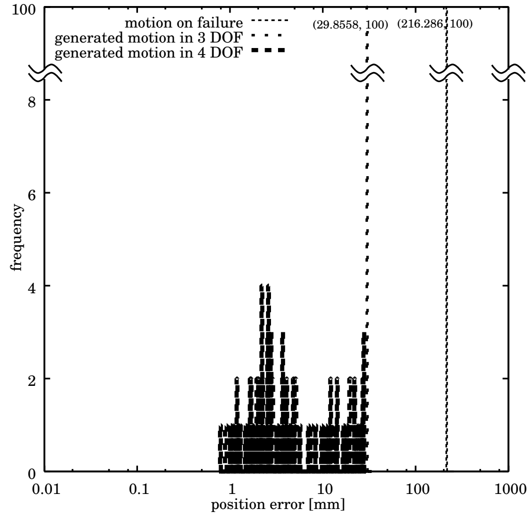
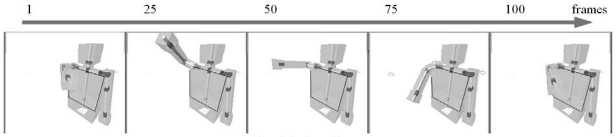


Fig. 11. The frequency histogram of the position error

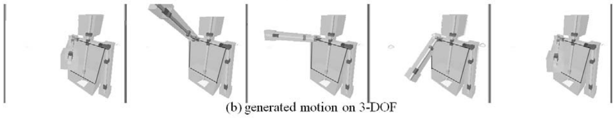
in expanded 4 DOF. The new trajectory achieved with the generated motion is well matched the optimum trajectory which is generated by exploring at all the 100 postures in expanded DOF. It is considered that some of the target points could not be existed on reachable area even if in 4 DOF. It is expected that adding the other redundancy joints make the generated trajectory nearer and nearer.

To evaluate the errors between the designed trajectory and the others, the frequency histogram of the position error at each posture is shown as Fig.11. Abscissa axis shows the logarithmic position error between each trajectory and the designed one at the same posture label, vertical axis shows frequency histogram. About 216mm certain position error is observed on joint failure. It shows that the motion on failure achieves the failure trajectory including a certain error. About 30mm certain position error is observed on the motion generated in designed DOF. It is consider that the reachable area has no same target points by joint failure, and the explored postures are existed on boundary surface of the reachable area. The generated motion in designed DOF is accomplished about 86% similar trajectory with the designed one referenced failure trajectory to 0% on changed structure. The position errors in expanded DOF are found widely in the left side of the errors in designed DOF. Some of the target points have the position error like that of in designed DOF, but almost of the target points are matched well. The mean position error between the new trajectory generated in 4 DOF and the designed one is 7.4mm, which is accomplished about 97% similar trajectory with the designed one.

Some of the time-series postures of each motion are shown as Fig.12. The generated proper postures indicating the target points including less position error are generated effectively with adding redundancy waist yaw joint as (c) of Fig.12. It is expected that the proper motion achieving the same trajectory is generated by adding the other redundancy joints on changed structure.



(a) original motion



(b) generated motion on 3-DOF

(c) generated motion on 4-DOF

Fig. 12. The time-series postures of the motion “draw a circle”

VI. CONCLUSION

We proposed a motion adaptation method against structure changes of a multi DOF robot. We showed that the motion adaptation could execute efficiency by exploring the adequate corresponding postures on a few typical postures and estimating all the proper postures based on the result of exploration. Even if the generated motions wouldn’t have achieved the designed trajectories, the new motions achieving the designed trajectories would be generated by exploring with adding redundancy joints.

In this paper, we intended the motions based on position control. The other motion control systems such as force control, balance control and so on are necessary for a robot, too. It is expected that the proper motions are generated with applying this proposed method to the other control system by preparing the evaluation function best suited to each system. It calls for further research and experiment.

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