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Global Reconfiguration Capability Evaluation and On-line Preview Control

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Abstract: This paper shows global reconfiguration capability evaluation for redundant manipulator while its hand tracking target trajectory and the shape avoiding obstacle. In this research, aiming at constructing an automation system that can operate a given task to the arbitrarily shaped target object without preparatory operation, we propose a production system composed of redundant manipulator and movable camera that observe the target's shape on-line. In such a system, the configuration of the robot should always be prepared to keep the highest avoidance manipulability to evade the object quickly that may appears suddenly in the moving camera view. We evaluated configurations of manipulator by using the index representing Avoidance Manipulability Ellipsoid Shape Index with Potential (AMSIP).

Keywords: Redundant manipulators, Single-Preview Control, Multi-Preview Control, Reconfiguration.

1. INTRODUCTION

Over the past two decades, redundant manipulators are used for various tasks, for example, welding, sealing and grinding. These kinds of tasks require that the manipulator plan its hand onto a desired trajectory (trajectory tracking) and avoid its intermediate links, meaning all comprising links of robot except the top link with the end-effecter, from obstacles existing near the target object and also the target object itself (obstacle avoidance).

There are many researches on a motion control of redundant manipulators discussing how to use the redundancy. The proposed solutions so far to this problem can be broadly categorized into two classes: Global Methods and Local Methods. Global Methods [1],[2] solve the collision avoidance problem by an entire path planning, being only suited for structured and static environment. Moreover, the computational cost of Global Methods is expensive and usually increases exponentially along with the number of manipulator's joints. On the other hand, Local Methods [3],[4] can be applied to the collision problems in unstructured and dynamic environment. Local Method has the ability to be flexible and adapt its motion to changing environment even with limited information. The information of the environment used in Local Method is naturally obliged to perform the tasks on-line in limited recognition time.

Our concern in this research is whether we can connect the concepts of Local Method and Global Method by introducing a concept of Multi-Preview Control strategy. If the future information required for path planning can be available to use for Local Method, then it should be possible that the real-time configuration control by Local Method may take the advantage of the Global Method into the configuration control of the Local Method. This is the research direction what we want to pursue and to make clear. Though this question has not been fully answered in this report, we can posit a clue to approach it. Our research pursues adaptive system using Local Method. The features of our system are shown in Fig.1 where the camera's observable area symbolizes the restricted information of environment. In Fig.1, the camera

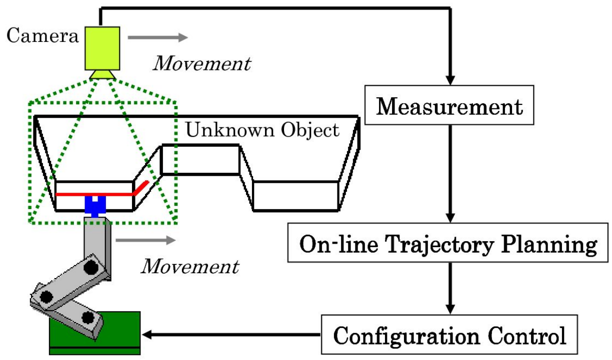

Fig. 1 Processing system for unknown object

and the manipulator's hand are supposed to move synchronously to achieve on-line operation depending on the real-time restricted information. When the camera detects a new obstacle appearing suddenly in the scene, the manipulator must change its configuration immediately for avoiding it.

In our previous researches, we proposed Single-Preview Control Method [5] and Multi-Preview Control Method [6]. These method including the target object — be seen as an obstacle to be avoided —, use imaginary manipulator based on 1-Step GA to explore future trajectory information and AMSIP [5] to evaluate configurations of manipulator. The AMSIP index is composed of evaluations — (1): a shape changeability of redundant manipulator while the hand tasks a given trajectory as a primary task and (2): obstacle-avoiding margin —, where (1) depends on bully the manipulator's structure and the current configuration and (2) relies on the obstacle's shape and motion if it can move. The AMSIP index is defined in the space of residue redundancy that can be exploited for the second task of shape-changing while keeping the hand's tracking task be done primarily. By examining the AMSIP distribution, we noticed a phenomenon that there happens to appear a possible transition path of the manipulator's configuration globally in the whole redundant space, we named it "Global Transition Phase, GTP". On this paper, the possibility to utilize the GTP in redundant space is discussed. The following is contents of successive sections. AMSIP is explained in section 2. Concept of Preview Control Method is presented in section 3. Difference of two Preview Control Method is explained in section 4.In addition, we will find merits to use AMSIP by simulations presented in section 5.

2. AVOIDANCE MANIPULABILITY SHAPE INDEX WITH POTENTIAL

We proposed Avoidance Manipulability Ellipsoid and Avoidance Manipulability Shape Index (AMSI) in [7], and Avoidance Manipulability Shape Index with Potential (AMSIP) in [5]. Avoidance Manipulability Ellipsoid is applied from Manipulability Ellipsoid proposed by Prof. Yoshikawa in [8]. We will elucidate them briefly in this section.

Then, hand velocity $\dot{\boldsymbol{r}}_{nd}$ is given, $\dot{\boldsymbol{q}}_n$ is solved as

$$\dot{\boldsymbol{q}}_n = \boldsymbol{J}_n^+ \dot{\boldsymbol{r}}_{nd} + (\boldsymbol{I}_n - \boldsymbol{J}_n^+ \boldsymbol{J}_n)\,{}^1\boldsymbol{l} \tag{1}$$

where $\boldsymbol{J}_n^+$ is the pseudo-inverse of Jacobean Matrix $\boldsymbol{J}_n$ and $\boldsymbol{I}_n$ is a $n \times n$ unit matrix. In addition, ${}^1\boldsymbol{l}$ is an arbitrary vector. Trajectory tracking of the hand and collision avoidance can executed simultaneously through this vector ${}^1\boldsymbol{l}$. Here, control variable ${}^1\boldsymbol{l}$ is determined so as to make actual manipulator's shape at current time $\boldsymbol{q}(t)$ close to future optimal shape by referring to the future optimal shapes of imaginary manipulators. The relation of the desired angular velocity of the i-th link ${}^1\dot{\boldsymbol{r}}_{id}$ and $\dot{\boldsymbol{r}}_{nd}$ is shown in Eq.(2).

$${}^1\dot{\boldsymbol{r}}_{id} = \boldsymbol{J}_i \boldsymbol{J}_n^+ \dot{\boldsymbol{r}}_{nd} + \boldsymbol{J}_i(\boldsymbol{I}_n - \boldsymbol{J}_n^+ \boldsymbol{J}_n)\,{}^1\boldsymbol{l} \tag{2}$$

Here we define two variables shown in Eq.(3) and Eq.(4).

$$\Delta^1\dot{\boldsymbol{r}}_{id} \triangleq {}^1\dot{\boldsymbol{r}}_{id} - \boldsymbol{J}_i \boldsymbol{J}_n^+ \dot{\boldsymbol{r}}_{nd}, \tag{3}$$

$${}^1\boldsymbol{M}_i \triangleq \boldsymbol{J}_i(\boldsymbol{I}_n - \boldsymbol{J}_n^+ \boldsymbol{J}_n). \tag{4}$$

According to Eq.(2),Eq.(3) and Eq.(4), $\Delta^1\dot{\boldsymbol{r}}_{id}$ can be rewritten as

$$\Delta^1\dot{\boldsymbol{r}}_{id} = {}^1\boldsymbol{M}_i\,{}^1\boldsymbol{l}. \tag{5}$$

In Eq.(5), $\Delta^1\dot{\boldsymbol{r}}_{id}$ is called the first avoidance velocity and ${}^1\boldsymbol{M}_i$ is a $m \times n$ matrix called the first avoidance matrix.

Next, we will represent the avoidance manipulability measure and the Avoidance Manipulability Ellipsoid. Providing that ${}^1\boldsymbol{l}$ is restricted as $\|{}^1\boldsymbol{l}\| \leq 1$, then the extent where $\Delta^1\dot{\boldsymbol{r}}_{id}$ can move is denoted as

$$\Delta^1\dot{\boldsymbol{r}}_{id}^T ({}^1\boldsymbol{M}_i^+)^T\,{}^1\boldsymbol{M}_i^+ \Delta^1\dot{\boldsymbol{r}}_{id} \leq 1. \tag{6}$$

If $rank({}^1\boldsymbol{M}_i) = m$, the ellipsoid represented by Eq.(6) is named the first complete avoidance manipulability ellipsoid. If $rank({}^1\boldsymbol{M}_i) = p < m$, the ellipsoid is named as the first partial avoidance manipulability ellipsoid.

The volume of each Avoidance Manipulability Ellipsoid indicates mobility of each link (shape-changeability). The larger total volume indicates the higher whole avoidance manipulability. We evaluated total volume as Avoidance Manipulability Shape Index (AMSI). Then we proposed Avoidance Manipulability Shape Index with Potential (AMSIP) which considers AMSI and the distance between the manipulator and target object. And we verified the superiority of AMSIP through the simulation in [5].

3. CONCEPT

Single-Preview Control and Multi-Preview Control use the future trajectory information obtained by the camera to control actual manipulator. Basically, these methods make the actual manipulator close to the future manipulator (imaginary manipulator) whose configuration possesses the higher avoidance manipulability and ensures non-collision. Single-Preview Control uses an imaginary manipulator with very limited information and Multi-Preview Control uses several imaginary manipulators with more information.

Fig.2 describes the effectiveness of multiple preview control, where the times defined by t_0, t_1, t_2, t_3 and t_4 respectively. And "•" indicates several local optimal configurations at each future time whose evaluation values ${}^1S$ presented in [5] are plus and are denoted here by S_{1a}, S_{1b}, S_{1c} ($S_{1a} < S_{1b} < S_{1c}$) at $t = t_1$, and S_{2a}, S_{2b}, S_{2c} ($S_{2a} < S_{2b} < S_{2c}$) at $t = t_2$, and S_{3a}, S_{3b}, S_{3c} ($S_{3a} < S_{3b} < S_{3c}$) at $t = t_3$ and S_{4b}, S_{4c} ($S_{4b} < S_{4c}$) at $t = t_4$. The value S evaluates superiority of the configuration and safety concerning collision with the working object, and $S < 0$ means collision. The manipulator stays at initial configuration when time $t = t_0$. If we do not use preview control method, we almost can not know the future information, so control of the current manipulator's configuration will be blind without any reference. If we use single preview depending on only one future optimal configuration at one future time, then the configuration will be controlled to S_{1c} at time $t = t_1$, to S_{2c} at time $t = t_2$ and to S_{3c} at time $t = t_3$. Shall we provide that the value of S_{4a} has negative value represented by "∘" meaning future possible

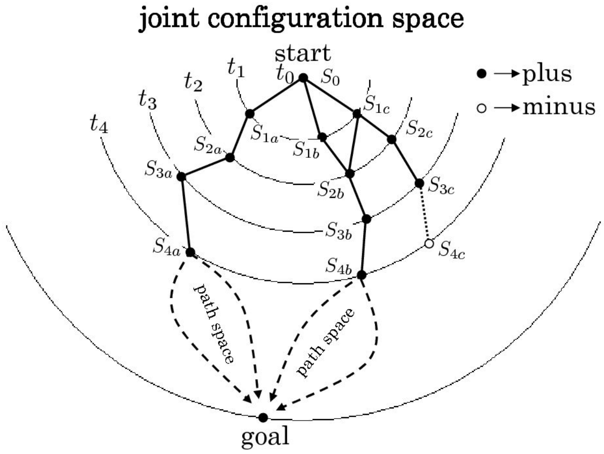

Fig. 2 The concept of single-preview and multi-preview

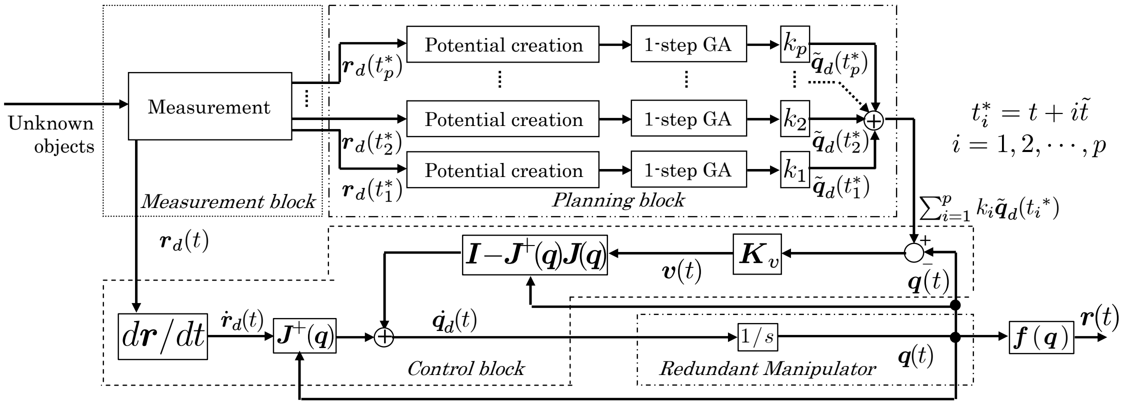

Fig. 3 Multi-Preview control system

configuration from S_{3c} can not avoid collision with surroundings or target object. The configuration of redundant manipulator corresponding to S_{3c} at time $t = t_3$ is trapped in hardship because the future information at only one future time is very local. The real-time motion will have to be stopped at time $t = t_3$ for safety. However, if we expand the future information by selecting three future optimal configurations at three future times, which is Multi-Preview. The configuration will be controlled to S_{1c} at time $t = t_0$ by the future optimal reachable sequences $S_0 \to S_{1c} \to S_{2c} \to S_{3c}$ estimated from $S_{ij} (i = 1, 2, 3; j = a, b, c)$, where the other possible sequences $S_0 \to S_{1a} \to S_{2a} \to S_{3a}$, $S_0 \to S_{1b} \to S_{2b} \to S_{3b}$ and $S_0 \to S_{1c} \to S_{2b} \to S_{3b}$ are inferior selection. Then, the possible future sequences at time t_1 are restricted to $S_{1c} \to S_{2b} \to S_{3b} \to S_{4c}$ and $S_{1c} \to S_{2c} \to S_{3c} \to S_{4a}$, and then both are evaluated. Then multi-preview controller can judge and exclude the collision configuration S_{4a}, then it will choose the future optimal reachable sequences $S_{1c} \to S_{2b} \to S_{3b} \to S_{4c}$. By repeating such evaluation of future configuration sequences and possible route changing, multi-preview control system will possibly avoid dangerous sequences connecting to clashing in the future and can widen out the reachable possibility from current configuration to goal configuration.

According to above discussion, we can conceptually think that Multi-Preview Control can improve the limitation of Single-Preview Control.

4. MULTI PREVIEW CONTROL

Multi-Preview Control System is shown in Fig.3which is a configuration control method to change current manipulator's shape satisfying non-collision requirement by referring to the future configurations based on an on-line measurement.

It consists of an on-line measurement block, a path planning block, a redundancy control block and redundant manipulator. On the assumption that current time is represented by t, and the future times are defined as $t_i^* = t + i\tilde{t}$, $(i \in [1, p])$ where $\tilde{t}$ denotes preview time and i is the number of future times. A measurement block detects a desirable hand position $\boldsymbol{r}_d(t_i^*)$ on the surface of the target object at time t_i^*, which is reasonably assumed to be possible to detect the future information only in the detected camera image in Fig.1. Firstly, potential space based on the detected shape of the target object is created around it at the path planning block. Then the path planning block outputs the optimal shape $\tilde{\boldsymbol{q}}_d(t_i^*)$ corresponding to the maximum ${}^1S$ presented in [5] at the future time t_i^* (imaginary manipulator) by 1-Step GA. The control block outputs desired joint angular velocity $\dot{\boldsymbol{q}}_d(t)$ that makes actual manipulator's shape at current time $\boldsymbol{q}(t)$ close to the optimal shape in the future by referring to $\sum_{i=1}^{p} \tilde{\boldsymbol{q}}_d(t_i^*)$.

An equation which realizes this control system is named as Preview Control Equation and expressed as follows

$$
\begin{aligned}
\dot{\boldsymbol{q}}_d &= \boldsymbol{J}_n^+ \dot{\boldsymbol{r}}_{nd} \\
&+ (\boldsymbol{I}_n - \boldsymbol{J}_n^+ \boldsymbol{J}_n) \boldsymbol{K}_v (\boldsymbol{q}_d(t) - \boldsymbol{q}(t))
\end{aligned} \tag{7}
$$

where $n \times 1$ matrix $\boldsymbol{q}_d(t)$ is defined as

$$
\boldsymbol{q}_d(t) = \begin{bmatrix} q_{1d}(t) \\ \vdots \\ q_{jd}(t) \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{p} k_i \tilde{q}_{1d}(t_i^*) \\ \vdots \\ \sum_{i=1}^{p} k_i \tilde{q}_{jd}(t_i^*) \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \tag{8}
$$

when redundant degrees j remains and the redundancy is used for the joints from 1 to j.

The transition of AMSIP and the manipulator's shape using Multi-Preview Control System is shown in Fig.4. According to Fig.4, we can find that the manipulator can always keep higher AMSIP value by using Multi-Preview Control. And the AMSIP value obtained by this system moves from one higher peak to another higher peak as time in multi peak AMSIP distributions. This verifies the validity of Multi-Preview Control in 2-dimension by 4-link planar manipulator.

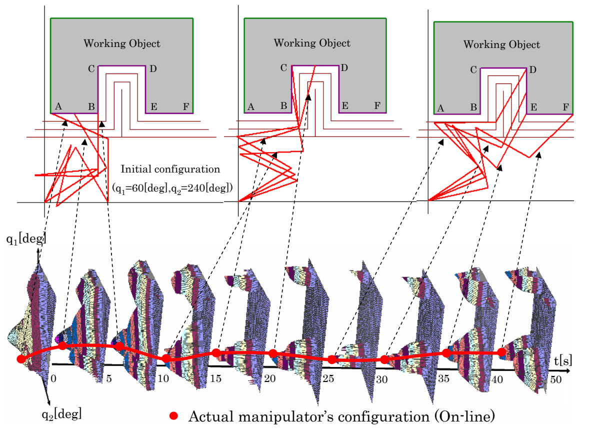

Fig. 4 Actual manipulator's configurations in whole

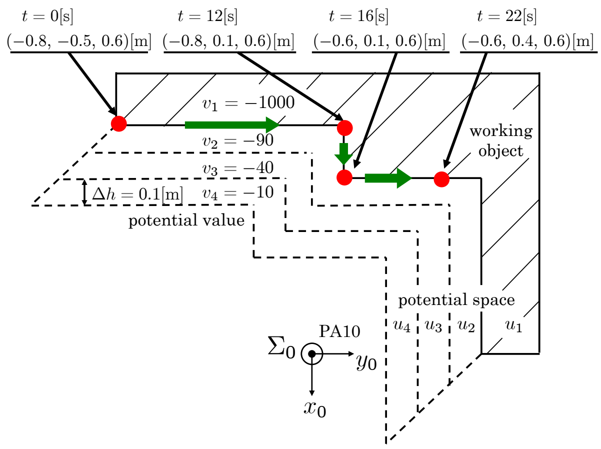

Fig. 5 Simulation's configuration

5. SIMULATIONS

We examine the AMSIP value distributed in a whole sphere of redundant degrees based on a target object's shape given in Fig.5. Since the AMSIP distribution relies on both target object's shape and the redundant manipulator's shape, we need to assume a given target objects form and also a predetermined manipulator's structural configuration. Then, a top view of the target object and corresponding potential spaces are set in Fig.5, and we use exact model of the 7-link manipulator named PA10 (Mitsubishi Heavy Industries, Ltd.). The desired trajectory $\boldsymbol{r}_d(t)$ depicted in the figure is defined as follows:

when $0 \le t < 10$;

$$\boldsymbol{r}_d(t) = \begin{cases} r_{dx}(t) & = -0.8[m] \\ r_{dy}(t) & = -0.5 + 0.05t[m] \\ r_{dz}(t) & = 0.6[m] \\ \phi_d(t) & = 0[rad] \\ \theta_d(t) & = -\frac{\pi}{2}[rad] \end{cases} \tag{9}$$

when $10 \le t < 12$;

$$\boldsymbol{r}_d(t) = \begin{cases} r_{dx}(t) & = -0.8[m] \\ r_{dy}(t) & = -0.5 + 0.05t[m] \\ r_{dz}(t) & = 0.6[m] \\ \phi_d(t) & = -\frac{\pi(t-10)}{8}[rad] \\ \theta_d(t) & = -\frac{\pi}{2}[rad] \end{cases} \tag{10}$$

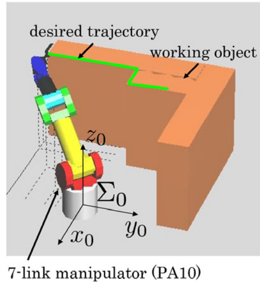

Fig. 6 PA10 and desired trajectory

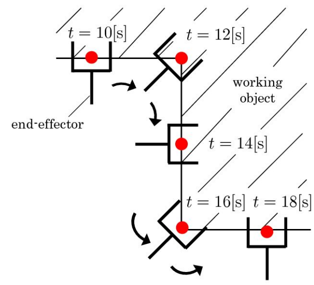

Fig. 7 Transition of orientation around corner

when $12 \le t < 14$;

$$\boldsymbol{r}_d(t) = \begin{cases} r_{dx}(t) & = -0.8 + 0.05(t-12)[m] \\ r_{dy}(t) & = 0.1[m] \\ r_{dz}(t) & = 0.6[m] \\ \phi_d(t) & = -\frac{\pi(t-12)}{8} - \frac{\pi}{4}[rad] \\ \theta_d(t) & = -\frac{\pi}{2}[rad] \end{cases} \tag{11}$$

when $14 \le t < 16$;

$$\boldsymbol{r}_d(t) = \begin{cases} r_{dx}(t) & = -0.8 + 0.05(t-12)[m] \\ r_{dy}(t) & = 0.1[m] \\ r_{dz}(t) & = 0.6[m] \\ \phi_d(t) & = \frac{\pi(t-14)}{8} - \frac{\pi}{2}[rad] \\ \theta_d(t) & = -\frac{\pi}{2}[rad] \end{cases} \tag{12}$$

when $16 \le t < 18$;

$$\boldsymbol{r}_d(t) = \begin{cases} r_{dx}(t) & = -0.6[m] \\ r_{dy}(t) & = 0.1 + 0.05(t-16)[m] \\ r_{dz}(t) & = 0.6[m] \\ \phi_d(t) & = \frac{\pi(t-16)}{8} - \frac{\pi}{4}[rad] \\ \theta_d(t) & = -\frac{\pi}{2}[rad] \end{cases} \tag{13}$$

when $18 \le t \le 22$;

$$\boldsymbol{r}_d(t) = \begin{cases} r_{dx}(t) & = -0.6[m] \\ r_{dy}(t) & = 0.1 + 0.05(t-18)[m] \\ r_{dz}(t) & = 0.6[m] \\ \phi_d(t) & = 0[rad] \\ \theta_d(t) & = -\frac{\pi}{2}[rad] \end{cases} \tag{14}$$

where t means time and the task is given to be completed from $t = 0$ to $t = 22$[s]. The above desired hand trajectory $\boldsymbol{r}_d(t)$ is expressed by using a floor fixed coordinates Σ_0 depicted in Fig.5. The working space dimension of the manipulator's hand task is set to be 5, where position dimension is 3 (x, y, z) and posture dimension is 2 (ω_y, ω_z) and in this case, $\omega_y = \dot{\theta}_d$, $\omega_z = \dot{\phi}_d$. Then the manipulator has 2 redundant DoF because PA10 has 7 DoF. And we gave this 2 redundant DoF to 1-st joint, q_1, and 2-nd joint, q_2. Resolving inverse kinematics of PA10, we can determine q_3 to q_7 from $\boldsymbol{r}_d(t)$ and q_{1d}, q_{2d} given by preview control as Eq.(8). AMSIP distributions are shown from Fig.8 to Fig.10. Figure 8 represents time-series with each AMSIP distribution representing by 3-D expression (upper side) and by 2-D (lower side). A high AMSIP value means that the manipulator has higher shape-changeability and keeps distance between its links and the working object (obstacle) to be safe. That, an AMSIP value equals0 (color is black) means there cannot exist inverse kinematics solution to use redundancy.

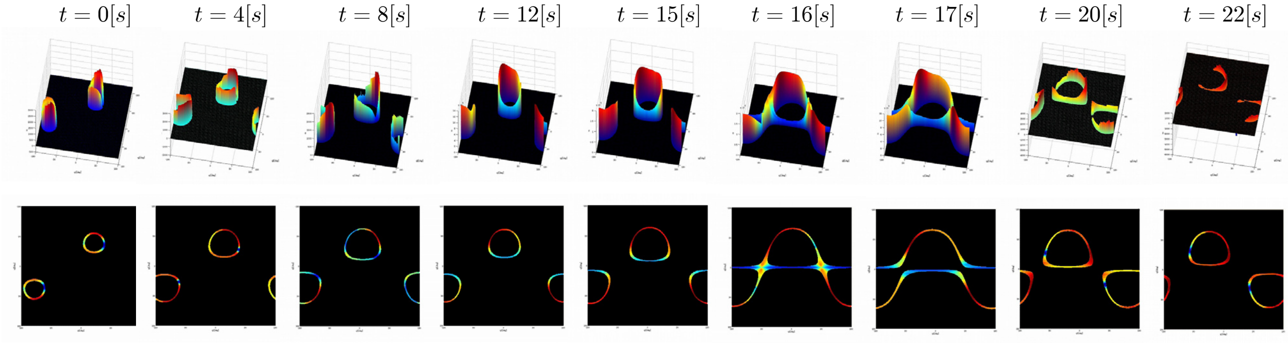

Fig. 8 AMSIP distribution from t = 0 [s] to t = 22 [s]

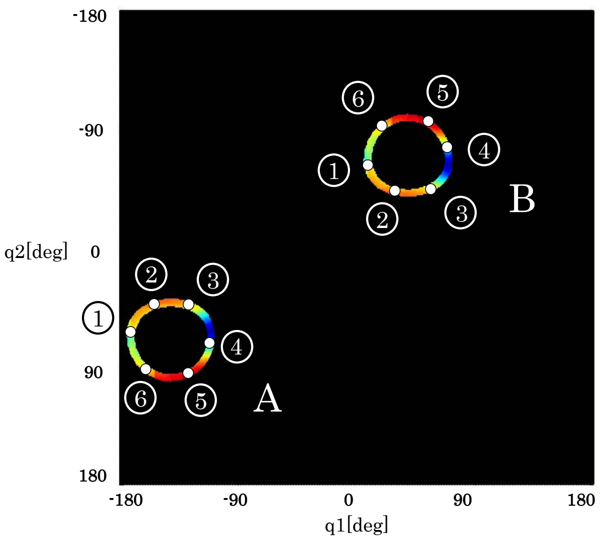

Fig. 9 AMSIP distribution at $t = 0[s]$

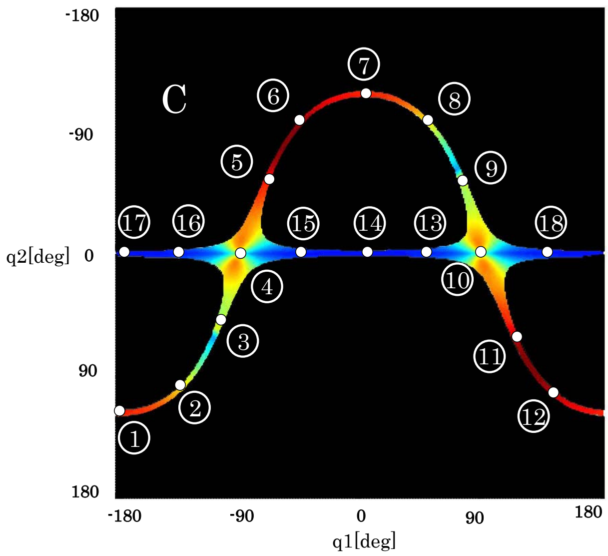

Fig. 10 AMSIP distribution at $t = 16[s]$

We focus AMSIP distribution at $t = 0$ [s] (Fig.9) and $t = 16$[s] (Fig.10). At $t = 0$[s], we named the bottom left circle as A, and the lower right circle as B. The numbers put to each point of the circle correspond shapes of the manipulator, which are shown in Fig.11. The two circles of A and B indicates separate possible configuration where shapes are represented in Fig.11, where the circle A's configurations are extended on the above position of Fig.11, and the circle B's are exhibited below the A's in the figure. Please notice the ① –⑥ in the Fig.9 corresponds to the number of the shapes in Fig11. Seeing A-shapes and B-shapes of the manipulator in sequence of ① –⑥ , we can understand that is (1); hand's pose is controlled to a given desired fixed value, (2); the redundancy is used for arbitrary position of the elbow, (3); is corresponding configuration of A and B are identical. The result (3) is thought to come from the structure of this robot that does not have a shoulder, making right shoulder shape and left-shoulder one be identical. In addition, the circles A and B are separated each other in redundant space, therefore the manipulator cannot change the configuration from A to B or vice versa while achieving tracking target trajectory. Then we named it "Local Transition Phase, LTP".

On the other hand, the shape C in Fig.10 shows the distribution at $t = 16$[s]. In the same way, the shapes of manipulator at $t = 16$[s] are shown in Fig.12. Then, examining the manipulator's shape. Seeing the C-shapes in sequence of ① –⑥ and ⑦ –⑫ in the figure, we can understand same items listed above concerning Fig.9 and Fig.11, that is (1); hand's posed are controlled to a given desired fixed value, (2); the redundancy is used for arbitrary position of the elbow, (3); one configuration of ① –⑥ and ⑦ –⑫ are identical. In addition, the C in the distribution is connected —there is no part isolated—, therefore the manipulator can change its shape into any C's configuration while achieving tracking target trajectory. Then we named it "Global Transition Phase, GTP".

6. CONCLUSION

In this paper, by using AMSIP distribution, we examined global and local reconfiguration capability while tracking hand's target trajectory. The results of analyses and simulations, allow us to explain the global reconfiguration can be achieved when connected single-string-shape in AMSIP distribution.

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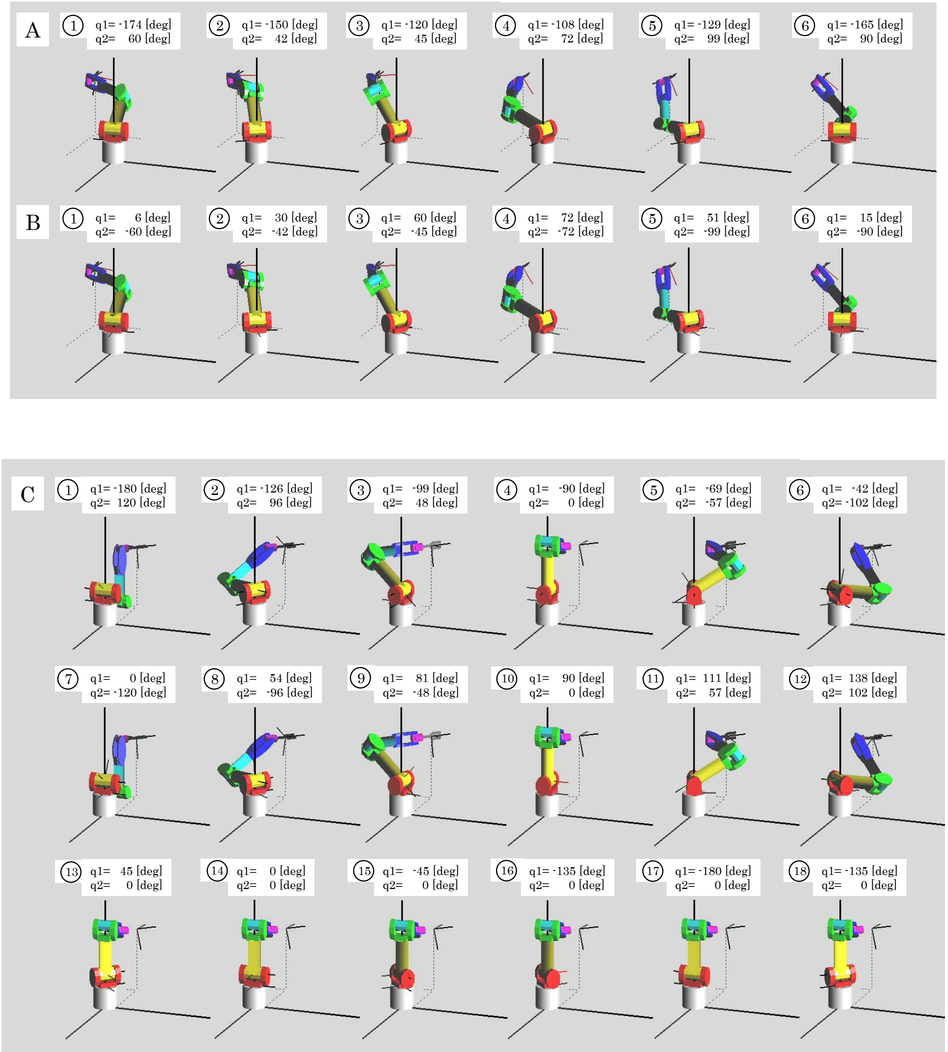

Fig. 12 Shape of Manipulator

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