Conceptual Configuration Control of Redundant Manipulators Inheriting Local/Global Merits: Multi-preview Control

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***Abstract*—This paper proposes a new approach, Multi-Preview Control, to achieve an on-line control of trajectory tracking and obstacle avoidance for redundant manipulators, whose control strategy positions between on-line local method and off-line global method (path planning). In the trajectory tracking process, manipulator is required to keep a configuration with maximal avoidance manipulability in real-time. Multi-preview uses several future optimal configurations to control current configuration to complete task of trajectory tracking and obstacle avoidance on-line with highest avoidance manipulability and reachability. We verify the validity of multi-preview control through simulations and evaluate its effectiveness by comparing it with single-preview and path planning.**

I. INTRODUCTION

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

There are many researches on the motion of redundant manipulators discussing how to use the redundancies. The proposed solutions to this problem can be broadly categorized into two classes: Global and Local Methods. Global Methods [1],[2] solve the collision avoidance problem by an entire path planning. In [2], Ahuactzin and Gupta have proposed an approach to find a feasible path corresponding to a desired position and orientation of end-effector from a given initial configuration of the robot. Such a global method's computational cost is expensive, and usually increases exponentially along with the number of manipulator's joints. Moreover, it is obvious that the entire path planning is only suited for structured and static environments and is inapplicable to dynamic environments with moving obstacles. Considering these limitations, global method has been utilized only as an off-line path planning tool in the high level of manipulators control hierarchy. On the other hand, to achieve an ability adaptive to dynamic environments, a system must make efforts

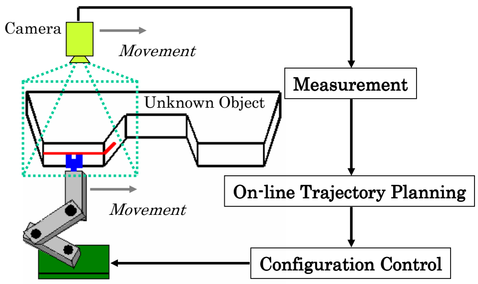


Fig. 1. Processing system for unknown object

to be flexible as much as possible even in a situation of limited information about surroundings. Such methodology is named as Local Method [3],[4], and this adaptivity requires that the system be tolerable for the changing conditions and possess real-time measurement ability. Local method can deal with moving obstacles in an unstructured workspace. However, to perform the tasks on-line by local method, the information of the environment is naturally restricted in local information by limited recognition time, this means local methods inherit inadequate information about environment, remaining the possibility that the arm of the redundant manipulator may be trapped in an undesired situation. Moreover, note that most configuration tracking methods are based on local method assuming that a feasible solution exists.

Our research also pursues adaptive system using local method. The feature of our system is shown in Fig.1 where the camera scene area means symbolically the restricted information of the environment, and it contains future trajectory information even though restricted near future. In Fig.1, the camera and the manipulator's hand are supposed to move synchronously because achieving on-line operation depends on the real-time information of unknown target object obtained by this moving camera covering restricted area. When the camera detects an obstacle appearing suddenly in the scene, the configuration of manipulator is required to change immediately so that it can avoid this obstacle. Therefore, in the whole on-line trajectory tracking process, always keeping the avoidance manipulability (shape-changeability) [5] of whole manipulator high is very necessary to prepare abrupt appearance of obstacles.

The avoidance matrix ($\boldsymbol{M}_i$), which is very important to analyze avoidance manipulability as a measure to evaluate the shape-changeability, had initially been defined and used for controling the redundant manipulator's configuration based on prioritized multiple tasks [6]. However, the proposed controller can not decouple the interacting motions of multiple tasks even though the redundant degree be much higher than the required motion degree of the multiple tasks, which is thought to stem from the incompleted definition of Jacobian matrix concerning the motion of what number of links the matrix describes. Comparing our definition of Jacobian matrix with [6], the detailed difference and explanation are shown in sections III and IV.

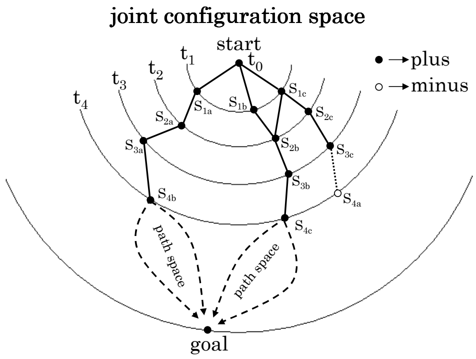


Fig. 2. Overview of local method, preview control and path planning

Depending on avoidance matrix, we present a concept of the avoidance manipulability ellipsoid as an index evaluating avoidance manipulability of the manipulator by $\boldsymbol{M}_i$. Then, combining with 1-step Genetic Algorithm [7] considering potential spaces [8] around the measured target object, the real-time optimal configurations of the manipulator at future times can be evaluated at current time. Finally, by multi-preview control for solving reachability problem, these future optimal configurations of imaginary manipulators can be used to control current actual manipulator to achieve on-line trajectory tracking and obstacle avoidance satisfying reachability based on high avoidance manipulability. By comparing simulation results from single-preview control used in our previous research with path planning in off-line condition and multi-preview control, we exhibit that multi-preview control improves single-preview control by obtaining more information in the future, meanwhile multi-preview realizes the on-line control. Being gifted with both merits of Local Method (on-line control) and Global Method (global accuracy) is the most meaningful point of multi-preview control.

II. Overview of Preview Control

Our research is to use inverse kinematic knowledge in the velocity relation to solve a classical on-line trajectory tracking problem of redundant manipulators. The redundancy indicates that one position of the manipulator's hand corresponds to a sub-space in joint configuration space (redundancy solutions). The trajectory tracking problem in our research includes two

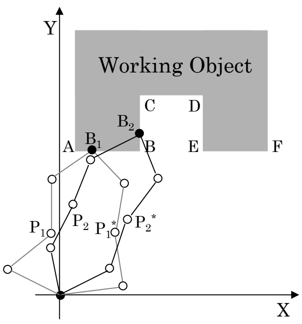


Fig. 3. An example of single preview

main sub-problems: Reachability problem (how to connect in all time all optimal solutions to a goal configuration) and On-line optimization problem (how to select the optimal solution among many solutions in each varying time). Fig.2 describes the overview of 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 are plus and are denoted 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 safty concerning collision with the working object, and $S < 0$ means collison. The manipulator stays at initial configuration when time $t = t_0$. If we use local 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 configuration from S_{3c} can not avoide 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 tiem $t = t_3$ 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 $t = t_1$ by the future optimal reachable sequences $S_{1c} \rightarrow S_{2c} \rightarrow S_{3c}$ estimated from $S_{ij} (i = 1, 2, 3; j = a, b, c)$, where the other possible sequences $S_{1a} \rightarrow S_{2a} \rightarrow S_{3a}$, $S_{1b} \rightarrow S_{2b} \rightarrow S_{3b}$ and $S_{1c} \rightarrow S_{2b} \rightarrow S_{3b}$ are inferior selection. Then, the possible future sequences from S_{1c}, $S_{2b} \rightarrow S_{3b} \rightarrow S_{4c}$ and $S_{2c} \rightarrow S_{3c} \rightarrow S_{4a}$ are evaluated, from which multi-preview controller can judge and exclude the collision configuration S_{4a}, then it will choose the future optimal reachable sequences $S_{2b} \rightarrow S_{3b} \rightarrow S_{4c}$. By repeating such evaluation of future configuration sequences and possible route changing, multi-preview control system will possibly

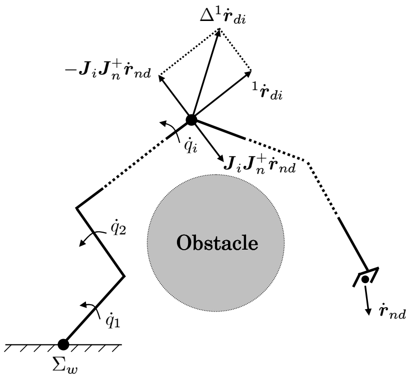


Fig. 4. Obstacle avoidance of intermediate links

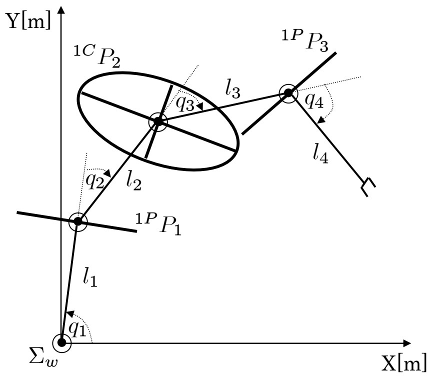


Fig. 5. Avoidance manipulability ellipsoids

avoide dangerous sequences connecting to clashing in the future and can widen out the reachable possibility from current configuration to goal configuration. In addition, if we hope for complete collision avoidance, global exploration in whole configuraiton space corresponding to the whole trajectory is inevitable, which is just suitable for off-line control system.

Fig.3 is used to explain the importance of preview control. When the hand reaches the position B_1, two kinds of the manipulator's configurations denoted by P_1 and ${P_1}^*$, representing symbolically infinite choice of configurations, both can avoid collision. However, when the hand reaches the position B_2, only the configuration of ${P_2}^*$ in the two configurations denoted by P_2 and ${P_2}^*$ can avoid collision. If the manipulator's configuration is selected as P_1 at hand point B_1, the angular velocities of joints will be high values to change its configuration like ${P_2}^*$ near the corner B. This poses a possibility that the manipulator crashes to corner B when the required high angular velocity is over maximum velocity of the joint. Therefore, the manipulator's configuration must be prepared to the configuration ${P_1}^*$ that is similar future configuration ${P_2}^*$. This requires that the current manipulator's configuration should be determined in a consideration of future possible configuration or be determined by several future possible configurations, which is so-call preview control.

III. Avoidance Manipulability

Here we assume that the desired trajectory ($\boldsymbol{r}_{nd}$) and the desired velocity of the manipulator's hand ($\dot{\boldsymbol{r}}_{nd}$) are given as primary task. Then, we can obtain

$$\dot{\boldsymbol{r}}_{nd} = \boldsymbol{J}_n \dot{\boldsymbol{q}}_n \tag{1}$$

From (1), we can obtain

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

In (2), $\boldsymbol{J}_n$ is Jacobian matrix differentiated $\boldsymbol{r}_n$ by $\boldsymbol{q}_n$, $\boldsymbol{J}_n^+$ is pseudo-inverse of $\boldsymbol{J}_n$, $\boldsymbol{I}_n$ is $n\times n$ unit matrix, and ${}^1\boldsymbol{l}$ is an arbitrary vector satisfying ${}^1\boldsymbol{l} \in R^n$. The left superscript "1" of ${}^1\boldsymbol{l}$ means the first avoidance sub-task executed by using redundant DoF. If the rest DoF can execute the second sub-task besides the first sub-task, we define it by ${}^2\boldsymbol{l}$. The following definitions about the left superscript "1" are also. In this research, we define this first avoidance sub-task (first demanded avoidance velocity) by ${}^1\dot{\boldsymbol{r}}_{di}$, which is assumed to be given from an avoidance control system of higher level. The relation of ${}^1\dot{\boldsymbol{r}}_{di}$ and $\dot{\boldsymbol{r}}_{nd}$ is denoted as (3) by substituting (2) into ${}^1\dot{\boldsymbol{r}}_{di} = \boldsymbol{J}_i\dot{\boldsymbol{q}}_n$.

$$ {}^1\dot{\boldsymbol{r}}_{di} = \boldsymbol{J}_i\boldsymbol{J}_n^+\dot{\boldsymbol{r}}_{nd} + \boldsymbol{J}_i(\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)\ {}^1\boldsymbol{l} \tag{3}$$

Here, we define two variables shown as

$$\Delta^1\dot{\boldsymbol{r}}_{di} \overset{\triangle}{=} {}^1\dot{\boldsymbol{r}}_{di} - \boldsymbol{J}_i\boldsymbol{J}_n^+\dot{\boldsymbol{r}}_{nd} \tag{4}$$

and

$$ {}^1\boldsymbol{M}_i \overset{\triangle}{=} \boldsymbol{J}_i(\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n) \tag{5}$$

In (4), $\Delta^1\dot{\boldsymbol{r}}_{di}$ is called by "the first avoidance velocity". In (5), ${}^1\boldsymbol{M}_i$ is a $m\times n$ matrix called by "the first avoidance matrix". Then, $\Delta^1\dot{\boldsymbol{r}}_{di}$ can be rewritten as

$$\Delta^1\dot{\boldsymbol{r}}_{di} = {}^1\boldsymbol{M}_i{}^1\boldsymbol{l} \tag{6}$$

The relation between ${}^1\dot{\boldsymbol{r}}_{di}$ and $\Delta^1\dot{\boldsymbol{r}}_{di}$ is shown in Fig.4. From (6), we can obtain ${}^1\boldsymbol{l}$ shown as

$$ {}^1\boldsymbol{l} = {}^1{\boldsymbol{M}_i}^+\Delta^1\dot{\boldsymbol{r}}_{di} + (\boldsymbol{I}_n -{}^1\boldsymbol{M}_i^+\ {}^1\boldsymbol{M}_i)^2\boldsymbol{l} \tag{7}$$

Assuming that ${}^1\boldsymbol{l}$ is restricted as $\|{}^1\boldsymbol{l}\| \le 1$, then the extent where $\Delta^1\dot{\boldsymbol{r}}_{di}$ can move is denoted as

$$\Delta^1{\dot{\boldsymbol{r}}_{di}}^T({}^1\boldsymbol{M}_i^+)^T\ {}^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di} \le 1 \tag{8}$$

If $rank({}^1\boldsymbol{M}_i) = m$, (8) represents that $\Delta^1\dot{\boldsymbol{r}}_{di}$ can be described by an ellipsoid expanded in m-dimension space and the vector $\forall\Delta^1\dot{\boldsymbol{r}}_{di}\in R^m$ exists in the space expanded by the first avoidance matrix ${}^1\boldsymbol{M}_i$ as

$$\Delta^1\dot{\boldsymbol{r}}_{di} = {}^1\boldsymbol{M}_i{}^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di}, \quad \Delta^1\dot{\boldsymbol{r}}_{di}\in R({}^1\boldsymbol{M}_i) \tag{9}$$

which indicates that $\Delta^1\dot{\boldsymbol{r}}_{di}$ can be arbitrarily realized in m-dimension space and (6) always guarrantees the solution ${}^1l$ corresponding to $\forall\Delta^1\dot{\boldsymbol{r}}_{di}\in R^m$. In this way, the ellipsoid represented by (8) is named "the first complete avoidance manipulability ellipsoid", which is denoted by ${}^{1C}P_i$.

If $rank({}^1\boldsymbol{M}_i) = p < m$, $\forall\Delta^1\dot{\boldsymbol{r}}_{di}\in R^m$ does not satisfy (9). The another first avoidance velocity $\Delta^1\dot{\boldsymbol{r}}^*_{di}$, that is, the orthogonal projection of $\Delta^1\dot{\boldsymbol{r}}_{di}$ onto $R({}^1\boldsymbol{M}_i)$,

$$\Delta^1\dot{\boldsymbol{r}}^*_{di} = {}^1\boldsymbol{M}_i{}^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di}, \quad \Delta^1\dot{\boldsymbol{r}}^*_{di}\in R({}^1\boldsymbol{M}_i) \tag{10}$$

can be partially executed. Further, we can obtain

$$\Delta^1\dot{\boldsymbol{r}}_{di}^{*\,T}({}^1\boldsymbol{M}_i^+)^T{}^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di}^*\leq 1 \tag{11}$$

In (11), $\Delta^1\dot{\boldsymbol{r}}_{di}^*$ can be described by an ellipsoid expanded in p-dimension space. This ellipsoid is named "the first partial avoidance manipulability ellipsoid", which is denoted by ${}^{1P}P_i$. Because $p < m$, the partial avoidance manipulability ellipsoid can be thought as a segment of the complete avoidance manipulability ellipsoid.

Taking a 4-link redundant manipulator ($n = 4$) in 2-dimension space ($m = 2$) for example shown in Fig.5, the origin of the working coordinate system Σ_w is fixed at the root of the first link. The joint angles, q_i ($i = 1, 2, 3, 4$ and unit is $[rad]$), are denoted along each rotational axis as anticlockwise direction is positive. All length of links is defined by $l_i = 0.25$ ($i = 1, 2, 3, 4$ and unit is $[m]$). When the manipulator's hand position is fixed at $\boldsymbol{r}_{4d} = (0.6, 0.3)$, the joint angles are confirmed as $q_1 = 1.396$, $q_2 = -0.524$, $q_3 = -0.631$ and $q_4 = -1.153$ respectively. In this given configuration,The avoidance manipulability ellipsoids corresponding to the first and the third links (${}^{1P}P_1$ and ${}^{1P}P_3$) are denoted by two lines, which can be thought as segment of ellipsoid area. The avoidance manipulability ellipsoid corresponding to the second link (${}^{1C}P_2$) is denoted by a whole ellipsoid area in 2-dimensional space.

IV. PLURAL AVOIDANCE TASKS AND AVOIDANCE MANIPULABILITY ELLIPSOID

In section III, we defined the first avoidance manipulability ellipsoid ${}^1P_i$ ($i = 1, \cdots, n-1$). However, in fact these intermediate links (except the end-effector of manipulator) can not realize their own avoidance velocities simultaneously. If the first avoidance task, that is, the first avoidance velocity, $\Delta^1\dot{\boldsymbol{r}}_{di}$ or $\Delta^1\dot{\boldsymbol{r}}_{di}^*$ has been realized at the certain i-th links. Next, we will consider the possibility to execute the secondly demanded velocity except the i-th link. Substituting (7) into (2), we can obtain

$$\begin{aligned}\dot{\boldsymbol{q}}_n &= \boldsymbol{J}_n^+\dot{\boldsymbol{r}}_{nd} + (\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di} \\ &\quad +(\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)(\boldsymbol{I}_n - {}^1\boldsymbol{M}_i^{+1}\boldsymbol{M}_i)^2\boldsymbol{l}\end{aligned} \tag{12}$$

Substituting (12) into ${}^2\dot{\boldsymbol{r}}_{dj} = \boldsymbol{J}_j\dot{\boldsymbol{q}}_n$, we can obtain

$$\begin{aligned}{}^2\dot{\boldsymbol{r}}_{dj} &= \boldsymbol{J}_j\boldsymbol{J}_n^+\dot{\boldsymbol{r}}_{nd} + \boldsymbol{J}_j(\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di} \\ &\quad +\boldsymbol{J}_j(\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)(\boldsymbol{I}_n - {}^1\boldsymbol{M}_i^{+1}\boldsymbol{M}_i)^2\boldsymbol{l}\end{aligned} \tag{13}$$

By defining $\Delta^2\dot{\boldsymbol{r}}_{dj}$ and ${}^2\boldsymbol{M}_j$ as

$$\begin{aligned}\Delta^2\dot{\boldsymbol{r}}_{dj} &\triangleq {}^2\dot{\boldsymbol{r}}_{dj} - \boldsymbol{J}_j\boldsymbol{J}_n^+\dot{\boldsymbol{r}}_{nd} \\ &\quad -\boldsymbol{J}_j(\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di}\end{aligned} \tag{14}$$

and

$${}^2\boldsymbol{M}_j \triangleq \boldsymbol{J}_j(\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)(\boldsymbol{I}_n - {}^1\boldsymbol{M}_i^{+1}\boldsymbol{M}_i) \tag{15}$$

then, we can obtain

$$\Delta^2\dot{\boldsymbol{r}}_{dj} = {}^2\boldsymbol{M}_j{}^2\boldsymbol{l} \tag{16}$$

The forms of (16) and (6) are similar. Therefore, the analysis method of the second avoidance manipulability ellipsoid ${}^2P_j$ ($j = 1, \cdots, n-1; \{j{\neq}i\}$) and the first avoidance manipulability ellipsoid ${}^1P_i$ are also similar. In other words, whether the second avoidcance task can be realized or not depends on the rank value of second avoidance matrix ${}^2\boldsymbol{M}_j$ ($j = 1, \cdots, n-1; \{j{\neq}i\}$). If $rank({}^2\boldsymbol{M}_j) > 0$, the second avoidcance task can be realized. Similarly, we can judge whether the third avoidcance task can be realized or not by the third avoidance matrix ${}^3\boldsymbol{M}_k$ as

$$\begin{aligned}{}^3\boldsymbol{M}_k &\triangleq \boldsymbol{J}_k(\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)(\boldsymbol{I}_n - {}^1\boldsymbol{M}_i^{+1}\boldsymbol{M}_i)(\boldsymbol{I}_n - {}^2\boldsymbol{M}_j^{+2}\boldsymbol{M}_j) \\ &\quad (k = 1, \cdots, n-1;\ \{k{\neq}i\}{\cap}\{k{\neq}j\})\end{aligned} \tag{17}$$

According to above analysis for ${}^1\boldsymbol{M}_i$, ${}^2\boldsymbol{M}_j$ and ${}^3\boldsymbol{M}_k$, by the similar method, the execution possibility of the fourth or more avoidance tasks can be judged.

Here, we use an 7-link manipulator in 2-dimension space as an example to analyse the avoidance manipulability ellipsoid when the manipulator deals with plural avoidance tasks. Fig.6(a) shows the first avoidance manipulability ellipsoids as ${}^1P_i$ ($i = 1, \cdots, 6$). When the arbitrary first avoidance task (the first demanded avoidance velocity ${}^1\dot{\boldsymbol{r}}_{d3}$) is given to the third link, there exists the corresponding first avoidance velocity ($\Delta^1\dot{\boldsymbol{r}}_{d3}$) in 2-dimension space because $rank({}^1\boldsymbol{M}_3) = 2$. After ${}^1\dot{\boldsymbol{r}}_{d3}$ is realized, the second avoidance manipulability ellipsoids are shown in Fig.6(b) as ${}^2P_j$ ($j = 1, 2, 4, 5, 6$). By comparing ${}^1P_i$ with ${}^2P_j$, we can find that ${}^{2P}P_1$ and ${}^{2P}P_6$ are shorter than ${}^{1P}P_1$ and ${}^{1P}P_6$. Moreover, ${}^{2P}P_2$ and ${}^{2P}P_4$ become the partial avoidance manipulability ellipsoids represented by two vertical lines of the third and the fourth links respectively. The reason is that the given ${}^1\dot{\boldsymbol{r}}_{d3}$ has the effect of making the tips of the second and fourth links just move along one direction around the tip of the third link. ${}^{2C}P_5$ is still the complete avoidance manipulability ellipsoid, however the size of ${}^{2C}P_5$ is smaller than ${}^{1C}P_5$ because the singular values of ${}^2\boldsymbol{M}_5$ are smaller that the ones of ${}^1\boldsymbol{M}_5$. When we consider the second avoidance manipulability ellipsoids, $rank({}^2\boldsymbol{M}_j) = 1$ ($j = 1, 2, 4, 6$) and $rank({}^2\boldsymbol{M}_5) = 2$, which indicates that only the tip of the fifth link can arbitrarily realize the second avoidance velocity in 2-dimension space, the tips of the other links can realize the second velocity along one direction.

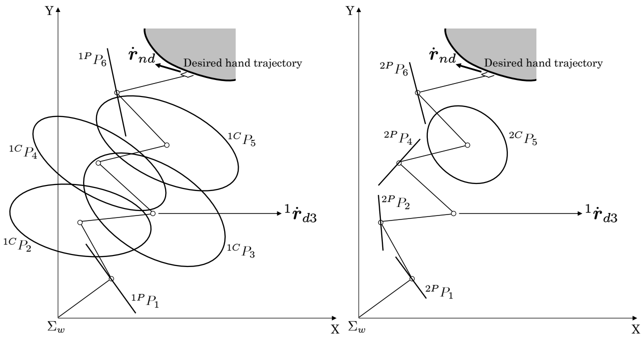
V. OBSTACLE AVOIDANCE STRATEGY

A. AMSI

Here, avoidance manipulability shape index (AMSI) expressed by avoidance manipulability ellipsoid is defined. The volume of avoidance manipulability ellipsoid of i-th link is given as

$${}^1V_i = c_m \cdot {}^1w_i \tag{18}$$

where, c_m and ${}^1w_i$ are defined as



(a) First avoidance manipulability ellipsoids

(b) Second avoidance manipulability ellipsoids

Fig. 6. Plural avoidance manipulability ellipsoids

$$c_m = \begin{cases} \frac{2(2\pi)^{(m-1)/2}}{1\cdot 3\cdots(m-2)m} & (m: odd) \\ \frac{(2\pi)^{m/2}}{2\cdot 4\cdots(m-2)m} & (m: even) \end{cases} \tag{19}$$

$$^1w_i = {}^1\sigma_{i1}\ {}^1\sigma_{i2}\cdots\ {}^1\sigma_{im} \tag{20}$$

In (20), $^1\sigma_{i1}$, $^1\sigma_{i2}, \cdots,$ $^1\sigma_{im}$ are the singular values of $^1\boldsymbol{M}_i$. When the value of ^1V_i is the highest, the avoidance manipulability of i-th link is the best. Then, AMSI (Avoidance Manipulability Shape Index) denoting avoidance manipulability of whole manipulator is defined as

$$^1E = \sum_{i=1}^{n-1} {}^1V_i a_i \tag{21}$$

In (21), if $m = 2$, $^1V_1$, $^1V_{n-1}$ denote the length, $^1V_{2,3,\cdots,(n-2)}$ denote area. And $a_1 = a_{n-1} = 1[m^{-1}]$, $a_{2,3,\cdots,(n-2)} = 1[m^{-2}]$. ^1E denotes a number without unit.

B. AMSIP

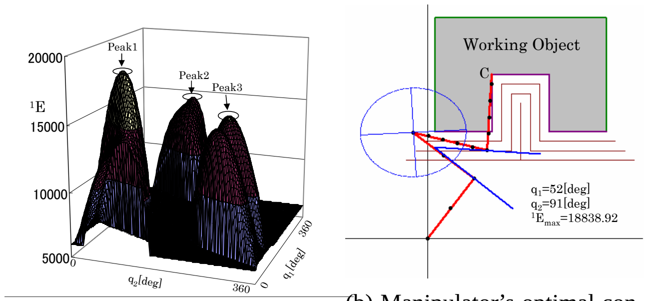
By using AMSI, although avoidance ability of whole manipulator is the highest, the manipulator will possibly collide with the obstacle because it does not consider the distance between the manipulator and the obstacle. Therefore, we construct the potential spaces along the object's shape detected by camera. This improved index considering collision by constructing the potential spaces is AMSIP, which is defined as

$$^1S = {}^1E + U \tag{22}$$

where, $U < 0$ denotes total potential value. Therefore, ^1S will come down by U and the possibility of the collision will increase once the manipulator moves into potential spaces (detailed explanation of potential spaces is shown in [8]).

C. Analyses of AMSI and AMSIP

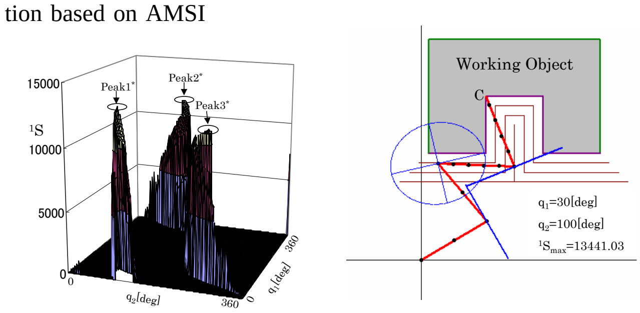
When the manipulator's hand moves to position C in Fig.7(b), the distribution of AMSI about q_1 and q_2 is shown in Fig.7(a), and the distribution of AMSIP is shown in Fig.8(a), where q_1 and q_2 are joint angles of link1 and link2 respectively and they constitute redundancy space of joint angles, q_3 and



(a) 3-D AMSI distribution

(b) Manipulator's optimal configuration

Fig. 7. 3-D AMSI distribution and manipulator's optimal configuration based on AMSI



(a) 3-D AMSIP distribution

(b) Manipulator's optimal configuration

Fig. 8. 3-D AMSIP distribution and manipulator's optimal configuration based on AMSIP

q_4 are determined depending on the hand position once q_1 and q_2 are confirmed. Comparing Fig.7(a) with Fig.8(a), the obvious difference can be found that the shapes of $Peak^*$ of ^1S are smaller and thiner than the shapes of $Peak$ of ^1E. However, from Fig.7(b) and Fig.8(b), which denote the manipulator's optimal configurations corresponding to $Peak1$ and $Peak1^*$ respectively, we can find that AMSIP can avoid collision with higher avoidance manipulability. Therefore, we v ıt AMSIP is more effective than AMSI.

VI. MULTI-PREVIEW CONTROL

A. Reachability

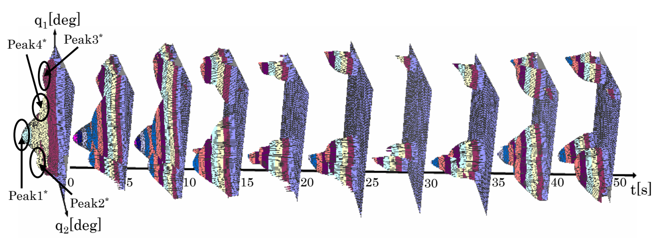


Fig. 9. 3-D ^1S distribution in whole tracking process

In previous research, we did not concern a key question, that is, reachability. Indeed due to moving obstacles in the environment, there may exist an optimal configuration in future time, but there may not be reachable from the current configuration. We assume that the whole tracking process will be finished within 50[s]. We can detect the 3-D AMSIP ^1S distributions at ten different given times in whole tracking process shown in Fig.9. From Fig.9, we can clearly find that

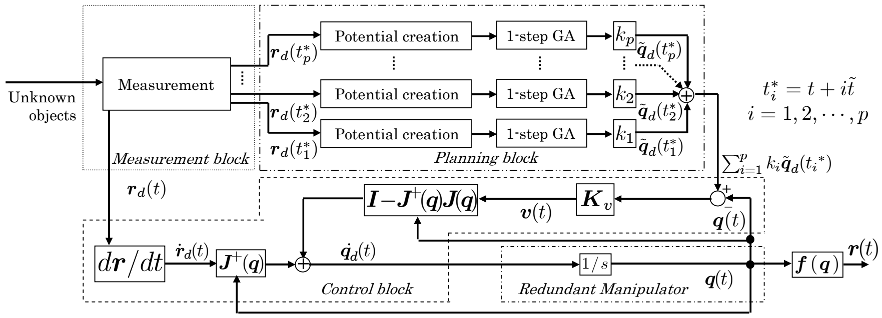


Fig. 10. Multi-preview control system

there are four peaks of ${}^{1}S$ when $t = 0[s]$, $t = 5[s]$ and $t = 10[s]$ denoted by $peak1^*$, $peak2^*$, $peak3^*$ and $peak4^*$ respectively. However, $peak4^*$ disappears from $t = 15[s]$ to end, which indicates the optimal configuration around $peak4^*$ will become dangerous configuration after $15[s]$ when manipulator's hand tracks the trajectory.

B. Multi-Preview Control System

Multi-preview control system depicted in Fig.10 consists of a real-time measurement block, a path planning block, a redundancy control block and a redundant manipulator. On the assumption that current time is represented by t, and the future times are defined as $t_i^* = t + i\tilde{t}$ where $\tilde{t}$ denotes preview time and $i = 1, 2, \cdots, p$, p denotes the number of future times. Firstly, the measurement block can detect desirable hand positions $\boldsymbol{r}_d(t_i^*)$ on the surface of the target object at future times t_i^*. Then, the potential spaces detected by camera are created around the target object at the planning block automatically. Next, the planning block outputs desired joint angles $\tilde{\boldsymbol{q}}_d(t_i^*)$ corresponding to future time t_i^* satisfying non-collision found by 1-Step GA. Here, we make an assumption that $\tilde{\boldsymbol{q}}_d(t_i^*)$ are "imaginary manipulators"and p also denotes the number of imaginary manipulators. At last, when desired velocity $\dot{\boldsymbol{r}}_d(t)$ is given, the control block outputs desired joint angular velocity $\dot{\boldsymbol{q}}_d(t)$ as

$$\dot{\boldsymbol{q}}_d(t) = \boldsymbol{J}^+(\boldsymbol{q})\dot{\boldsymbol{r}}_d(t) + (\boldsymbol{I}_n - \boldsymbol{J}^+(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q}))\boldsymbol{v}(t) \tag{23}$$

In (23), $\boldsymbol{v}(t)$ is an arbitrary vector, which is used for making current joint angle $\boldsymbol{q}(t)$ of actual manipulator close to future joint angles of imaginary manipulators $\tilde{\boldsymbol{q}}_d(t_i^*)$ without collision, so its definitions are very key and varied.

In the case of single-preview control system, we just use one future optimal configuration of imaginary manipulator at one future time $t_1^* = t + \tilde{t}$ $(i = 1)$ to control the current joint angle $\boldsymbol{q}(t)$ of actual manipulator, then $\boldsymbol{v}(t)$ is defined as

$$\boldsymbol{v}(t) = \boldsymbol{K}_v[\tilde{\boldsymbol{q}}_d(t_1^*) - \boldsymbol{q}(t)] \tag{24}$$

In (24), $\boldsymbol{K}_v$ is a positive definite diagonal matrix representing gains, that is, $\boldsymbol{K}_v = diag[k_{v1}, k_{v2}, \cdots, k_{vn}]$. Substituting (24) into (23) constitutes the whole single-preview control system. Obviously, single-preview is typical local method, the future information from which is too local to finish reachability although it is suitable for on-line control.

In the case of multi-preview control system, we use several optimal configurations of imaginary manipulators at future times $t_i{}^* = t + i\tilde{t}$ $(i = 1, 2, \cdots, p,$ p is finite and $p \geq 2)$ to control the current joint angle $\boldsymbol{q}(t)$ of actual manipulator to make $\boldsymbol{q}(t)$ not only close the future optimal configurations without collision but also keep high reachability. For example, when $p = 3$, it means that we adopt three future optimal configurations at three different future times $t + \tilde{t}$, $t + 2\tilde{t}$ and $t + 3\tilde{t}$ to control current configuration. Therefore, variable $\boldsymbol{v}(t)$ in multi-preview control system is defined as

$$\boldsymbol{v}(t) = \boldsymbol{K}_v[\sum_{i=1}^{p} k_i \tilde{\boldsymbol{q}}_d(t_i{}^*) - \boldsymbol{q}(t)] \tag{25}$$

In (25), $\sum_{i=1}^{p} k_i \tilde{\boldsymbol{q}}_d(t_i{}^*)$ indicates the synthetical evaluation of p future optimal configurations, k_i are weight coefficients satisfying $0 < k_i < 1$ and $\sum_{i=1}^{p} k_i = 1$. We can select arbitrary value of preview time $\tilde{t}$ and number of preview control p and weight coefficient k_i according to different conditions. By comparing multi-preview with single-preview, as shown in Fig.2, multi-preview is also local method and suitable for on-line control. But it improves the limitation of single-preview by more information of future dynamic environments, which is possible to realize reachability.

However, in the condition that p is infinite, that is, $p = +\infty$. As shown in Fig.2, the all corresponding optimal configurations from start position to goal position in the desired trajectory, connecting which will constitute an optimal configuration path planning, have been found before working. Therefore, this system will become off-line path planning rather than on-line preview. In section VII, we will compare and analyse their difference by simulations.

VII. SIMULATION

The trajectory consists of five parts, shown as $A-B$, $B-C$, $C-D$, $D-E$ and $E-F$ respectively. The coordinate of A is fixed at position of $(10cm, 140cm)$, the each length of trajectory is defined as $l_{A-B} = l_{B-C} = l_{C-D} = l_{D-E} = l_{E-F} = 75[cm]$ and the length of each link is defined as $l_1 = l_2 = l_3 = l_4 = 100[cm]$. The whole simulation time is set by $50[s]$.

A. Simulation of Single-Preview Control

Firstly, we use single-preview control to do some simulations and the single-preview time $\tilde{t}$ is set by $10[s]$. ${}^{1}S$ of actual manipulator at ten different given times in whole tracking process denoted by red points and configurations corresponding to ${}^{1}S$ at these ten times are shown in Fig.11, where the red line connecting these red points denotes the trajectory changings of ${}^1S$ of actural manipulator in whole tracking process. From Fig.11, we can find that actual manipulator almost can achieve on-line trajectory tracking except for the collision with working object when $t = 30[s]$ because the future information is very local. Collision position is described as "a" and corresponding ${}^1S$ is negative described as "b" in Fig.11.

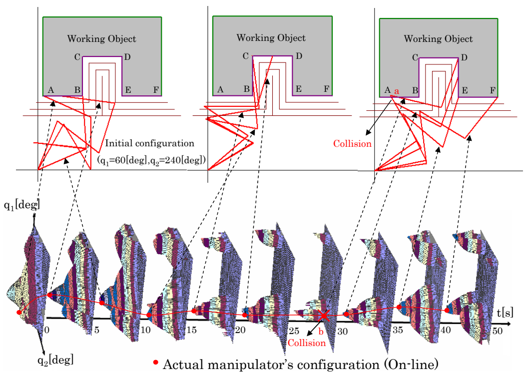


Fig. 11. Actual manipulator's configurations in whole tracking process based on single-preview control

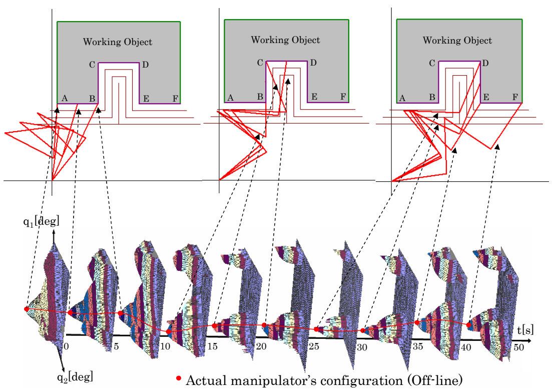


Fig. 12. Actual manipulator's configurations in whole tracking process based on path planning

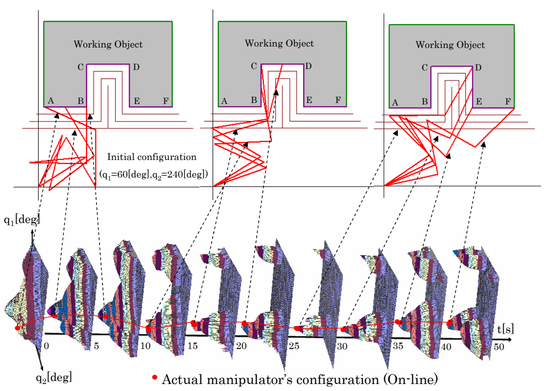


Fig. 13. Actual manipulator's configurations in whole tracking process based on multi-preview control

B. Simulation of Path Planning

Simulation result in the condition that $p = +\infty$ is shown in Fig.12, ${}^1S$ of actual manipulator are at peaks in each ${}^1S$ distribution in whole process, which indicate the maximum ${}^1S$ and their corresponding configurations are also optimal. But this path planning is just suitable for off-line control.

C. Simulation of Multi-Preview Control

Here, we adopt three-preview control to do the same simulations, three future times are defined by $t_1{}^* = t + \tilde{t}$, $t_2{}^* = t + 2\tilde{t}$ and $t_3{}^* = t + 3\tilde{t}$ respectively (here, $\tilde{t} = 5[s]$). Then, we define $k_1 = 0.3$, $k_2 = 0.65$ and $k_3 = 0.05$ (notice that weight coefficients k_i has been presented in (25)). In this way, we use these three future optimal configurations of imaginary manipulators, that is $0.3\tilde{\boldsymbol{q}}_d(t_1^*) + 0.65\tilde{\boldsymbol{q}}_d(t_2^*) + 0.05\tilde{\boldsymbol{q}}_d(t_3^*)$ from (25), to control current configuration of actual manipulator. The simulation result is shown in Fig.13. From Fig.13, we can find that collision occurred at $30[s]$ by using single-preview control has been avoided by using three-preview control and actual manipulator can achieve on-line trajectory tracking without collision meanwhile keeping higher avoidance manipulability.

VIII. CONCLUSION

This paper proposes a new approach using multi-preview control system to solve a on-line trajectory tracking and obstacle avoidance problem for redundant manipulator. We verify the validity of multi-preview control through simulations of comparing it with single-preview control and path planning. We can think that multi-preview control is gifted with both merits of single-preview control and path planning.

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