Obstacle Avoidance of Redundant Manipulator Using Potential and AMSI

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Abstract: This study is intended to build a controller of redundant manipulators with the simultaneous abilities of trajectory tracking and obstacle avoidance without any preparations of path planning to achieve full automation even for one production of one kind, while keeping the avoidance ability high and keeping its shape away from object to reduce the possibility that the manipulator crashes to the object. To evaluate the avoidance ability of the intermediate link, we proposed a scalar value of Avoidance Manipulability Shape Index(AMSI), which is independent of the obstacle's shape. On the other hand, the danger to crash to the obstacle is depending on the shape of the obstacle, which could be evaluated by the potential field set around the obstacle. This paper proposes control method of the manipulator's shape based on the AMSI to simultaneously avoid obstacles and keep the avoidance ability high with potential.

Keywords: Redundant Manipulators, Avoidance Manipulability, Avoidance Manipulability Shape Index, Potential

1. Introduction

Redundant manipulators are used for the welding and grinding operation. If a system to be able to manufacture working objects of unknown shape without any preparation procedures is created, humans' works for such preparations could be abbreviated full automation will be achieved. It is necessary to create such system as shown in Fig.1, which includes measurement of object's shape, trajectory planning, trajectory tracking and obstacle avoidance in the feedback control loop. Furthermore, assuming measurement of all object shape is difficult, so it is necessary that the manipulator have to keep always-high avoidance ability to avoid object, which is thought to be obstacle.

In this study, we aim for building a controller with the simultaneous abilities of trajectory tracking and obstacle avoidance, that is, keeping the avoidance ability high and keeping its shape away from object to reduce the possibility that the manipulator crashes to the object. Manipulability ellipsoids[1] symbolizing the ability of the mobility of manipulator's hand had been proposed. Based on the concept of the manipulability proposed so far we proposed avoidance manipulability ellipsoid[2] that represents shape-change ability of each intermediate link while tracking the desired hand trajectory. This index can represent the avoidance ability of each link by the size of corresponding ellipsoid, but it can not represent the avoidance ability of whole manipulator's shape.

Then, Avoidance Manipulability Shape Index(AMSI)[3] was proposed as an index representing the avoidance ability of whole manipulator's shape. By using this index, the control system was constructed that manipulator can keep avoidance ability high while tracking the hand trajectory. However, the control system based on the AMSI can keep the whole manipulator's shape-changing ability to be high, without any consideration of the positional relations between the manipulator and the obstacle, that is target object with unknown shape here.

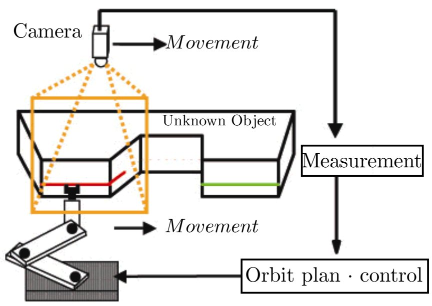

Fig. 1. Processing System for Unknown Object

We use potential space as a method to take the distance of a manipulator and an object into consideration. In this paper, we proposes a control system for the redundant manipulator by using Avoidance Manipulability Shape Index with Potential(AMSIP), which is combined AMSI with the evaluation by potential field to analyze the positional relation of the manipulator and the obstacle. Then, by using AMSIP, we constructed trajectory tracking/obstacle avoidance control system that manipulator can keep high shape-change ability while executing some tasks on an object by its hand. And we confirmed the performances by simulations.

2. Preview Control System

Preview control system[4][5] is a configuration control method to change current arm's shape satisfying non-collision requirements referring the future configuration based on an on-line measurement. The shape to satisfy non-collision requirements in the future time could be found by optimization process using GA(Genetic Algorithm).

Preview control system mentioned above is depicted in Fig.2, and it consists of an on-line measurement block, a path planning block, a redundancy control block, and a redundant manipulator. We define that current time is represented by t, and the time in the future at t is defined as $t = t + \tilde{t}$ with preview time $\tilde{t}$. A measurement block detects a desir-

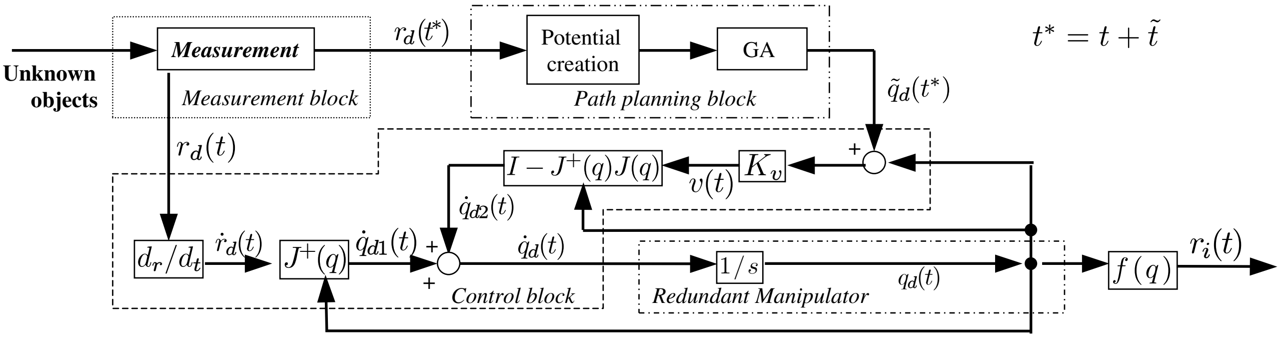

Fig. 2. Preview control system

able hand position $\boldsymbol{r}_d(t\ \ )$ on the surface of the target object at time t . At first, potential space based on the detected shape of the target object is created around the target object at the planning block. Then, the planning block outputs joint angle $\tilde{\boldsymbol{q}}_d(t\ \ )$ satisfying not to collide with the object by GA using the potential space by considering a manipulator at time t in imagination in order to judge the possibility of collision of the robot and the object. We call this "imaginary manipulator". The control block outputs desired joint angular velocity $\dot{\boldsymbol{q}}_d(t)$ that brings joint angle $\boldsymbol{q}(t)$ at current time t close to the desired joint angle in the future, $\tilde{\boldsymbol{q}}_d(t\ \ )$, to satisfy non-collision requirements at time t .

Representing the vector of position and posture of each link by $\boldsymbol{r}_i \in R^m$ and the vector of joint angle by $\boldsymbol{q} = [q_1, q_2, \cdots, q_n]^T$, $\boldsymbol{r_i}$ is given Eq.(1) as a function of $\boldsymbol{q}$.

$$\boldsymbol{r_i} = \boldsymbol{f_i}(\boldsymbol{q}), (i = 1, 2, \cdots, n) \tag{1}$$

By differentiating Eq.(1) by time t, we get,

$$\dot{\boldsymbol{r}}_{\boldsymbol{i}} = \boldsymbol{J_i}(\boldsymbol{q})\dot{\boldsymbol{q}}, \tag{2}$$

Where, $\boldsymbol{J}_i(\boldsymbol{q}) \in R^{m\ \ n}$ represents Jacobean matrix differentiated $\boldsymbol{r}_i$ by $\boldsymbol{q}$.

When desired hand velocity $\dot{\boldsymbol{r}}_d(t)$ is given, the solution $\dot{\boldsymbol{q}}_d(t)$ of Eq.(2) is given as follows in Eq.(3).

$$\dot{\boldsymbol{q}}_d(t) = \boldsymbol{J}^+(\boldsymbol{q})\dot{\boldsymbol{r}}_d(t) + (\boldsymbol{I} - \boldsymbol{J}^+(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q}))\boldsymbol{v}(t) \tag{3}$$

Where $\boldsymbol{J}^+(\boldsymbol{q})$ is pseudo-inverse of Jacobean matrix $\boldsymbol{J}(\boldsymbol{q})$, and $\boldsymbol{I}$ is $n \times n$ unit matrix. In Addition, $\boldsymbol{v}(t)$ is an arbitrary vector, through this value we can execute trajectory tracking of the hand and the collision avoidance simultaneously. In this study, control variable $\boldsymbol{v}(t)$ is determined so as to bring joint angles at current time $\boldsymbol{q}(t)$ close to joint angles of imaginary manipulator $\tilde{\boldsymbol{q}}_d(t\ \ )$ at time t to satisfy non-collision requirements, and is given by Eq.(4),

$$\boldsymbol{v}(t) = \boldsymbol{K}_{pr}(\tilde{\boldsymbol{q}}_d(t\ \ ) - \boldsymbol{q}(t)), \tag{4}$$

where $\boldsymbol{K}_{pr}$ is a positive definite diagonal matrix representing gains, that is, $\boldsymbol{K}_{pr} = diag[k_{v1}, k_{v2}, \cdots, k_{vn}]$.

Substitution Eq.(4) into Eq.(3) constitutes preview control system to use the future possible configuration, that is, the joint angles $\tilde{\boldsymbol{q}}_d(t\ \ )$ satisfying non-collision requirements obtained by configuration planning at time t is utilized to control for current configuration, $\boldsymbol{q}(t)$. This is why we call this control system "Preview Control", which is depicted in Fig.2 for utilizing the redundancy. This system works well to prepare the corner, however, what is problem here is that this system does not work based on the evaluation of the avoiding ability, which is related to the current configuration at time t. This fact gives us a motivation to construct an avoiding controller while keeping its configuration-changing ability always be best. Therefore, an index that can evaluate avoidance ability of intermediate links is necessary, and that it should be calculated on-line. In the next chapter, we explain avoidance manipulability ellipsoids that can evaluate avoidance ability of intermediate links.

3. Avoidance Manipulability

3.1. Complete Avoidance Ellipsoids

Here we discuss the case that a hand desired trajectory $\boldsymbol{r}_{nd}$ and desired velocity $\dot{\boldsymbol{r}}_{nd}$ are given as primary task, then $\dot{\boldsymbol{q}}$ to realize $\dot{\boldsymbol{r}}_{nd}$ is given as,

$$\dot{\boldsymbol{q}} = \boldsymbol{J}_n^+\dot{\boldsymbol{r}}_{nd} + (\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)\ {}^1\boldsymbol{l}, \tag{5}$$

where ${}^1\boldsymbol{l}$ is an arbitrary vector of ${}^1\boldsymbol{l} \in R^n$. The first term of right side of Eq.(5) gives a solution to make $\|\dot{\boldsymbol{q}}\|$ minimize in the space of $\dot{\boldsymbol{q}}$ while realizing $\dot{\boldsymbol{r}}_{nd}$. Additionally, the second term gives joint angle velocity components that can change the manipulator's shape regardless with the realization of $\dot{\boldsymbol{r}}_{nd}$ as the first primary task. When an interference with an object occurred by changing the configuration in accordance with $\boldsymbol{J}_n^+\dot{\boldsymbol{r}}_{nd}$, it is determined depending on orthogonal projection to null space of arbitrary vector ${}^1\boldsymbol{l}$ whether the obstacle avoidance could be completed while executing $\dot{\boldsymbol{r}}_{nd}$.

In the following, we discuss the ability to avoid obstacle concerning the i-th link ($1 \le i \le n-1$), that is, the avoidance manipulability of intermediate links. When the first subtask is given to the i-th link, we represent the demanded avoidance velocity by ${}^1\dot{\boldsymbol{r}}_{di}$. The ${}^1\dot{\boldsymbol{r}}_{di}$ is a variable that should be determined by geometric relation of a manipulator with an obstacle, in this chapter, we assume that it is given from an avoidance control system of higher level. The relation of ${}^1\dot{\boldsymbol{r}}_{di}$ and $\dot{\boldsymbol{r}}_{nd}$ is got by substituting Eq.(5) into Eq.(2) as follows,

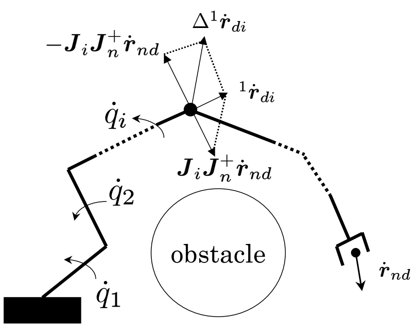

Fig. 3. Obstacle avoidance of intermediate links

$$^1\dot{\boldsymbol{r}}_{di} = \boldsymbol{J}_i\boldsymbol{J}_n^+\dot{\boldsymbol{r}}_{nd} + \boldsymbol{J}_i(\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)\ ^1\boldsymbol{l}, \tag{6}$$

Left side superscript "1" is representing that the avoidance velocity $^1\dot{\boldsymbol{r}}_{di}$ is the first avoidance task. Here we define the following two variables concerning the terms in the above equation,

$$^1\dot{\boldsymbol{r}}_{di} - \boldsymbol{J}_i\boldsymbol{J}_n^+\dot{\boldsymbol{r}}_{nd} \triangleq \Delta^1\dot{\boldsymbol{r}}_{di}, \tag{7}$$

$$\boldsymbol{J}_i(\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n) \triangleq {}^1\boldsymbol{M}_i, \tag{8}$$

Then, Eq.(6) is rewritten as,

$$\Delta^1\dot{\boldsymbol{r}}_{di} = {}^1\boldsymbol{M}_i\ ^1\boldsymbol{l}, \tag{9}$$

where, $^1\boldsymbol{M}_i$ is a matrix of $R^{m\ \ n}$. We show the relation of Eq.(7) in Fig.3. To realize the first avoidance demand velocity $^1\dot{\boldsymbol{r}}_{di}$, in spite of the velocity $\boldsymbol{J}_i\boldsymbol{J}_n^+\dot{\boldsymbol{r}}_{nd}$ at i-th link caused by the influence of hand velocity $\dot{\boldsymbol{r}}_{nd}$, it is necessary to generate $\Delta^1\dot{\boldsymbol{r}}_{di}$ by $\dot{q}_1, \dot{q}_2, \cdots, \dot{q}_i$. $^1\boldsymbol{M}_i$ is projection matrix of $^1\boldsymbol{l}$. When $\dot{\boldsymbol{r}}_{nd}$ is given, it depends on $^1\boldsymbol{M}_i$ whether it can realize $\forall\ ^1\dot{\boldsymbol{r}}_{di} \in R^m$ through $\Delta^1\dot{\boldsymbol{r}}_{di}$. Possibility to realize $\forall\Delta^1\dot{\boldsymbol{r}}_{di}$ can be judged through $^1\boldsymbol{M}_i$. In this sense, we call $^1\boldsymbol{M}_i$ as "the first avoidance matrix of the i-th link". A unit of the $(\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)$ is no dimension, then we can see from Eq.(8) that the unit of each component of $^1\boldsymbol{M}_i$ is identical to corresponding elements in $\boldsymbol{J}_i$. Therefore, $^1\boldsymbol{l}$ could be thought new input to achieve $\Delta^1\dot{\boldsymbol{r}}_{di}$. From Eq.(9), $^1\boldsymbol{l}$ to realize $\Delta^1\dot{\boldsymbol{r}}_{di}$ is given as,

$$^1\boldsymbol{l} = {}^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di} + (\boldsymbol{I}_n - {}^1\boldsymbol{M}_i^+\ ^1\boldsymbol{M}_i)\ ^2\boldsymbol{l}. \tag{10}$$

$^2\boldsymbol{l}$ is $^2\boldsymbol{l} \in R^n$, the same as $^1\boldsymbol{l} \in R^n$. From Eq.(10), the next relation is obtained directly,

$$\|^1\boldsymbol{l}\|^2 \geq \Delta^1\dot{\boldsymbol{r}}_{di}{}^T({}^1\boldsymbol{M}_i^+)^T\ ^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di}. \tag{11}$$

Providing that the new input $^1\boldsymbol{l}$ is restricted as $\|^1\boldsymbol{l}\| \leq 1$, then the extent where $\Delta^1\dot{\boldsymbol{r}}_{di}$ can move, is given as,

$$\Delta^1\dot{\boldsymbol{r}}_{di}{}^T({}^1\boldsymbol{M}_i^+)^T\ ^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di} \leq 1. \tag{12}$$

When the vector $\forall\Delta^1\dot{\boldsymbol{r}}_{di} \in R^m$ exists in the space expanded by the first avoidance matrix $^1\boldsymbol{M}_i$, that is,

$$\Delta^1\dot{\boldsymbol{r}}_{di} \in R({}^1\boldsymbol{M}_i), \tag{13}$$

then it implies that Eq.(9) has always the solution $^1\boldsymbol{l}$. Besides the necessary and sufficient condition that the Eq.(13) holds is that $\Delta^1\dot{\boldsymbol{r}}_{di}$ satisfies,

$$\Delta^1\dot{\boldsymbol{r}}_{di} = {}^1\boldsymbol{M}_i\ ^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di}. \tag{14}$$

In this case, Eq.(12) represents ellipsoids expanded in a space of m dimension. The first avoidance-demanded velocity in m dimensional space represented by Eq.(6) can be realized through $\Delta^1\dot{\boldsymbol{r}}_{di}$ determined by the input $^1\boldsymbol{l}$ in Eq.(9). We call the ellipsoids represented by Eq.(12) "the first complete avoidance manipulability ellipsoids" of the i-th link, and denoted by $^{1C}P_i$.

3.2. Partial Avoidance Ellipsoids

From Eq.(8), the range area of the first avoidance matrix is depending on $\boldsymbol{J}_i(\boldsymbol{q})$ and $(\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)$. Therefore, here, we analyze the condition that $\forall\Delta^1\dot{\boldsymbol{r}}_{di} \in R^m$ does not satisfy Eq.(13). In this case, $rank({}^1\boldsymbol{M}_i) < m\ holds$. This time, orthogonal projection of $\Delta^1\dot{\boldsymbol{r}}_{di}$ onto $R({}^1\boldsymbol{M}_i)$, which is demoted here by $\Delta^1\dot{\boldsymbol{r}}_{di}$ is given as,

$$\Delta^1\dot{\boldsymbol{r}}_{di} = {}^1\boldsymbol{M}_i\ ^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di}, \tag{15}$$

Since $\Delta^1\boldsymbol{r}_{di}$ always satisfies $\Delta^1\dot{\boldsymbol{r}}_{di} \in R({}^1\boldsymbol{M}_i)$, $^1\boldsymbol{l}$ that satisfies the following Eq.(16) exists.

$$\Delta^1\dot{\boldsymbol{r}}_{di} = {}^1\boldsymbol{M}_i\ ^1\boldsymbol{l} \tag{16}$$

Substituting $^1\boldsymbol{M}_i^+ = {}^1\boldsymbol{M}_i^+\ ^1\boldsymbol{M}_i\ ^1\boldsymbol{M}_i^+$ into Eq.(12), then

$$({}^1\boldsymbol{M}_i^+\ ^1\boldsymbol{M}_i\ ^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di})^T\ ^1\boldsymbol{M}_i^+\ ^1\boldsymbol{M}_i\ ^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di} \leq 1, \tag{17}$$

is got. By using Eq.(15), the above equation is

$$(\Delta^1\dot{\boldsymbol{r}}_{di})^T\ ({}^1\boldsymbol{M}_i^+)^T\ ^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di} \leq 1. \tag{18}$$

Ellipsoids that exist in range space of $^1\boldsymbol{M}_i$ defined by Eq.(18) is named here "the first partial avoidance manipulability ellipsoids", and is denoted by $^{1P}P_i$.

Since $\Delta^1\dot{\boldsymbol{r}}_{di}$ and $\Delta^1\dot{\boldsymbol{r}}_{di}$ obtained by Eq.(14) and Eq.(15) are vectors existing in range space of $^1\boldsymbol{M}_i$, then the solution $^1\boldsymbol{l}$ of Eq.(9) always exists. Therefore, in the both cases of a complete avoidance ellipsoid and a partial avoidance ellipsoid, by considering $\Delta^1\underline{\dot{\boldsymbol{r}}}_{di}$ satisfying the following Eq.(19),

$$\Delta^1\underline{\dot{\boldsymbol{r}}}_{di} = {}^1\boldsymbol{M}_i^+\ ^1\boldsymbol{M}_i^+\Delta^1\dot{\boldsymbol{r}}_{di}, \tag{19}$$

we can always obtain the solution of Eq.(9), that is, $^1\boldsymbol{l}$.

A concept of manipulability gave an evaluation index of manipulator's shape by expressing mobility performance of a hand with a manipulability ellipsoid, as shown in Fig.4. On the other hand, proposed avoidance manipulability defines an evaluation index of the shape-change ability while executing an objective trajectory-tracking task of a hand, by avoidance manipulability ellipsoids, $^{1P}P_1$ and $^{1P}P_3$ are the first partial avoidance manipulability ellipsoids, and $^{1C}P_2$ is the first complete avoidance manipulability ellipsoid, as shown in Fig.5. However, the avoidance manipulability ellipsoid of manipulator's each link evaluates merely the mobility of each link. So, avoidance manipulability ellipsoids are not enough to evaluate whole manipulator's shape. When we execute trajectory tracking and obstacle avoidance, it is necessary and important to keep avoidance ability of whole manipulator's shape high. In the following chapter, we propose an evaluation index of whole manipulator's shape.

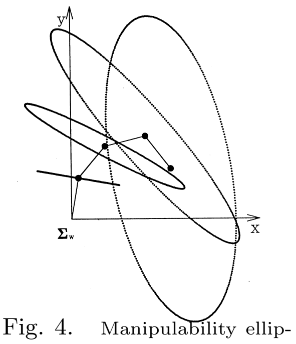

Fig. 4. Manipulability ellipsoids

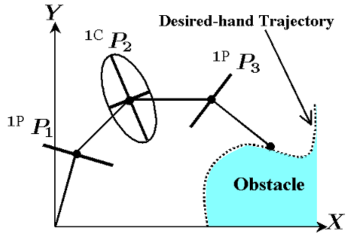

Fig. 5. Avoidance manipulability ellipsoids

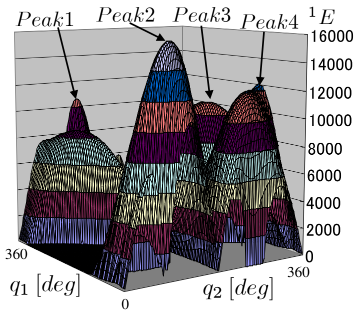

Fig. 6. ^1E distribution when that hand is fixed at (x,y)=(50,100)

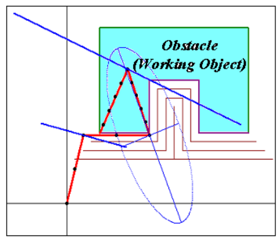

Fig. 7. Manipulator shape of Peak2

4. Avoidance Manipulability Shape Index

As described in a foregoing chapter, the index of avoidance ability of each intermediate link could be expressed by avoidance manipulability ellipsoids, which is concretely evaluated by the volume of each avoidance manipulability ellipsoids. The volume of i-th link's avoidance manipulability ellipsoids, which is called AMI, is given as,

$$^1V_i = c_m \cdot {}^1w_i, \tag{20}$$

where m is dimension of workspace, and c_m is defined as,

$$c_m = \begin{cases} (2\ )^{m/2} & [2 \cdot 4 \cdots (m-2)m] \quad \text{(m:odd)} \\ 2(2\ )^{(m\ \ 1)/2} & [1 \cdot 3 \cdots (m-2)m] \quad \text{(m:even)} \end{cases}. \tag{21}$$

In this study, we discuss avoidance manipulability using planar redundant manipulator as an example, so the dimensions of workspace is two, then ^1V_i means area. The avoidance manipulability ellipsoids of the first link and the $(n-1)$-th link are straight lines as shown in Fig.5, whose area is zero. Since even these two reduced ellipsoids could be useful for obstacle avoidance, the length of straight line should be treated as one of the avoidance manipulability. Each Avoidance Manipulability Ellipsoid represents the shape-changing ability, however, even when the avoidance manipulability of the i-th link has good manipulator's shape, it can not say that the j-th link also does. To evaluate the whole avoidance manipulability of manipulator, the following value is defined,

$$^1E = \sum_{i=1}^{n} a_i {}^1V_i. \tag{22}$$

where, the unit of a_i in this case is $a_1 = a_{n-1} = [m^{-1}]$, $a_{2,3,\ ,(n-2)} = [m^{-2}]$ to make the summation possible in Eq.(22) by changing all terms into non-dimension. We think that this simple scalar value can represent avoidance ability of whole manipulator, and optimum configuration control on a viewpoint of avoidance ability could be constructed by using index. We call this index as "Avoidance Manipulability Shape Index, AMSI ". We show a distribution of AMSI of 4-link manipulator in Fig.6 on the conditions that the hand position is fixed at (x,y)=(50,100) and the two degree of freedom for the possible shape variations are given to q_1 and q_2. The manipulator's shape of the highest peak at this distribution, $Peak2$, is shown in Fig.7. As you see in Fig.7, although avoidance ability of whole manipulator is highest, the manipulator is colliding with the object. This simple example shows that the AMSI does not consider the shape of object, and then naturally we have to add the evaluation value of the distance between the links and the object into AMSI to construct an optimum configuration control while avoiding the object.

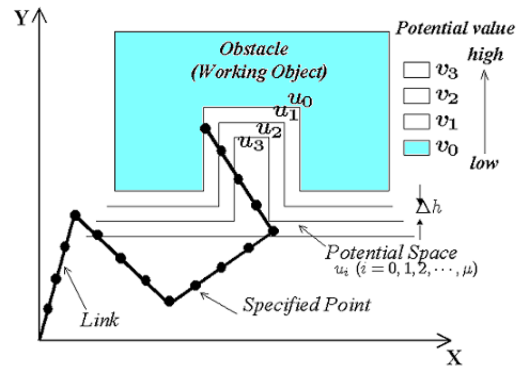

Fig. 8. Potential space and specified point

5. AMSI with potential

5.1. Evaluation index using potential space

AMSI is a index of how much the whole manipulator's shape has shape-changing ability while the hand tracking the desired hand trajectory, and dose not consider the distance between the manipulator and the working object, then manipulator may collide with the object. Therefore, the configuration control system much includes the evaluation of the distance between the links and the obstacle involving the working object. In this research, we use potential space to estimate the distance, which has been adopted many times so far.

The potential space $u_j (j = 0, 1, 2, \cdots, \ )$ is set along the object's shape at Δh intervals as show in Fig.8, and the potential value of each potential space u_j is set to $v_j (j = 0, 1, 2, \cdots, \ )$. Next, the specified n points are placed on each link of the manipulator, and the coordinates in the working space of the specified points are represented by $s_\gamma(x_\gamma, y_\gamma)[\gamma = 1, 2, \cdots, n_h]$. Evaluation value $a(s_\gamma)$ in specified point s_γ is given as,

$$a(s_\gamma) = v_j \quad (s_\gamma \in u_j, j = 0, 1, 2, \cdots, \ )$$
$$a(s_\gamma) = 0 \quad otherwise.$$

Total potential value U of certain manipulator's shape is

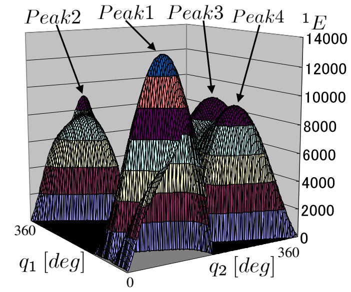

Fig. 9. ^1E distribution when that hand is fixed at (x,y)=(125,175)

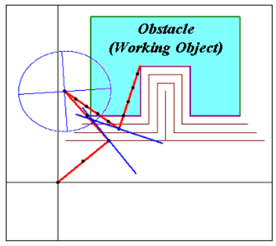

Fig. 10. Manipulator shape at Peak1

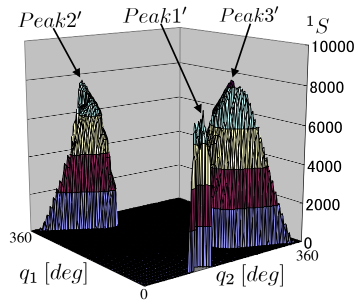

Fig. 11. ^1S distribution when that hand is fixed at (x,y)=(125,175)

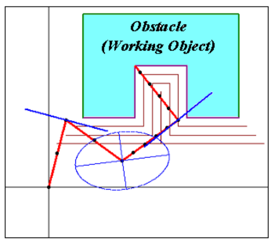

Fig. 12. Manipulator shape at Peak3'

given by Eq.(23).

$$U = \sum_{\gamma=1}^{n_h} a(s_\gamma) \tag{23}$$

The possibility of the collision increases according to the manipulator is position in potential space. From this reason, each potential value is set to negative value as a penalty in this report. Therefore, if U is a large value, it means that the manipulator is away from the object. Moreover, it is necessary to set the potential value v_0 in order to judge the case whether the manipulator is colliding with the object through U. From these things, we call this avoidance ability index with potential evaluation as AMSIP(Avoidance Manipulability Shape Index with Potential), and AMSIP is defined

$$^1S = {}^1E + U. \tag{24}$$

Potential value is set negative as mentioned above, so the value of ^1S comes down by U when the manipulator is approaching to the object.

5.2. Analysis by AMSIP

To verify the usefulness of the AMSIP, we analyze the shape of the 4-link redundant manipulator by ^1S, when the hand position is fixed at point (x,y)=(125,175). The potential value $v_j (j = 0, 1, 2, 3)$ is set at $v_0 = -20000$, $v_1 = -625$, $v_2 = -25$, $v_3 = -5$. To compare AMSI with AMSIP, the distribution of AMSI with the above-mentioned conditions is shown in Fig.9, and the manipulator's shape of the highest value $Peak1$ is shown in Fig.10. As you see, the manipulator

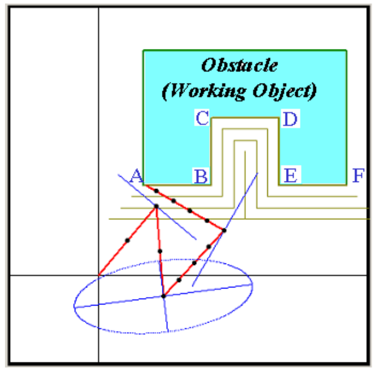

Fig. 13. Desired-hand Trajectory with Concave Shape

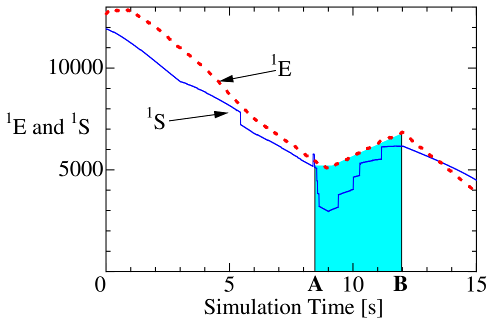

Fig. 14. AMSI and AMSIP value of Trajectory tracking by proposed method

has high avoidance ability, but it is colliding with the working object. It is caused by the defect that AMSI does not consider the distance between manipulator and object.

Next the distribution of AMSIP is depicted in Fig.11. Here the negative value of ^1S is abbreviated to zero. As you see in Fig.11, the highest peak $peak1$ in Fig.9 have disappeared. This shows that the manipulator's shape at $Peak1$ of Fig.9 collided or approached with the object. By considering potential space, we can evaluate the manipulator's shape from the avoidance ability among the configuration shape of the possible choice without collision. So manipulator's shape shown in Fig.12 corresponding to the maximum value in Fig.11 $Peak3'$ have high avoidance ability without collision.

5.3. Trajectory tracking control based on AMSIP

What is difficult to control the manipulator's shape by using AMSIP is that the distribution of ^1S changes according to time, since the hand's position varies with time. Accordingly, keeping the best shape for obstacle avoidance is a problem to execute tracking of time-varying highest peak in the configuration space of the redundancy. In order to search and track this solution in real time process, we can choose 1-step GA ($eneticAlgorithm$)[6],[7].

As we explained in chapter 2, in this study, we use preview control system. Considering ^1S given by Eq.(24) as a fitness function in 1-step GA, the best configuration of imaginary manipulator at the future time t , $\tilde{\boldsymbol{q}}_d(t\ )$, is got, which is substituted into Eq.(4). Then the shape of the current manipulator at time t, $\boldsymbol{q}(t)$, approaches to the best shape $\tilde{\boldsymbol{q}}_d(t\ )$ while keeping hand trajectory tracking.

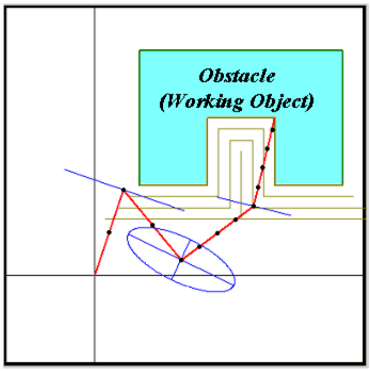

Fig. 15. Trajectory tracking simulation using AMSIP

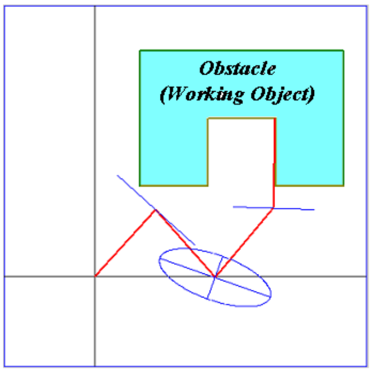

Fig. 16. Trajectory tracking simulation using AMSI

The trajectory is shown in Fig.13, that is the line connecting from A to F, and the working object implies obstacle at the same time. While tracking this desired-hand trajectory, the configuration of the 4-link redundant manipulator is controlled by preview control whose future reference shape $\tilde{\boldsymbol{q}}_d(t\ )$ is determined by 1-step GA of real-time optimization with the fitness functions, ${}^1S$ and ${}^1E$. The time transitions of ${}^1S$ and ${}^1E$ are depicted in Fig.14. From Eq.(24), we understand that the difference value from ${}^1E$ to ${}^1S$ means the negative value of potential U. In this figure, comparatively by large value of U is appeared from time 8.4[s] to 12[s], both are pointed by A and B. The shape of the manipulator controlled based on AMSI, ${}^1E$ at time 9[s] is shown in Fig.16, we can see that the fourth link approaches very near to the obstacle, which can not be thought as safe configuration. On the other hand, the figure whose simulation conditions are completely the same except the evaluation function of AMSIP, ${}^1S$, is shown in Fig.15. As you see, the distance from the fourth link to the obstacle is enlarged comparatively than the one depicted in Fig.16. Then, the effectiveness to use AMSIP instead of AMSI is shown by this result.

6. Conclusion

This paper proposed a preview control system with real-time optimization in the configuration shape for redundant manipulators, which execute simultaneous tasks of trajectory tracking of hand and avoidance control of intermediate links from obstacles including working objects. As the index of the optimization, we used AMSIP, and for the real-time optimization we used 1-step GA. The simulation show that trajectory tracking and avoidance control was successfully executed while keeping avoidance ability high and keeping its shape away from object.

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