Analysis for Configuration Prediction of Redundant Manipulators based on Avoidance Manipulability

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1. INTRODUCTION

Over the past two decades, redundant manipulators were used for various tasks, for example, welding, sealing and grinding. These kinds of tasks require that the manipulator plans 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).

Multi-Preview Control can refer to many shapes of manipulator optimized by avoidance manipulability to induce the current manipulator's shape [1], and avoid collisions with the obstacles. However, because Multi-Preview Control can not immediately compensate the error when manipulator is tracking trajectory or avoiding obstacle, there are still existing possible situations that manipulator could not avoid collision effectually. Moreover in actual working situation, oscillation or overshoot on the tracking trajectory of manipulator's hand may occur because manipulator has dynamics. The features of our system are shown in Fig.1 where the camera scene area symbolizes the restricted information of environment.

For these problems, the prediction of manipulators' future configuration has possibility of effectively compensating a tracking error. In other words, predictive control of redundant manipulator considering avoidance manipulability may realize fast and precision working. Therefore this paper explores an effectiveness of the prediction of future configuration of redundant manipulator based on Multi-Preview Control. In order to make the manipulator avoid obstacles and track working object successfully, we have defined the AMSIP [2] and we have proposed multi-preview control method which based on 1-step GA to calculate the future configuration of imaginary manipulator. About the redundant part $\boldsymbol{l}(t)$ which denotes in control formula of Multi-Preview Control, we have proposed a concept named predictive control which based on future time to make the configuration of imaginary manipulator and the predictive value of actual manipulator closer. However, the configuration of actual manipulator sometimes can not be predicted prosperously, and sometimes, the manipulability degree can not be predicted correctly. Therefore, in our paper, we have analyzed the correctness of configuration prediction based on different predictive interval time $\tilde{t}$ through simulations.

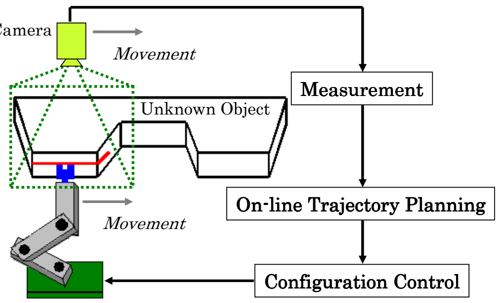

Fig.1 Processing system for unknown object

2. AVOIDANCE MANIPULABILITY SHAPE INDEX WITH POTENTIAL

We proposed Avoidance Manipulability Ellipsoid and Avoidance Manipulability Shape Index (AMSI) in [1], and Avoidance Manipulability Shape Index with Potential (AMSIP) in [2]. Avoidance Manipulability Ellipsoid is applied from Manipulability Ellipsoid proposed by Prof. Yoshikawa in [3]. We will elucidate them briefly in this section.

When the desired 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 velocity of the i-th link ${}^1\dot{\boldsymbol{r}}_{id}$ and the desired hand velocity $\dot{\boldsymbol{r}}_{nd}$ 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).

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

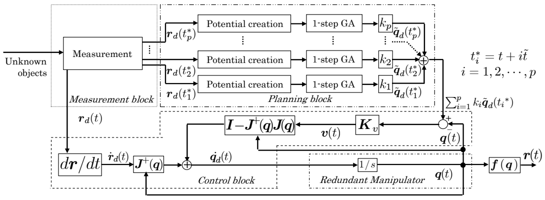

Fig.2 Multi-Preview Control system

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

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

$$\Delta^1\dot{\boldsymbol{r}}_{id} = {}^1\boldsymbol{M}_i\ {}^1\boldsymbol{l}. \quad (5)$$

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 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

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

If $rank({}^1\boldsymbol{M}_i) = m$, the ellipsoid represented by Eq.(6) is named as 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 [2].

3. MULTI-PREVIEW CONTROL

Multi-Preview Control controls current manipulator's shape by referring several imaginary manipulator's shape at several future times. As shown in Fig.2, Multi-Preview Control System 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 [1] 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

$$\dot{\boldsymbol{q}}_d = \boldsymbol{J}_n^+\dot{\boldsymbol{r}}_{nd} + (\boldsymbol{I}_n - \boldsymbol{J}_n^+\boldsymbol{J}_n)\boldsymbol{l}(t) \quad (7)$$

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

$$\boldsymbol{l}(t) = \boldsymbol{K}_v(\sum_{i=1}^{p}\tilde{\boldsymbol{q}}_d(t_i^*) - \boldsymbol{q}(t)) = \begin{bmatrix} \sum_{i=1}^{p}\tilde{q}_{1d}(t_i^*) - q_1(t) \\ \vdots \\ \sum_{i=1}^{p}\tilde{q}_{jd}(t_i^*) - q_j(t) \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (8)$$

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

4. PREDICTIVE CONTROL METHOD

We used predictive value of manipulator's configuration in preview control equation. In order to make the actual manipulator's posture be closer to the future configuration of imaginary manipulator, we changed the $\boldsymbol{l}(t)$ of the second part of Multi-preview's control equation as follow.

$$\boldsymbol{l}(t) = \boldsymbol{K_v}\sum_{i=1}^{p}k_i\Big(\tilde{\boldsymbol{q}}_d(t_i^*) - \widehat{\boldsymbol{q}}(t_i^*)\Big) \quad (9)$$

We thought that the $\widehat{\boldsymbol{q}}(t_i^*)$ is the future configuration's predictive value of manipulator. And in our research, we gave the following Eq.(10) because we define $t_i^* = t + i\cdot\tilde{t}$ in the previous section.

$$\boldsymbol{q}(t_i^*) = \boldsymbol{q}(t + i\cdot\tilde{t}), (i = 1, 2, \cdots, p) \quad (10)$$

After using Taylor expansion to calculate the predictive value $\widehat{\boldsymbol{q}}(t_i^*)$, then following equation Eq.(11), which is first approximation of Taylor expansion, could be derived,

$$\boldsymbol{q}(t+i{\cdot}\tilde{t}) \approx \boldsymbol{q}(t)+i{\cdot}\tilde{t}\dot{\boldsymbol{q}}(t) \tag{11}$$

To the differential part in Eq.(11), we did approximate calculation by using Eq.(12).

$$\dot{\boldsymbol{q}}(t) \approx \frac{\boldsymbol{q}(t)-\boldsymbol{q}(t-h)}{h} \tag{12}$$

Where h is a tiny value. Based on the above equations, we did first approximate calculation to the Taylor expansion for manipulations' future configuration value, and after replacing the differential term of Eq.(11) to Eq.(12), we can derive the predictive equation $\widehat{\boldsymbol{q}}(t_i^*)$ of actual manipulators' configuration as follow. In this paper, it is noticed that the predictive equation $\widehat{\boldsymbol{q}}(t_i^*)$ does not include the manipulators' dynamics.

$$\widehat{\boldsymbol{q}}(t_i^*) = (1+\frac{i{\cdot}\tilde{t}}{h})\boldsymbol{q}(t)-\frac{i{\cdot}\tilde{t}}{h}\boldsymbol{q}(t-h) \tag{13}$$

5. SIMULATION

In order to compare the Multi-Preview Control with predictive control, we use a 7-link manipulator for simulations, which is produced by Mitsubishi Heavy Industries named PA10. Hand tracking trajectory and given manipulator's shape are depicted in Fig.4, target hand trajectory is predefined. In addition, the kinematics of PA10 is implemented in the simulator. The solid line in Fig.3 expresses a target trajectory set to be followed. The simulation's screen shot is shown in Fig.3.

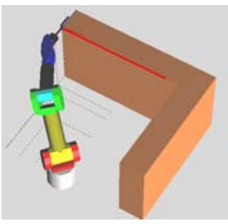

Fig.3 Outside appearance of simulation

The angle of actual manipulators' link 1 and the predictive angles $\hat{q}_1(t_1^*)$, $\hat{q}_1(t_2^*)$, $\hat{q}_1(t_3^*)$ of manipulators' link 1 are respectively indicated in Fig.5, Fig.9, Fig.11, Fig.13. The angle of actual manipulators' link 2 and the predictive angles $\hat{q}_2(t_1^*)$, $\hat{q}_2(t_2^*)$, $\hat{q}_2(t_3^*)$ of it are respectively indicated in Fig.6 when predictive interval time is 1.2[s]. Moreover, we use Runge Kutta method to calculate current angle of actual manipulator in simulation, the interval time h of Runge Kutta is 0.03 [s], and the value h also be used in Eq.(13). Obviously, the posture of manipulator could be closer to

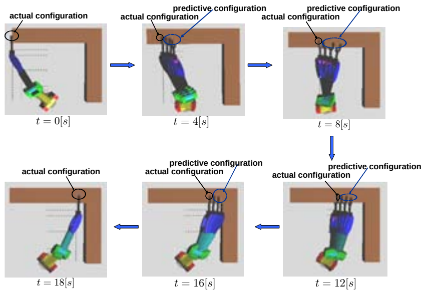

Fig.4 Screen shot of simulation

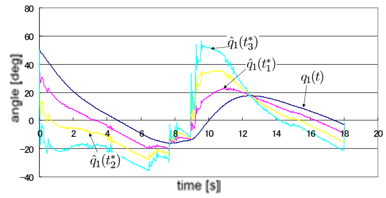

Fig.5 Actual and predictive angle of link 1 ($\tilde{t}$=1.2[s])

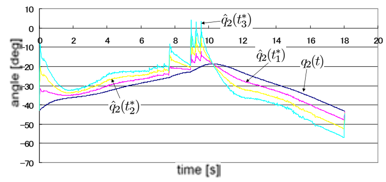

Fig.6 Actual and predictive angle of link 2 ($\tilde{t}$=1.2[s])

the future configuration expressed by predictive values. We thought that actual manipulators' posture could be forecasted effectively by using predictive control.

But in Fig.5 and Fig.6, we found that predictive values increased suddenly with high speed at t=9, and reason of the problem could be explained by Fig.7. In Fig.7 we could understand that values of angular velocity of link 1 and link 2 changed to two big values when t=9, because of the predictive Eq.(13) based on equation Eq.(12) which can also to be known as calculating angular velocity. So the problem of predictive values changing suddenly could be interpreted.

Finally, we investigated the manipulability degree $\omega(\boldsymbol{q}(t))$ of actual angles $\boldsymbol{q}(t)$ and the predictive angles $\hat{\boldsymbol{q}}(t_1^*)$, $\hat{\boldsymbol{q}}(t_2^*)$, $\hat{\boldsymbol{q}}(t_3^*)$ of manipulators based on Eq.(14), and showed the result by Fig.8, Fig.10, Fig.12, Fig.14 according to predictive interval time is 1.2[s], 0.6[s], 0.3[s], 0.15[s].

$$\omega(\boldsymbol{q}(t)) = \sqrt{\det \boldsymbol{J}_{\mathrm{n}}(\boldsymbol{q}(\mathrm{t}))\boldsymbol{J}_{\mathrm{n}}^{\mathrm{T}}(\boldsymbol{q}(\mathrm{t}))} \tag{14}$$

Observed Fig.8, Fig.10, Fig.12, Fig.14, we obviously can believe that predictive control can also predict the manipulability degree of manipulator. However, in Fig.8, when t=9 the value of manipulability degree get large suddenly, and manipulability degree become

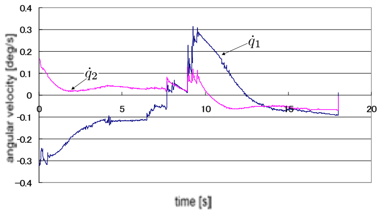

Fig.7 Angular velocity of link 1 and link 2 ($\tilde{t}$=1.2[s])

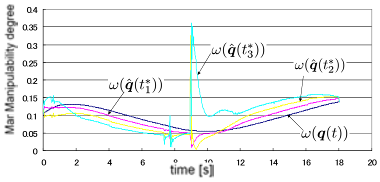

Fig.8 Manipulability degree ($\tilde{t}$=1.2[s])

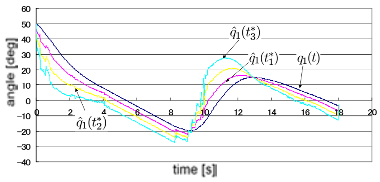

Fig.9 Actual and predictive angle of link 1 ($\tilde{t}$=0.6[s])

difficult to be predicted. About this problem, we also need to do further study.

6. CONCLUSION

In this paper, we explore the effectiveness of configuration prediction of redundant manipulator. Moreover, when the predictive interval time get smaller, configuration prediction get more correct simultaneously, and also, the manipulability prediction get more correct. In the future, we need to analyse and compare the AMSIP of multi-preview control and the AMSIP of predictive control and to do more investigations to continue to validate the effectiveness of predictive control.

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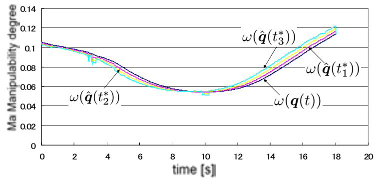

Fig.10 Manipulability degree ($\tilde{t}$=0.6[s])

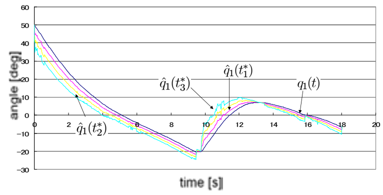

Fig.11 Actual and predictive angle of link 1 ($\tilde{t}$=0.3[s])

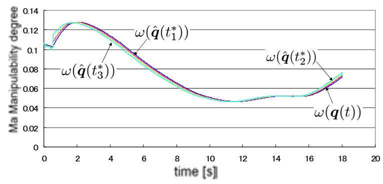

Fig.12 Manipulability degree ($\tilde{t}$=0.3[s])

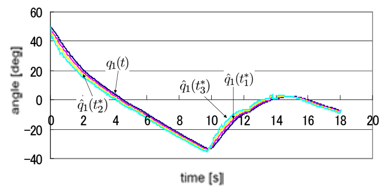

Fig.13 Actual and predictive angle of link 1 ($\tilde{t}$=0.15[s])

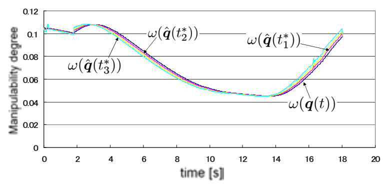

Fig.14 Manipulability degree ($\tilde{t}$=0.15[s])