Paper:

Performance Analysis for First-Order Configuration Prediction for Redundant Manipulators Based on Avoidance Manipulability

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This paper explores a performance of first-order configuration prediction for redundant manipulators based on avoidance manipulability in order to achieve an on-line control of trajectory tracking and obstacle avoidance for redundant manipulators. In the trajectory tracking process, manipulator is required to keep a configuration with maximal avoidance manipulability in real time. Predictive control in this paper uses manipulators' future configurations to control current configuration aiming at completing tasks of trajectory tracking and obstacle avoidance on-line and simultaneously with higher avoidance manipulability. We compare Multi-Preview Control with predictive control using redundant manipulator, and show the results through simulations. The effectiveness of predictive control using first-order configuration prediction is also validated in the case of not only straight target trajectory but also curve target trajectory. In addition, an influence of measurement noise on manipulator's joint angle is newly considered.

Keywords: configuration prediction, redundant manipulators, avoidance manipulability, noise environment

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 avoids its intermediate links, meaning all comprising links of robot except the top link with the end-effecter, from obstacles near the target object and also the target object itself (obstacle avoidance). In job shop type production of machine tool industry, a work with redundant manipulators needs a lot of preparatory plans, and therefore it is inefficient to complete the work. In order to reduce them and improve efficiency, although we consider a processing system as shown in **Fig. 1**, where the camera scene area symbolizes the restricted information of environment and it can repeat to recognize a part of unknown target object through camera and complete manipulator hand's trajectory tracking for a recognizing part of object shape, it is necessary for redundant manipulator to keep higher avoidance manipulability since it must avoid successively-emerging obstacles and complete trajectory tracking for the unknown target object.

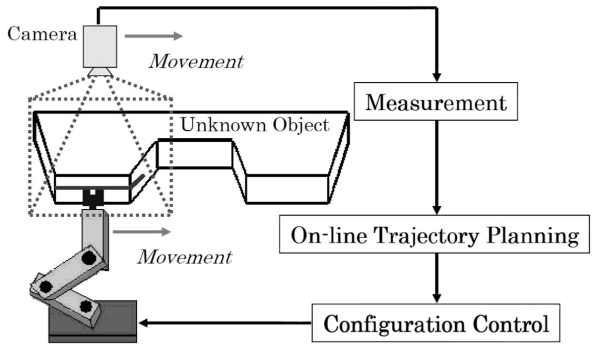

Fig. 1. Processing system for unknown object.

For this problem, Multi-Preview Control [1] can refer to many shapes of manipulator optimized by avoidance manipulability to induce the current manipulator's shape [2], and avoid collisions with the obstacles. In order to make the manipulator avoid obstacles and track working object successfully, we have defined Avoidance Manipulability Shape Index with Potential (AMSIP) [1] and proposed Multi-Preview Control method which is based on 1-step Genetic Algorithm (1-step GA) (please refer to [3] about its detail) to calculate the future configuration of imaginary manipulator. However, because Multi-Preview Control cannot immediately compensate the error when manipulator is tracking trajectory or avoiding obstacle, there are still the cases that manipulator cannot 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. For these problems, the prediction of actual manipulator's future configuration has possibility to compensate a tracking error effectively. In other words, predictive control of redundant manipulator considering avoidance manipulability may realize quick and accurate work. 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 makes the configuration of imaginary manipulator and the pre-

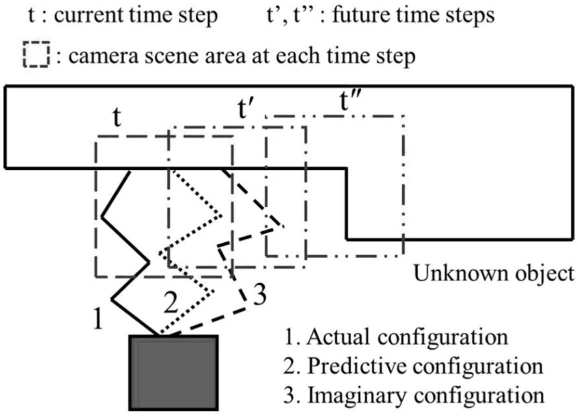

Fig. 2. Concept of predictive control.

dictive configuration of actual manipulator closer [4, 5]. It also means that the actual manipulator's configuration will be closer to the imaginary configuration to keep high avoidance manipulability by using predictive configuration as shown in **Fig. 2**. Although the effectiveness of the first-order configuration prediction in the predictive control was confirmed in the case of straight target trajectory [4, 5], the case of curve target trajectory aiming at realization of arbitrary target trajectory tracking with first-order configuration prediction has not been considered.

In this paper, we show the performance of first-order configuration prediction for redundant manipulator based on AMSIP in the case of straight target trajectory and curve target trajectory, and compare it to Multi-Preview Control [6]. Moreover, in order to check the performance of first-order configuration prediction of redundant manipulator under noise environment, an influence of measurement noise on manipulator's joint angle is newly considered. This paper is organized as follows. Sections 2 and 3 describe AMSIP and Multi-Preview Control respectively. Section 4 gives first-order configuration prediction in predictive control method as new method for configuration control of redundant manipulator. Section 5 explores the effectiveness of predictive control using first-order configuration prediction in the case of not only straight target trajectory but also curve target trajectory through numerical simulation. Moreover the influence of measurement noise on manipulator's joint angle is considered. Section 6 concludes this paper.

2. Avoidance Manipulability Shape Index with Potential

We proposed Avoidance Manipulability Ellipsoid, Avoidance Manipulability Shape Index (AMSI) in [7] and AMSIP. Avoidance Manipulability Ellipsoid is applied from Manipulability Ellipsoid proposed by Prof. Yoshikawa in [8]. 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

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

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 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 $\boldsymbol{q}(t)$ closer to optimal shape referring to the future optimal shapes of imaginary manipulators calculated by 1-step GA. 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).

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

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

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

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

According to Eqs. (2)–(4), $\Delta^1 \dot{\boldsymbol{r}}_{id}$ is rewritten as

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

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

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

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 AMSI. Then we proposed AMSIP which considers AMSI and potential meaning the distance between the manipulator and the target object. And we also verified the superiority of AMSIP through the simulation in [1].

3. Multi-Preview Control

Multi-Preview Control controls current manipulators' shapes by referring several imaginary manipulators' shapes at several future times. As shown in **Fig. 3**, Multi-Preview Control system consists of on-line measurement block, path planning block, 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. The 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. 3**. Firstly, potential space based on the detected shape of the target object is created around it at the path planning block. Then

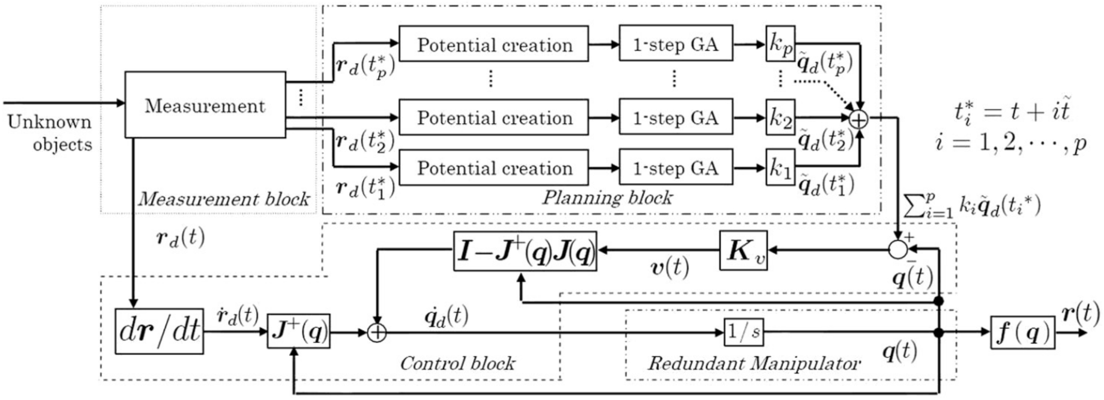

Fig. 3. Multi-Preview Control system.

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^*. The control block outputs desired joint angular velocity $\dot{\boldsymbol{q}}_d(t)$ that makes actual manipulator's shape $\boldsymbol{q}(t)$ at current time closer to the optimal shape in the future by referring to $\sum_{i=1}^{p} \tilde{\boldsymbol{q}}_d(t_i^*)$, where the optimal shape $\tilde{\boldsymbol{q}}_d(t_i^*)$ means imaginary manipulator's shape and is decided by using 1-Step GA [3]. 1-step GA is one of the genetic algorithms (GAs). Although GA operation maybe require long convergence time, this paper considers to solve real-time optimization problem with multi-peak and time-varying by means of 1-step GA, and it can calculate a semi-optimal solution within a finite time of each control period.

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

$$\begin{aligned}\dot{\boldsymbol{q}}_d &= \boldsymbol{J}_n^+ \dot{\boldsymbol{r}}_{nd} + (\boldsymbol{I}_n - \boldsymbol{J}_n^+ \boldsymbol{J}_n)\boldsymbol{l}(t)\\ &= \boldsymbol{J}_n^+ \dot{\boldsymbol{r}}_{nd} + (\boldsymbol{I}_n - \boldsymbol{J}_n^+ \boldsymbol{J}_n)\boldsymbol{K}_v \left(\sum_{i=1}^{p} \tilde{\boldsymbol{q}}_d(t_i^*) - \boldsymbol{q}(t)\right), \quad (7)\end{aligned}$$

where

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

When redundant degree of freedom j remains, the redundancy is used for the joints from 1 to j.

4. First-Order Configuration Prediction in Predictive Control

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 follows.

$$\boldsymbol{l}(t) = \boldsymbol{K}_v \sum_{i=1}^{p} k_i \left(\tilde{\boldsymbol{q}}_d(t_i^*) - \widehat{\boldsymbol{q}}(t_i^*)\right) \quad . \; . \; . \; . \; . \; . \quad (9)$$

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

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

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

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

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

$$\dot{\boldsymbol{q}}(t) \approx \frac{\boldsymbol{q}(t) - \boldsymbol{q}(t-h)}{h} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (12)$$

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

$$\widehat{\boldsymbol{q}}(t_i^*) = \left(1 + \frac{i{\cdot}\tilde{t}}{h}\right)\boldsymbol{q}(t) - \frac{i{\cdot}\tilde{t}}{h}\boldsymbol{q}(t-h) \quad . \; . \; . \; . \quad (13)$$

5. Simulation

5.1. Case of Straight Trajectory

In order to compare the Multi-Preview Control with predictive control, we use a 7-link manipulator for simu-

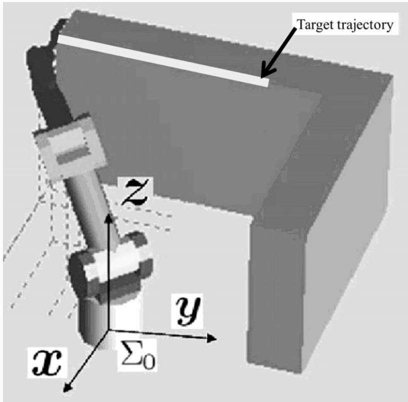

Fig. 4. Outside appearance of simulation.

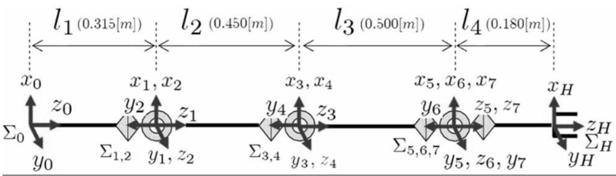

Fig. 5. Coordinate system of PA10.

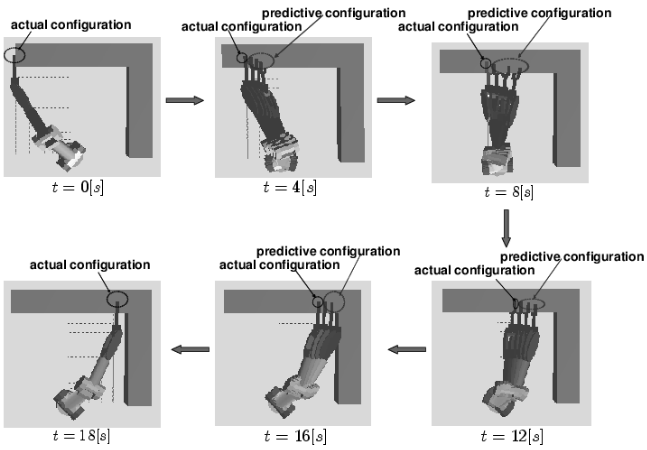

Fig. 6. Screen shot of simulation.

lations, 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 shown in **Fig. 5** is implemented in the simulator. The solid line in **Fig. 4** expresses a target trajectory set to be followed. The target hand trajectory is defined by five variables, that is, three for positional variables and two for posture variables. Therefore the redundant degree of freedom in this simulation is two and this paper gives the manipulator's redundancy to link 1 and link 2. The simulation's screen shot is shown in **Fig. 6**.

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 **Figs. 7–10**. The angle of actual manipulators' link 2 and the predictive angles $\hat{q}_2(t_1^*)$,

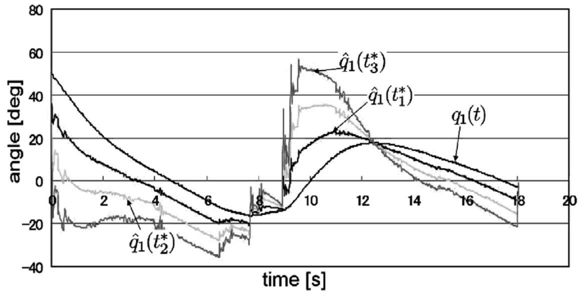

Fig. 7. Actual and predictive angle of link 1 ($\tilde{t} = 1.2$ s).

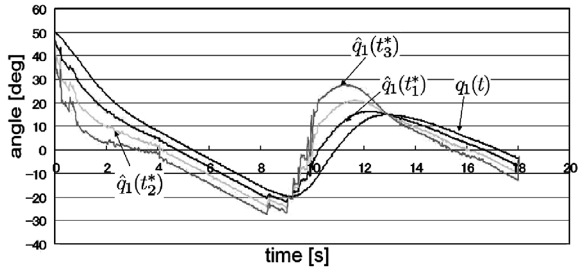

Fig. 8. Actual and predictive angle of link 1 ($\tilde{t} = 0.6$ s).

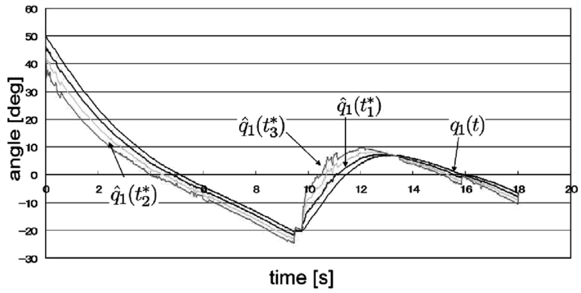

Fig. 9. Actual and predictive angle of link 1 ($\tilde{t} = 0.3$ s).

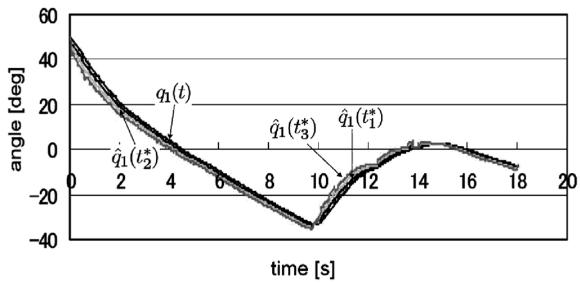

Fig. 10. Actual and predictive angle of link 1 ($\tilde{t} = 0.15$ s).

$\hat{q}_2(t_2^*)$, $\hat{q}_2(t_3^*)$ are respectively indicated in **Fig. 11** 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 the future configuration expressed by predictive values. We thought that the actual manipulators' posture could be forecasted effectively by using predictive control. But in **Figs. 7** and **11**, we found that the predictive values increased suddenly with high speed at $t = 9$, and the reason of the problem could be explained by **Fig. 12**. In

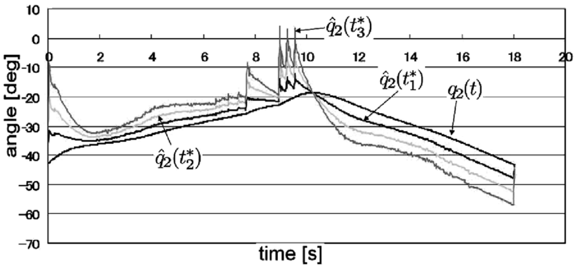

Fig. 11. Actual and predictive angle of link 2 ($\tilde{t} = 1.2$ s).

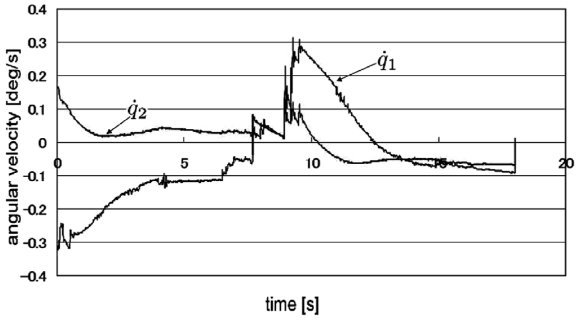

Fig. 12. Angular velocity of link 1 and link 2 ($\tilde{t} = 1.2$ s).

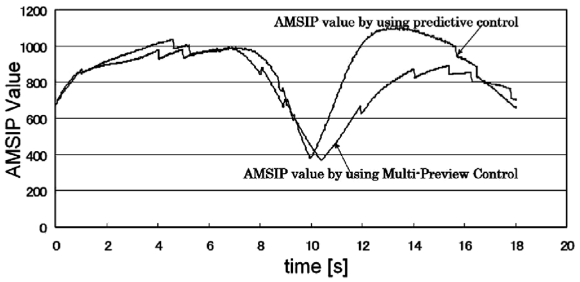

Fig. 13. AMSIP value.

Fig. 12 we could understand that the values of angular velocity of link 1 and link 2 changed to two big values when $t = 9$, because of the prediction Eq. (13) based on Eq. (12) which can also to be known as calculating angular velocity. So the problem of predictive values changing suddenly could be interpreted. Furthermore, we got the AMSIP average of actual manipulator's posture by using Multi-Preview Control and predictive control by fifteen times respectively, and indicated the average values by time t in **Fig. 13**. Compared with Multi-Preview Control, we believe that AMSIP value can maintain a higher value by using predictive control. Through simulations, we thought predictive control has a possibility to be superior to Multi-Preview Control. 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 results by **Figs. 14–17** according as predictive interval times are 1.2 s, 0.6 s, 0.3 s, and 0.15 s respectively.

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

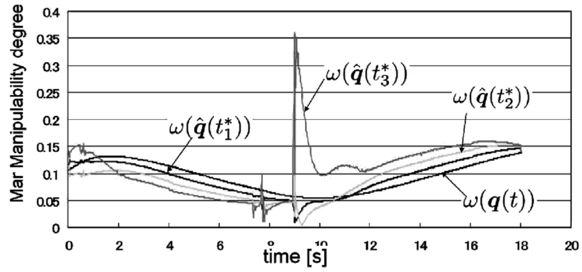

Fig. 14. Manipulability degree ($\tilde{t} = 1.2$ s).

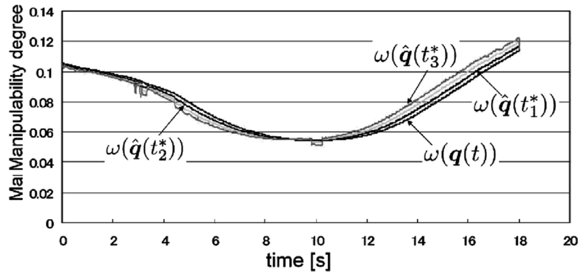

Fig. 15. Manipulability degree ($\tilde{t} = 0.6$ s).

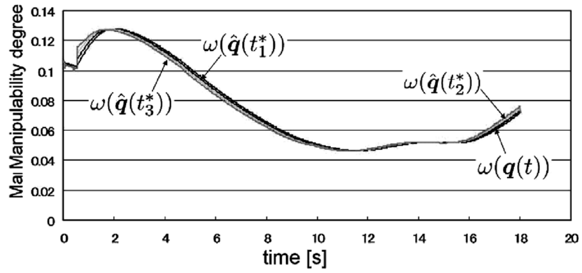

Fig. 16. Manipulability degree ($\tilde{t} = 0.3$ s).

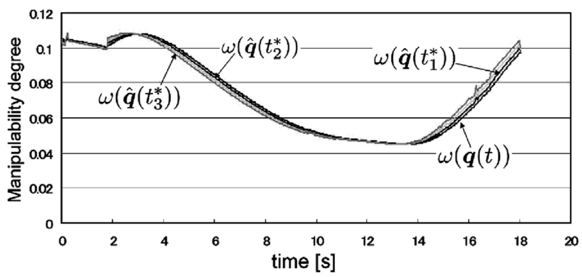

Fig. 17. Manipulability degree ($\tilde{t} = 0.15$ s).

Observed **Figs. 14–17**, we obviously can believe that predictive control can also predict the manipulability degree of manipulator. However, in **Fig. 14**, when $t = 9$ the value of manipulability degree gets large suddenly, and manipulability degree becomes difficult to be predicted. About this problem, we also need to do further study.

5.2. Case of Curve Trajectory

We want to know whether the manipulator will be predicted effectively or not when the target trajectory is curve trajectory, The solid line in **Fig. 18** expresses a target curve trajectory set to be followed. The angle of ac-

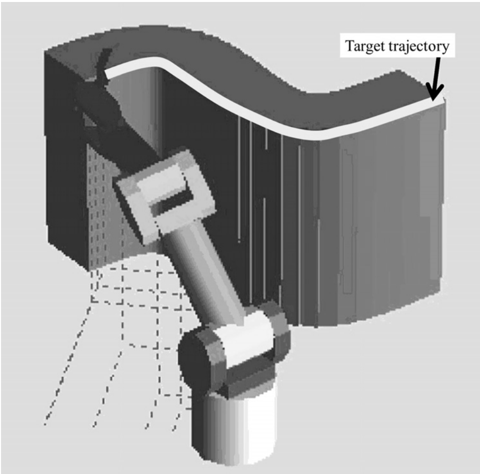

Fig. 18. Outside appearance of simulation.

tual 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 **Figs. 19** and **20** when predictive interval time are 0.3 s and 0.15 s. The angle of actual manipulators' link 2 and the predictive angles $\hat{q}_2(t_1^*)$, $\hat{q}_2(t_2^*)$, $\hat{q}_2(t_3^*)$ are respectively indicated in **Figs. 21** and **22** when predictive interval time are 0.3 s and 0.15 s. We believe that the posture of manipulator could be closer to the future configuration expressed by predictive values. We thought that the actual manipulators' posture could be also forecasted effectively by using predictive control in the curve trajectory. However, because the actual manipulators' angular velocity of link 1 and link 2 are not stable, so sometimes the predictive lines are not smooth enough. We also show the manipulability degree by **Figs. 23** and **24** when predictive interval time are 0.3 s and 0.15 s. We obviously can believe that predictive control can also predict the manipulability degree of manipulator. However, we think the prediction result is better when predictive interval time is smaller. Because the predictive lines in **Fig. 23** is not smooth enough, so we think the manipulability degree is hard to predict when predictive interval time is 0.3 s. Finally, we want to check the effectiveness of predictive control for curve trajectory. For simplicity, in this paper we got the AMSI value average of actual manipulator's posture by using Multi-Preview Control and predictive control by five times respectively when the target trajectory is curve trajectory, and indicated the average values by time t in **Fig. 25**. Compared with Multi-Preview Control, we believe that AMSI value can also maintain a higher value by using predictive control. Through simulations, it can find that predictive control has a possibility to be superior to Multi-Preview Control even if the target trajectory is curve.

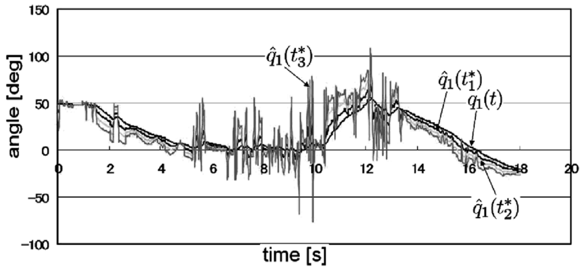

Fig. 19. Actual and predictive angle of link 1 ($\tilde{t} = 0.3$ s).

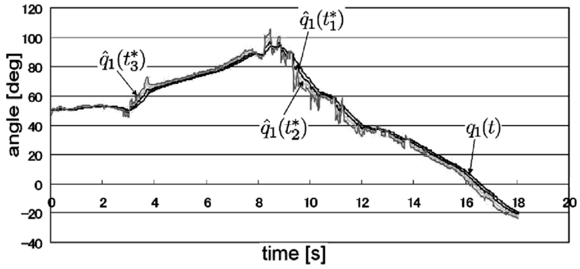

Fig. 20. Actual and predictive angle of link 1 ($\tilde{t} = 0.15$ s).

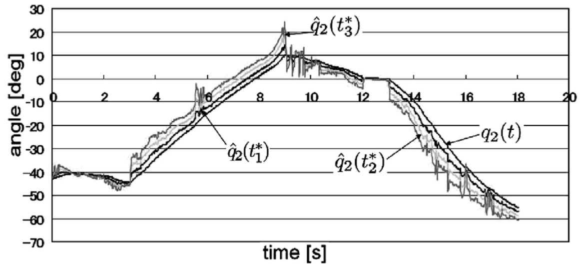

Fig. 21. Actual and predictive angle of link 2 ($\tilde{t} = 0.3$ s).

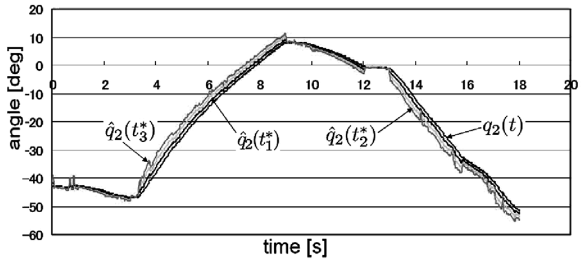

Fig. 22. Actual and predictive angle of link 2 ($\tilde{t} = 0.15$ s).

5.3. Influence of Measurement Noise on Joint Angles

In this subsection, we newly consider the influence of measurement noise on the joint angles in order to check the performance of first-order configuration prediction of redundant manipulator. This paper assumes that the measurement noise is white Gaussian noise with variance 0.03^2 and it is added to each joint angle calculated by Runge Kutta method in the simulation. The predictive interval time is set to be $\tilde{t} = 0.3$ s and the joint angle of link 1 in the case of straight target trajectory is explored for the interval times $h = 0.015, 0.03$ and 0.06 s of Runge Kutta method. Among **Figs. 26–28**, it is found that the influence of measurement noise becomes larger as the interval time h of Runge Kutta method gets shorter. Therefore the result says that the accuracy of configuration prediction is affected by the interval time h of Runge Kutta method under actual environment with measurement noise.

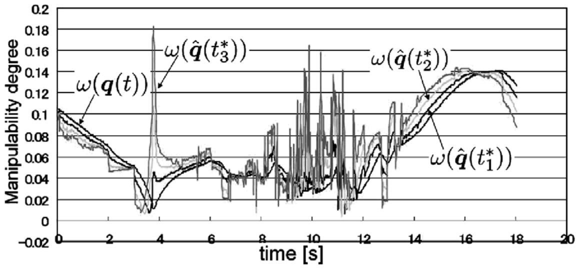

Fig. 23. Manipulability degree ($\tilde{t} = 0.3$ s).

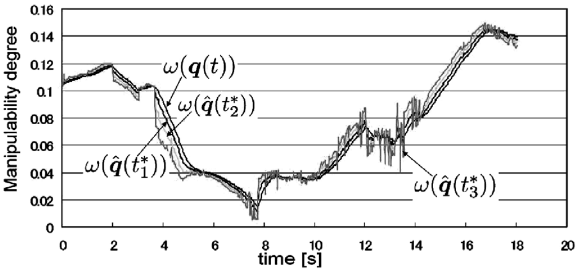

Fig. 24. Manipulability degree ($\tilde{t} = 0.15$ s).

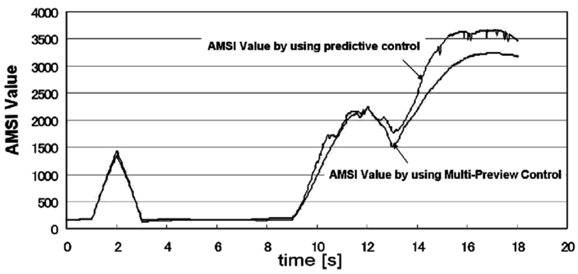

Fig. 25. AMSI value.

6. Conclusion

In this paper, we explored the performance of first-order configuration prediction for redundant manipulator in the case of straight target trajectory and curve target trajectory. When the predictive interval time gets smaller, the configuration and the manipulability degree predictions get more accurate simultaneously. Moreover the influence of measurement noise on joint angles of redundant manipulator was considered in order to check the performance of configuration prediction. As future works, we need to analyze and compare the AMSIP of Multi-Preview Control and predictive control in the case that the target trajectory is curve, and to do more investigations to continue to validate the effectiveness of predictive control. As shown in **Fig. 12**, the reason why the angular velocities change suddenly and largely will be also considered. In order to enhance the performance and implement the proposed system, force information of manipulator's hand should be considered.

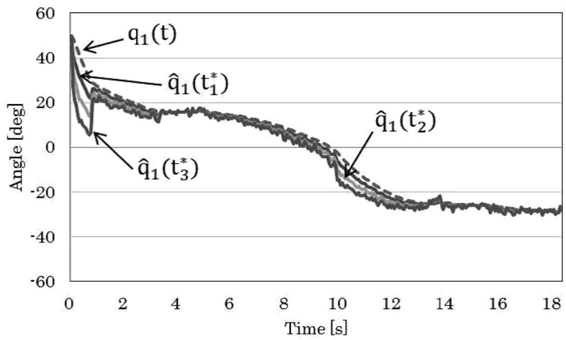

Fig. 26. Actual and predictive angle of link 1 with noise ($h = 0.06$ s).

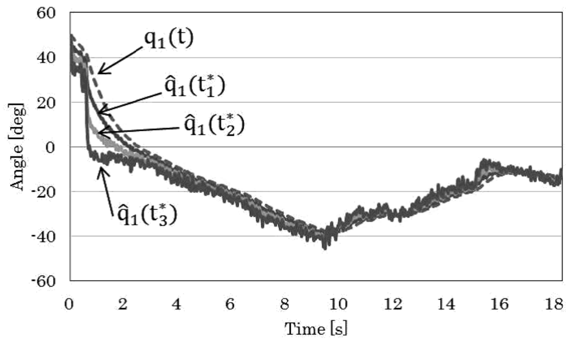

Fig. 27. Actual and predictive angle of link 1 with noise ($h = 0.03$ s).

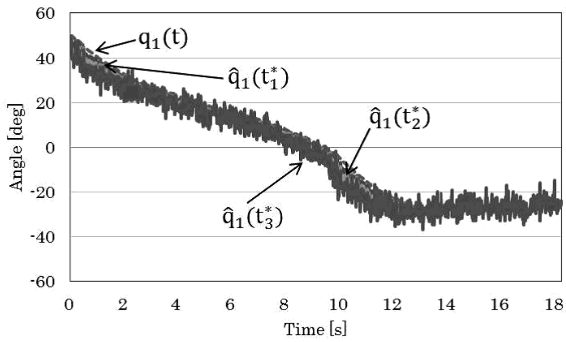

Fig. 28. Actual and predictive angle of link 1 with noise ($h = 0.015$ s).

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