Comparison between First and Second Order Prediction for On-line Configuration Control of Redundant Manipulator in Noise Environment

Akira Yanou[1], Mamoru Minami[1] and Takayuki Matsuno[1]

***Abstract*— This paper explores performance comparison between first and second order prediction for on-line configuration control of redundant manipulator including measurement noise on joint angles. When the trajectory tracking control is executed, the configuration of manipulator is required to be maintained at maximal avoidance manipulability in real time. In this paper, the predictions of manipulators' configurations are used for controlling the current manipulator's configuration so as to complete the tasks, which are trajectory tracking and obstacle avoidance on-line and simultaneously. During controlling process, the control input that achieves higher avoidance manipulability based on Avoidance Manipulability Shape Index with Potential (AMSIP) is calculated through a genetic algorithm. We compare the performance of first order prediction with second one in noise environment and show the results through simulation.**

I. INTRODUCTION

Redundant manipulators have been widely applied in industry. For example, there are the tasks such as welding, sealing and grinding. These kinds of tasks require the manipulator system to plan its hand onto a desired trajectory and avoid its intermediate links from obstacle near the target object and the target object itself. In this situation, the intermediate links mean all comprising links of robot except the top link with the end-effector. The above requirements are named as trajectory tracking and obstacle avoidance respectively. In job shop type production of machine tool industry, a work with redundant manipulators needs a lot of preparatory plans. In order to reduce the preparatory plans, we consider a processing system as shown in Fig. 1. In Fig. 1 the camera scene area symbolizes the restricted information of environment. Although it can repeat recognition of a part of unknown target object through the camera and complete the manipulator's hand trajectory tracking for a recognizing part of object shape, it requires the redundant manipulator to maintain higher avoidance manipulability because it must avoid obstacles and complete trajectory tracking for the unknown target object.

For this problem, Multi-Preview Control [1] can refer to some shapes of manipulator optimized by avoidance manipulability aiming at guidance of the current manipulator's shape and avoid collisions with the obstacles. In order to make the manipulator avoid obstacles and track working object successfully, Avoidance Manipulability Shape Index with Potential (AMSIP) [2] has been defined and Multi-Preview Control method, which is based on 1-step Genetic

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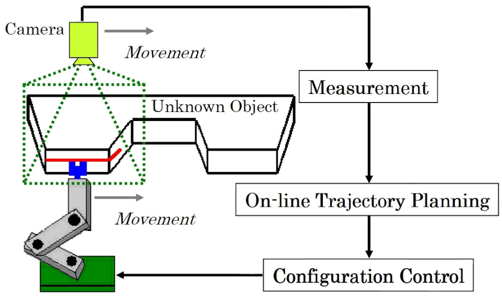

Fig. 1. Processing system for unknown object

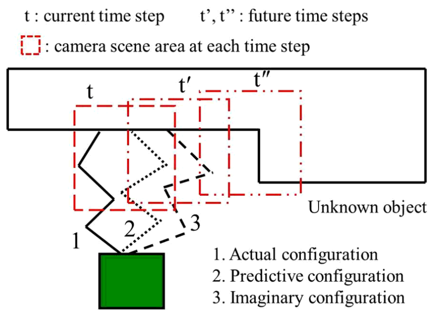

Fig. 2. Concept of predictive control

Algorithm (1-step GA) [3], has been proposed in order to calculate the future configuration of imaginary manipulator. However because Multi-Preview Control has not been able to compensate the error immediately during the controlling tasks, which are trajectory tracking and obstacle avoidance, there is a case that the manipulator system cannot avoid collision effectively. Moreover oscillation or overshoot in the trajectory tracking of manipulator's hand may occur in actual working situation 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, the predictive control of redundant manipulator considering avoidance manipulability may realize quick and accurate work. About the redundant part $\boldsymbol{l}(t)$ which is denoted in control equation of Multi-Preview Control, the concept named as predictive control, which makes the configuration of imaginary manipulator and the predictive configuration of actual manipulator closer, has been proposed[4], [5]. As shown in Fig. 2, the concept means that the actual manipulator's configuration will become closer to the imaginary configuration with maintaining high avoidance manipulability through predictive configuration. Although the effectiveness of predictive control is confirmed in the case of straight or curve target trajectory[6], [7], performance comparison of configuration prediction by first order prediction and second one is not explored in the case of including measurement noise on joint angles. Therefore this paper confirms an influence of measurement noise on joint angles in the case of first order prediction and second one through simulation.

This paper is organized as follows. Section 2 and section 3 describe AMSIP and Multi-Preview Control respectively. In section 4 gives predictive control method as new method for configuration control of redundant manipulator. Section 5 compares first order prediction with second one about the configuration control and shows AMSIP. Moreover the influence of measurement noise on joint angles is confirmed. Section 6 concludes this paper.

II. AVOIDANCE MANIPULABILITY SHAPE INDEX WITH POTENTIAL

Avoidance Manipulability Ellipsoid and Avoidance Manipulability Shape Index (AMSI) in [8], and AMSIP have been proposed. Avoidance Manipulability Ellipsoid is applied from Manipulability Ellipsoid proposed by Prof. Yoshikawa in [9]. In this section, their concepts are elucidated briefly. If desired hand velocity $\dot{\boldsymbol{r}}_{nd}$ is given, the joint angular velocity vector $\dot{\boldsymbol{q}}_n$ 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 pseudo-inverse of Jacobean Matrix $\boldsymbol{J}_n$ and $\boldsymbol{I}_n$ is $n \times n$ unit matrix. In addition, ${}^1\boldsymbol{l}$ is an arbitrary vector. Trajectory tracking of the hand and collision avoidance can achieved through the vector ${}^1\boldsymbol{l}$ simultaneously. The control variable ${}^1\boldsymbol{l}$ is determined so as to make the actual manipulator's shape $\boldsymbol{q}(t)$ at current time, which means joint angle vector, closer to optimal shape by referring to the future optimal shapes of imaginary manipulators calculated by 1-step GA. The relation between the desired velocity of the i-th link ${}^1\dot{\boldsymbol{r}}_{id}$ and the desired hand velocity $\dot{\boldsymbol{r}}_{nd}$ is given in Eq.(2).

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

We define two variables given in Eq.(3) and Eq.(4).

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

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

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

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

In Eq.(5), $\Delta^1 \dot{\boldsymbol{r}}_{id}$ is called as first avoidance velocity and ${}^1\boldsymbol{M}_i$ is $m \times n$ matrix called as first avoidance matrix. Next, Avoidance Manipulability Ellipsoid is represented. Providing that ${}^1\boldsymbol{l}$ is restricted as $\|{}^1\boldsymbol{l}\| \leq 1$, then the extent, where $\Delta^1 \dot{\boldsymbol{r}}_{id}$ can move, is denoted as

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

If $rank({}^1\boldsymbol{M}_i) = m$, the ellipsoid represented by Eq.(6) is named as first complete avoidance manipulability ellipsoid. If $rank({}^1\boldsymbol{M}_i) = p < m$, the ellipsoid is named as first partial avoidance manipulability ellipsoid. The volume of each Avoidance Manipulability Ellipsoid indicates mobility of each link (shape-changeability). That is, The larger total volume means the higher whole avoidance manipulability. We evaluated total volume as AMSI and AMSIP, which includes AMSI and a distance between manipulator and target object, was proposed. Moreover the superiority of AMSIP through simulation was verified[2].

III. MULTI-PREVIEW CONTROL

Multi-Preview Control[1] can control the current manipulator's shape by referring the imaginary manipulator's 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. Assuming that the current time is represented by t, each future times is 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 trajectory of target object at time t_i^*, which is reasonably assumed to be able to detect the future information only in the detected camera image of Fig. 1. Potential space calculated from the detected shape of target object is firstly created around it at the path planning block. Next the path planning block calculates the optimal shape $\tilde{\boldsymbol{q}}_d(t_i^*)$ based on the maximum ${}^1S$ presented in [1] at the future time t_i^*. The control block generates the desired joint angular velocity $\dot{\boldsymbol{q}}_d(t)$, which makes actual manipulator's shape $\boldsymbol{q}(t)$ closer to the optimal shape by referring to $\sum_{i=1}^{p} \tilde{\boldsymbol{q}}_d(t_i^*)$. The optimal shape $\tilde{\boldsymbol{q}}_d(t_i^*)$ means the imaginary manipulator's shape and is decided by using 1-Step GA [3].

The control equation of this system is named as Preview Control equation and expressed as follows

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

where

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

where it is assumed that the redundant degrees j remains and its redundancy is used for the joints from 1 to j. Fig.

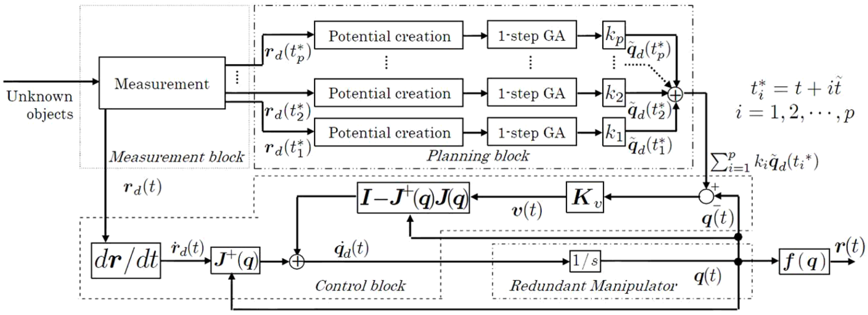

Fig. 3. Multi-Preview Control system

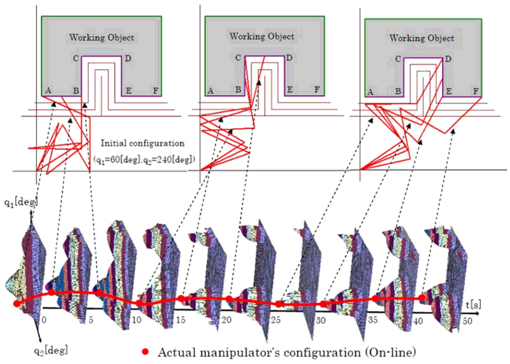

Fig. 4. Actual manipulator's configurations in whole tracking process based on Multi-Preview Control

4 gives an example of the manipulator's shape using Multi-Preview Control system and the transition of AMSIP. From Fig. 4, it is found that the manipulator can always maintain higher AMSIP value by using Multi-Preview Control, and the AMSIP value in multi peak distributions moves from one higher peak to another higher peak as time goes. This verifies the validity of Multi-Preview Control in 2-dimension by 4-link planar manipulator.

IV. PREDICTIVE CONTROL METHOD

In this section the predictive value of actual manipulator's configuration in preview control equation is used. In order to make the actual manipulator's configuration be closer to the imaginary manipulator's one, $\boldsymbol{l}(t)$ of the second part of preview control equation is modified as follows (the other part is the same as Multi-Preview Control).

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

$\widehat{\boldsymbol{q}}(t_i^*)$ is defined as predictive value of actual manipulator's configuration. This research gives the following Eq.(10), because of the definition $t_i^* = t + i{\cdot}\tilde{t} \quad (i = 1, 2, \cdots, p)$ in the previous section.

$$\boldsymbol{q}(t_i^*) = \boldsymbol{q}(t + i{\cdot}\tilde{t}) \tag{10}$$

By using Taylor series expansion [10] for calculation of the predictive value $\widehat{\boldsymbol{q}}(t_i^*)$, the following equation Eq.(11), which is second approximation of Taylor series expansion, can be obtained.

$$\boldsymbol{q}(t + i{\cdot}\tilde{t}) \approx \boldsymbol{q}(t) + i{\cdot}\tilde{t}\dot{\boldsymbol{q}}(t) + \frac{1}{2}(i{\cdot}\tilde{t})^2\ddot{\boldsymbol{q}}(t) \tag{11}$$

The approximate calculation through Eq.(12) and Eq.(13) is done for the differential part in Eq.(11).

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

$$\ddot{\boldsymbol{q}}(t) \approx \frac{\dot{\boldsymbol{q}}(t) - \dot{\boldsymbol{q}}(t-h)}{h} \tag{13}$$

h is a tiny value. Then the first order prediction $\widehat{\boldsymbol{q}}(t_i^*)$ of actual manipulator's configuration is derived by using these equations, replacing the differential term of Eq.(11) to Eq.(12) and $\ddot{\boldsymbol{q}}(t) = 0$.

$$\widehat{\boldsymbol{q}}(t_i^*) = (1 + \frac{i{\cdot}\tilde{t}}{h})\boldsymbol{q}(t) - \frac{i{\cdot}\tilde{t}}{h}\boldsymbol{q}(t-h) \tag{14}$$

In the same way, the second order prediction of actual manipulator's configuration is derived by replacing the differential term of Eq.(11) to Eq.(12) and Eq.(13).

$$\begin{aligned}\widehat{\boldsymbol{q}}(t_i^*) \;=\; & \Big(1 + \frac{i{\cdot}\tilde{t}}{h} + \frac{1}{2}(\frac{i{\cdot}\tilde{t}}{h})^2\Big)\boldsymbol{q}(t) - \Big(\frac{i{\cdot}\tilde{t}}{h} + (\frac{i{\cdot}\tilde{t}}{h})^2\Big) \\ & {\cdot}\boldsymbol{q}(t-h) + \frac{1}{2}(\frac{i{\cdot}\tilde{t}}{h})^2\boldsymbol{q}(t-2h)\end{aligned} \tag{15}$$

It is noticed that the predictive equation $\widehat{\boldsymbol{q}}(t_i^*)$ does not include the manipulator's dynamics in this paper.

V. SIMULATION

In order to compare first order prediction with second order one through simulations, a 7-link manipulator is used, which is produced by Mitsubishi Heavy Industries (PA10) and its structure is shown in Fig. 5.

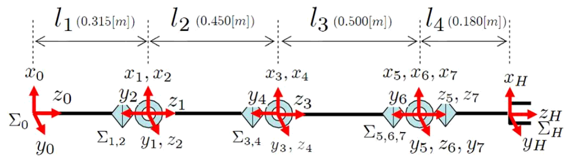

Fig. 5. Coordinate System of PA10

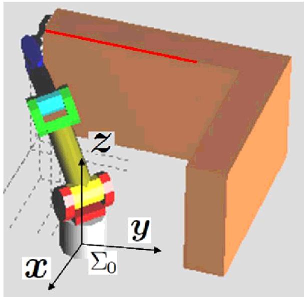

Fig. 6. Outside appearance of simulation

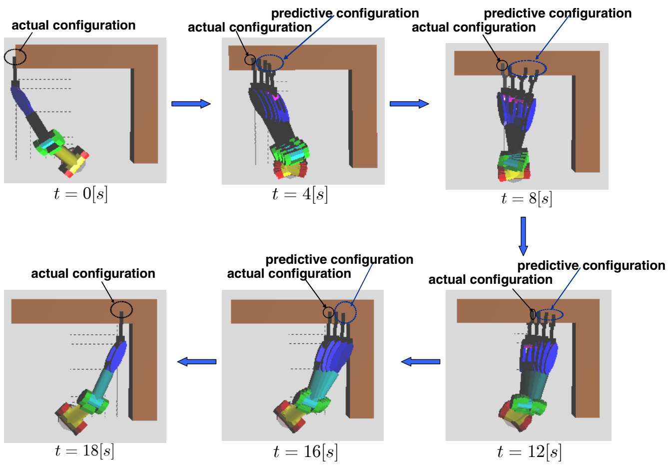

Fig. 7. Screen shot of simulation

A. Case of straight trajectory[6]

The tracking trajectory of manipulator's hand and the configuration are depicted in Fig. 6. The target trajectory (solid line in Fig. 6) is predefined and the kinematics of PA10 is implemented in the simulator. The simulation's screen shot is shown in Fig. 7. The link 1 angles of the actual manipulator and the predictive ones using first order prediction are indicated from Fig. 8 to Fig. 10. From Fig. 11 to Fig. 13, the results of link 1 angles of the actual manipulator and the predictive ones using second order prediction are given. The Runge-Kutta method with the interval time $h = 0.03$ [s] is used to calculate the current angle of the actual manipulator in simulation. The value h is used in Eq.(14) and Eq.(15). It finds that the configuration of actual manipulator becomes closer to the future configuration by predictive values from these figures. Therefore we believe that the actual manipulator's configuration can be predicted effectively by using predictive control whatever first order prediction or second order one is used. Furthermore, the average values of AMSIP with actual manipulator's configuration in the case of first order prediction and second order prediction are shown from Fig. 14 to Fig. 16. The difference of each figure is the predictive interval time $\tilde{t}$. With comparison between first and second order prediction, the AMSIP value can maintain a higher value by using second order prediction.

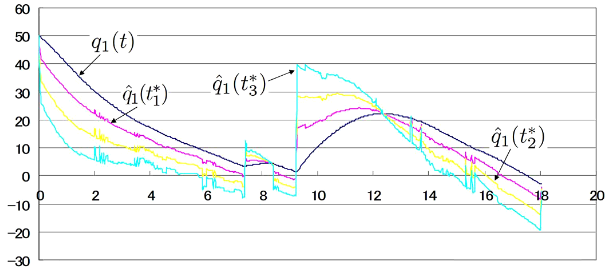

Fig. 8. Actual and predictive angle of link 1 by first order ($\tilde{t}$=0.9[s])

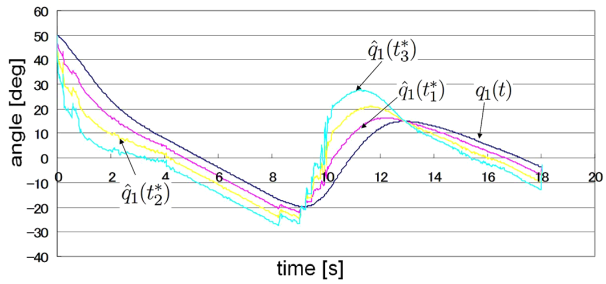

Fig. 9. Actual and predictive angle of link 1 by first order ($\tilde{t}$=0.6[s])

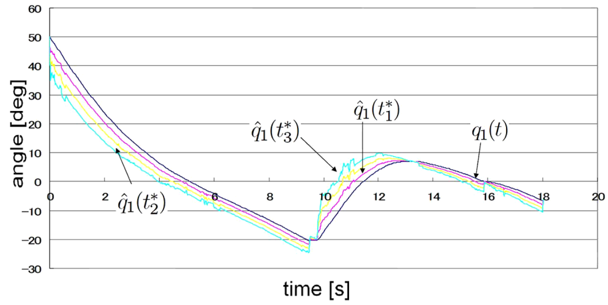

Fig. 10. Actual and predictive angle of link 1 by first order ($\tilde{t}$=0.3[s])

B. Influence of measurement noise on joint angles for first order prediction and second order one

This subsection confirms the influence of measurement noise on the joint angles in order to compare the performance of first and second 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 $\tilde{t}$=0.3[s] and the joint angle of link 1 in the case of straight target trajectory is explored for the interval times $h = 0.015, 0.03, 0.06$[s] of Runge-Kutta method. Among Fig.17 $\sim$ Fig.19 and Fig.20 $\sim$ Fig.22, 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. Moreover, it finds that each performance of first order and second order configuration prediction of redundant manipulator is almost same. Through these simulations, it is thought that second order prediction has a possibility to be superior to first order prediction.

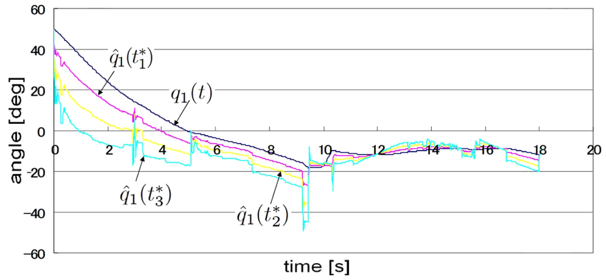

Fig. 11. Actual and predictive angle of link 1 by second order ($\tilde{t}$=0.9[s])

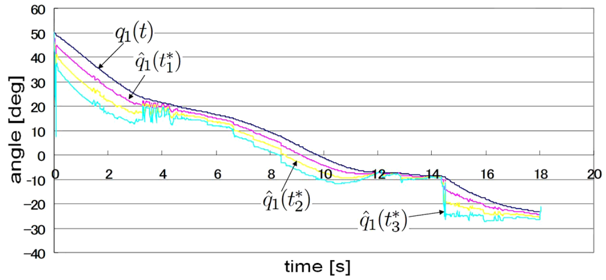

Fig. 12. Actual and predictive angle of link 1 by second order ($\tilde{t}$=0.6[s])

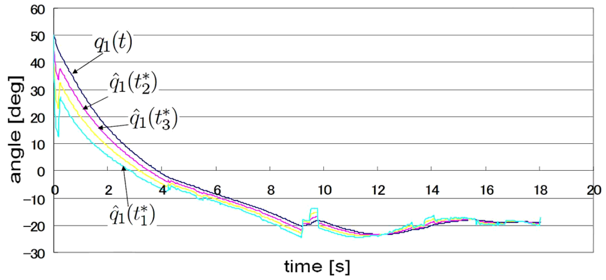

Fig. 13. Actual and predictive angle of link 1 by second order ($\tilde{t}$=0.3[s])

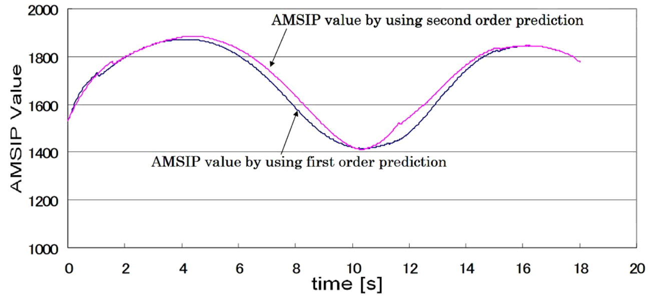

Fig. 14. AMSIP value by first order and second order ($\tilde{t}$=0.9[s])

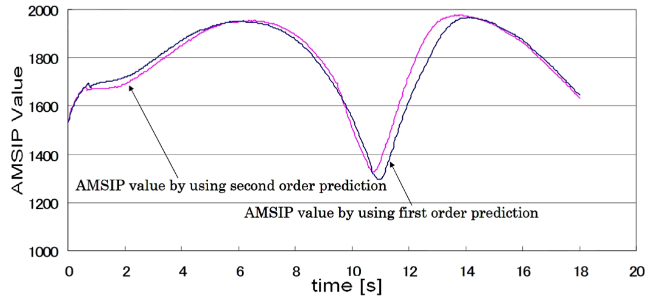

Fig. 15. AMSIP value by first order and second order ($\tilde{t}$=0.6[s])

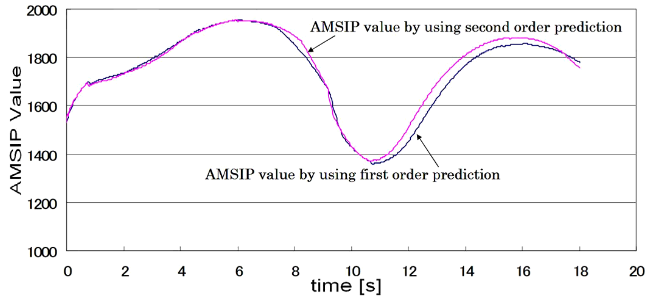

Fig. 16. AMSIP value by first order and second order ($\tilde{t}$=0.3[s])

VI. CONCLUSION

In this paper, we explored the performance of configuration prediction of redundant manipulator through AMSIP and the influence of measurement noise on joint angles of redundant manipulator was considered to check the performance of configuration prediction. As future works, we need to 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 in noise environment.

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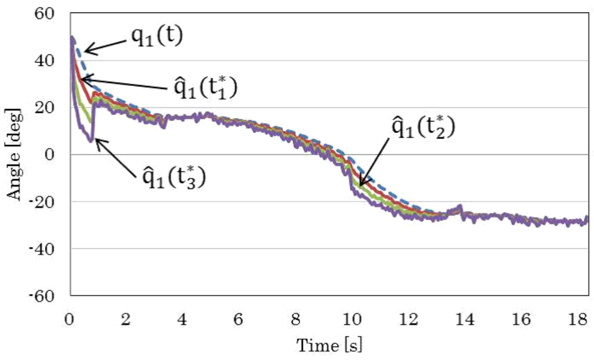

Fig. 17. Actual and predictive angle of link 1 with noise through first order prediction (h=0.06[s])

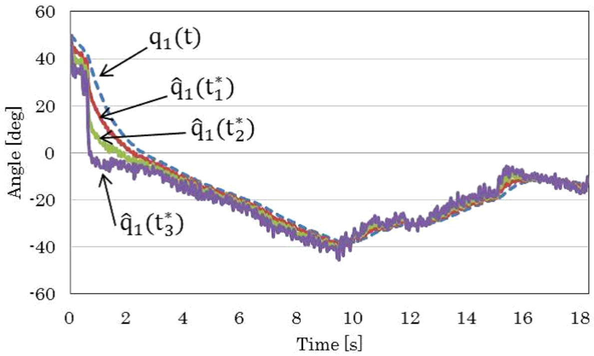

Fig. 18. Actual and predictive angle of link 1 with noise through first order prediction (h=0.03[s])

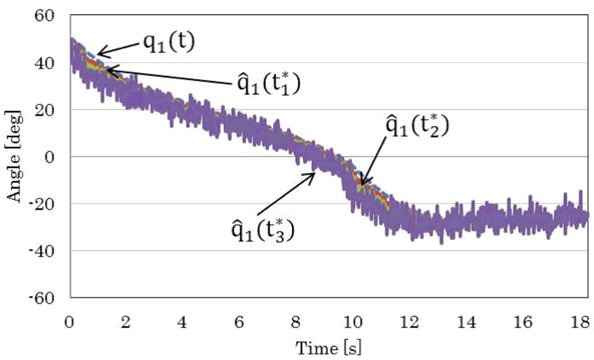

Fig. 19. Actual and predictive angle of link 1 with noise through first order prediction (h=0.015[s])

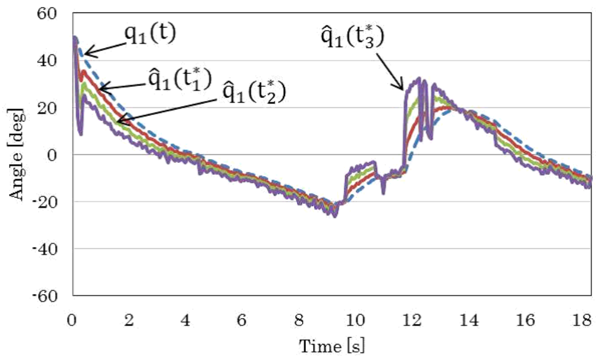

Fig. 20. Actual and predictive angle of link 1 with noise through second order prediction (h=0.06[s])

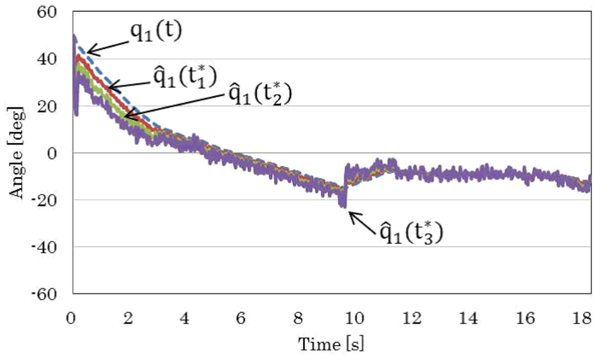

Fig. 21. Actual and predictive angle of link 1 with noise through second order prediction (h=0.03[s])

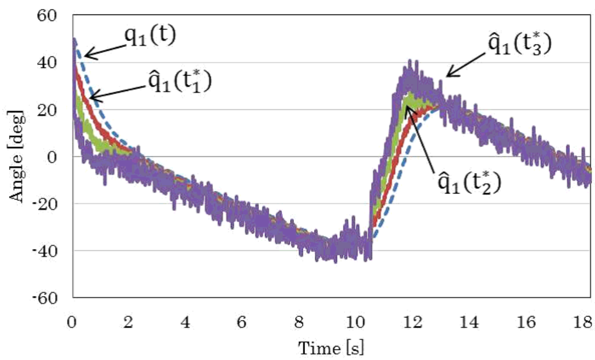

Fig. 22. Actual and predictive angle of link 1 with noise through second order prediction (h=0.015[s])