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Model-Based Control to Enhance a Novel Two Dimensional Positioning System

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Abstract: This paper presents a model-based control algorithm to address the delayed feedback that occurs in a novel two dimensional positioning system. The delayed feedback causes the motion control system unable to track the desire setpoint accurately and at the same time introduce following error. Thus, a Modified Smith Predictor is proposed to address the delayed feedback by having an inner plant model to predict the path during the delay. Furthermore, an online system identification scheme is proposed to improve the accuracy of the model used in Modified Smith Predictor. Simulation and experimental results of the Modified Smith Predictor and online system identification are presented.

Keywords: Model-Based Control, Smith Predictor, System Identification, and Time Delay

1. INTRODUCTION

Computer Numerical Control (CNC) has been widely used in the manufacturing sector in the mass production of consumer goods. Most common CNC machines have highly accurate position sensing capability in the range of 0.5 to 1 μm. However, machine errors such as geometrical error or thermal expansion of the machine's structure may occur over time which may not be sensed by independent axis encoding as the axes are subject to the same error, causing the end products to be out of tolerance. Therefore, a new positioning system using 2D vision as the primary feedback mechanism is proposed to perform online error mapping and compensation of the machine tool path in real time with the integration of computer vision[1].

The objective of such a system is to be able to move the planar motion of the XY table by tracking an active target display on an LCD monitor, as shown in Fig 1. Unlike the current CNC controller where desired trajectory of the overall path of a planar motion is generated for each individual axis, vision-based positioning performs XY planar motion by using a digital camera to track a set of active array targets that will be displayed dynamically on the LCD screen. Therefore, instead of using the feedback from the conventional position sensors such as rotary encoder or linear glass scale together with a kinematic model of the XY table to estimate the actual position, the position error of the XY stage is measured directly using the vision system, allowing online error mapping and compensation to be performed in real time[2].

2. MODIFIED SMITH PREDICTOR (MSP)

The integration of the vision system to the motion controller presents numerous challenges, and one of them is the delayed feedback. Unlike the optical position sensor that can output the feedback signal instantaneously to the motion controller, the current image processing algorithm needs around 100ms to 400ms to process the images captured by the digital camera, which causes the feedback delay. Thus, this paper presents a model based control algorithm to solve the feedback delay using a Modified Smith Predictor.

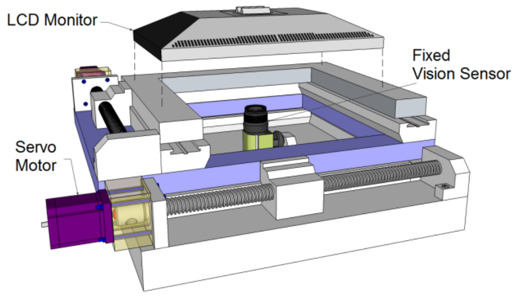

Fig 1: Vision sensor configuration

Smith Predictor is an algorithm designed to compensate control for long time delay, and is used in many industrial applications. Many modified versions of Smith Predictor (MSPs) were performed to improve the prediction performance and the disturbance rejection of the original Smith Predictor architecture [3-8]. Most of the MSP approaches use only one fixed plant model to predict the actual plant throughout the process.

This paper proposes a new MSP which can improve the accuracy of the plant model by using online system identification as illustrated in Fig 2, and analyzes the performance of the implementation of the proposed scheme to the described vision system. Similar to the ordinary Smith Predictor layout, a mathematical plant model, $G_{Model}(z)$ is used to serve as path predictor for the actual plant, $G_{Actual}(z)$ during the delay period. Unlike the ordinary Smith Predictor, $G_{Model}(z)$ will be updated in real time rather than remaining static[9].

Although online system identification has been implemented in some industrial applications, it has typically been used to obtain better controller gains for the application[10]. However, online system identification is proposed to be integrated with the Smith Predictor, shown in Fig 2 to update the plant model, represented by the dotted line. As a result, disturbances such as thermal expansion and wear of machine components can also be taken into account.

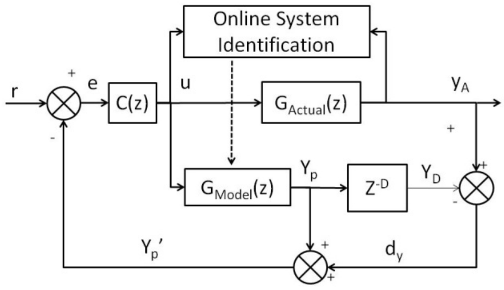

Fig 2: Modified Smith Predictor

3. SYSTEM IDENTIFICATION

The objective of system identification is to build mathematical model for dynamic system based on the observed data: input and output. The proposed positioning system uses two servo motors to drive a XY table, and system identification needed to be performed for each servo motor individually as the dynamics of each motor is different. As a preliminary stage of this research, only one axis was used to perform the studies of the proposed model-based controller.

3.1 Online System Identification

In order to update the plant model during the process, an online system identification process is proposed. Since the Smith Predictor relies heavily on the plant model to assist the system during the delay, online system identification process will be able to provide better estimation of the actual system.

Many online system identification methods have been developed to predict the plant model in real time: Least Mean Square, Normalized Least Mean Squares, Recursive Least Squares, and Kalman Filter. The Kalman Filter algorithm is chosen for this research to perform the online system identification because this algorithm will include quantification of the measurement noise and process noise when estimating the model. This is essential because the output of the plant model will be used as the actual path feedback during the delay period. In general, Kalman Filter algorithm minimizes the mean square error between the actual plant position and the estimated model output position so that the predicted plant model has a closer approximation of the actual plant dynamics.

4. RESULTS

4.1 System Identification

System identification was performed using LabView System Identification Toolkit, and Fig 3 shows the results of both the measured and simulated signal of the offline system identification process based on a 0.01-10Hz, 20V peak-to-peak sine sweep stimulus signal. The simulated signal shows close estimation of the actual measured data.

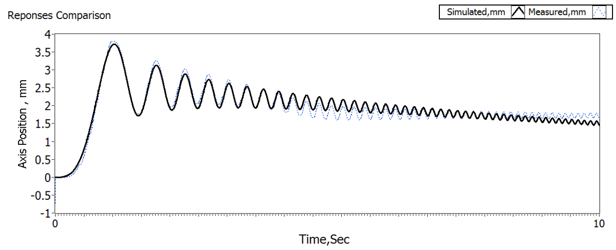

Fig 3: Measured (Dotted line) and simulated output (Solid line) waveforms

$$G_{Model}(z) = \frac{0.0000013445z^2 + 0.0000047939z + 0.00000106079}{z^3 - 2.6119z^2 + 2.23397z - 0.622284} \quad (1)$$

Eq. (1) shows the plant model's discrete transfer function generated by the offline system identification process. This model was used in the simulation and the hardware experiment of the Smith Predictor.

4.2 Smith Predictor

Simulation and hardware deployment of the Smith Predictor were performed. Before integrating the Smith Predictor with the vision sensor, the rotary encoder of the servo motor was used to emulate vision sensor, by enforcing the time delay within the feedback loop from the encoder to the motion controller. Two controllers were used in the simulation: 1) PI controller and 2) Smith Predictor using a PI controller, so that the results can be compared directly.

Table 1 shows the gains used in both controllers. These gains were tuned to comply to design requirements, in which the step response of the system is required to have less than 5% overshoot and less than 1% steady state error.

Table 1: Gains used in simulations

	Smith Predictor		PI Controller	
Delays	**P**	**I**	**P**	**I**
100ms	16	0.5	4.2	0.5
300ms	14	0.6	2	0.5

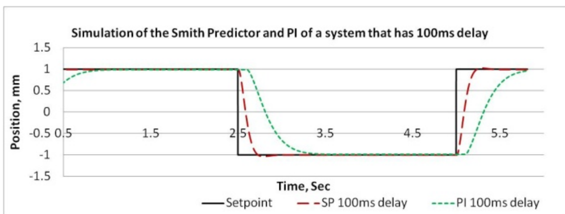

Fig 4: Simulation response with 100ms delay

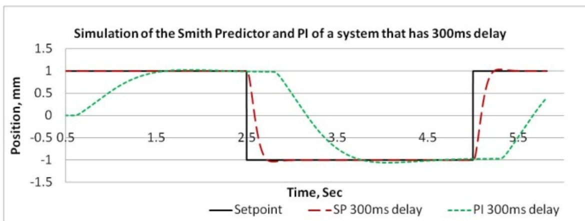

Fig 5: Simulation response with 300ms delay

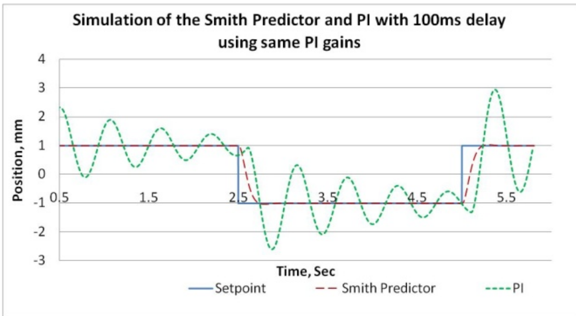

Fig 6: Simulation response with 100ms delay using same gains, P=16 and I=0.5

Table 2: Performance comparison for 100ms delay

	Smith Predictor	PI controller
Rise Time	0.225s	0.741s
Settling time	0.295s	1.352s

Fig 4 and Fig 5 illustrate the comparison of the Smith Predictor (Broken Red) and PI controller (Dotted Green) to track the setpoint (Solid Black) with 100ms and 300ms delays respectively. Based on the simulation results, it can be inferred that the Smith Predictor is capable to improve the setpoint tracking performance of the system. The step response of the Smith Predictor shown in Fig 4 and Fig 5 has faster settling time and rise time than the ordinary PI controller, shown in Table 2. Due to the delay in the feedback, the P gain of the PI controller cannot be further increased to improve the step response performance while complying with the system requirement. The PI controller will have introduce oscillation if the P gain increased, as seen in Fig 6, where the P and I gain of the PI controller were configured to have the same values as the Smith Predictor Controller's gains.

In order to verify the performance, the Smith Predictor Controller was deployed to the microcontroller of the prototype shown in Fig 7 and the actual responses are presented in Fig 8.


Fig 7: Prototype of the novel positioning system

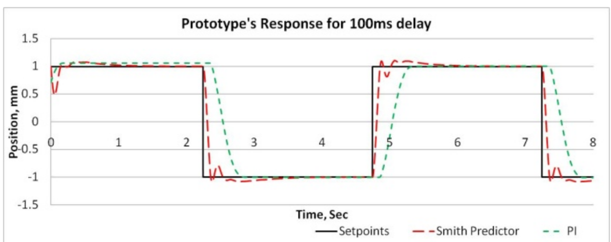

Fig 8: Prototype response using square wave reference

During the hardware experiments, the Smith Predictor has 4.5% overshoot as seen in Fig 8, which is still comply with the system requirement, and have better performance than the PI controller.

Based on the preliminary experimental results of the simulation and the hardware experiments, it shows that the Smith Predictor controller (Broken Red) has better tracking capability than the normal PI controller (Dotted Green).

4.2 Online System Identification

To further improve the accuracy of the plant model used in the Smith Predictor, preliminary study and simulation of online system identification was also performed.

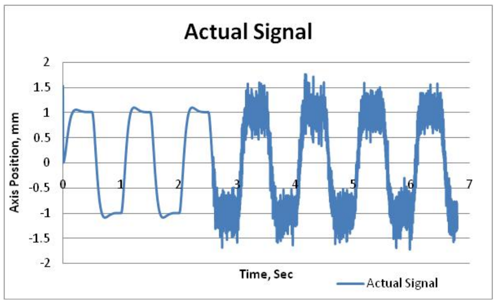

Fig 9: Actual signal with and without noise

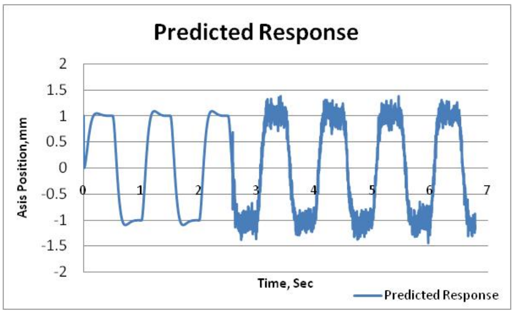

Fig 10: Online system identification model's output

Fig 9 shows the simulated feedback signal of the system. From 0 to 2.5 sec, no noise was injected but the Gaussian noise was injected into the feedback signal after 2.5 sec to emulate process or measured disturbance of the system. Fig 10 shows the predicted model output of the online system identification algorithm using the simulated output signal in Fig 9.

Fig 11 shows the model denominator coefficients of the discrete plant model before and after the noise were injected. Before the noise was injected, all the coefficients' values were constant, and were also close to the offline model's coefficients generated by the offline system identification, shown in Eq. (1). When the Gaussian noise was injected to the output signal at 2.5 sec, the online system identification sensed the changes in the output signal and start predicting the plant model recursively with respect to the measured output. Fig 12 and Fig 13 shows the close up look of the numerator and denominator coefficients of the discrete transfer function predicted by the online system identification when the noise was injected to the system.

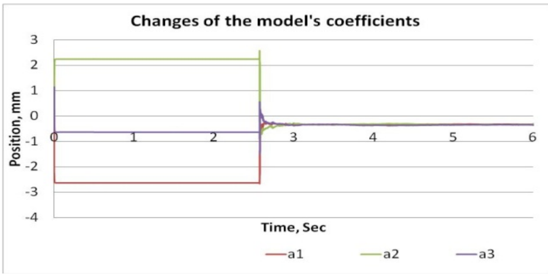

Fig 11: Changes of the denominator's coefficients of the model when noise was injected at 2.5 sec

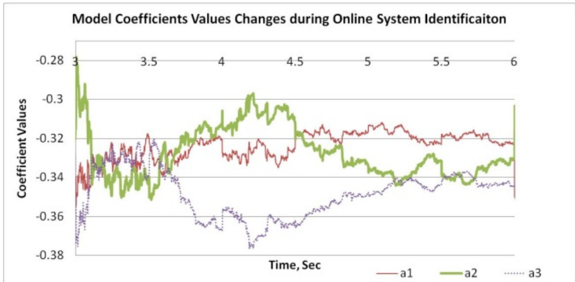

Fig 12: Changes of the denominator's coefficients of the model (Zoomed in from time 3 to 6.5 sec)

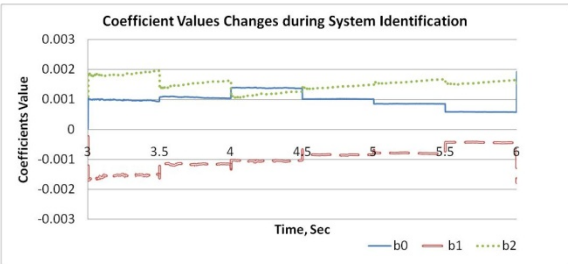

Fig 13 Changes of the numerator's coefficients of the model when noise was injected at 2.5 sec

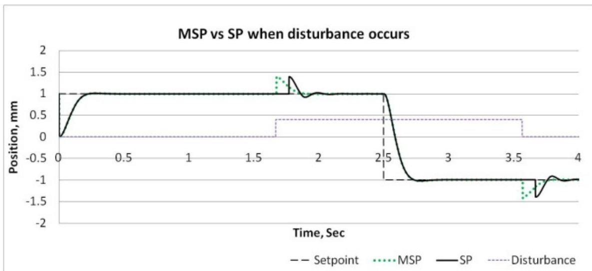

Fig 14: Simulation of the proposed MSP

Comparison between proposed MSP using online system identification to the ordinary Smith Predictor was also performed where a step input as the disturbance was injected to the feedback signal of the system shown in Fig 14. The simulation result shows that the MSP (Dotted Green) is capable to react faster than the SP (Solid Black) when the disturbance (Broken Purple) was detected. In addition, the ordinary Smith Predictor has overshoot while recovering from the disturbance as can be seen at time 1.8s and 3.8s at the same time the ordinary Smith Predictor react 68ms slower than the MSP. Based on the simulation, it can be seen that the online system identification enhances the disturbance rejection performance of the system.

5. CONCLUSION

In this paper, simulation and experimental results of the Smith Predictor show that it is capable to improve the tracking performance of the system when delay occurs. The initial simulation of the proposed MSP using online system identification also shows that the MSP is able to improve the setpoint tracking of the system, reacting to the disturbance faster than the ordinary Smith Predictor with lesser overshoot.

For future work, the proposed MSP will be further tuned with a longer time delay and at the same time it will also be deployed to the prototype to further study the improvement on the actual system.

6. ACKNOWLEDGEMENT

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