Visual State Feedback Digital Control of a Linear Synchronous Motor using Generic Video-Camera Signal

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Abstract-**This paper describes an effective way to estimate state variables, such as motor speed and disturbance from visual signal by using a dual sampling rate observer. The dual sampling rate observer estimates the state variables at every DSP control period and corrects the estimation error at the instant that the measurement signal is detected. The effectiveness of the observer is verified through simulations and experiments. .**

I. INTRODUCTION

Actuation using electric drives has the advantages of high efficiency, good control quality, *etc*. However, it needs a position sensor in order to take these advantages. If the position information was acquired from generic video cameras, the motor installation would be easier. This technique would be substantially advantageous for position controls of linear drives and magnetically levitated movers. The paper deals with the application of dual sampling rate digital observer to this *"economic"* visual servo solution using generic video cameras. The visual position-feedback control has the following difficulties.

1. Calibration between graphic signal and motor position,
2. Coarse frame-rate of video signal, which results in narrow dynamic frequency range of position signal, and
3. Dead time in position feedback path caused by the complicated visual signal processing.

Since special consideration is needed for coarse frame rate and dead time handling, the paper deals with the problem 2 & 3 by applying and extended dual-rate sampling observer.[1]

II. PREDICTIVE DUAL-RATE SAMPLING OBSERVER

Lilit *etal.* [1] have proposed state-estimation whose position signal is substantially coarse for a traction system in low speed range. In [1], gain tuning method for the dual sampling rate digital state observer gave stable estimations. This feature gives a direct solution to the problem 2, One defines that T_1 is the period of intermittent position signal acquisition and T_2 is the digital period of a microprocessor, where T_1/T_2 . The ratio of the two periods is defined as $N=T_1/T_2$, which is assumed an integer for theoretical simplicity. The signal flow in the proposed predictive dual sampling observer is illustrated in Fig. 1.

Where the real system in continuous time domain is a time-invariant linear system, the corresponding digital system with its sampling period T_2 is represented using system matrix A_2, input matrix B_2, and output matrix C_2. z_2 is *z*-operator with the sampling period T_2 based on the real time information of input vector $\boldsymbol{u}$: The $\boldsymbol{u}$ is the thrust directly calculated from armature current in the following example. Estimated values are corrected by the output signal of the real system at every T_1: specifically the output signal is the mover position in this paper. The correction of the estimated state vector is described as follows:

$$\hat{\boldsymbol{x}}_{n+1}=A_2\hat{\boldsymbol{x}}_n+B_2\boldsymbol{u}_n+L_2(\boldsymbol{y}_n-\hat{\boldsymbol{y}}_n) \qquad n=mN$$

$$\hat{\boldsymbol{x}}_{n+1}=A_2\hat{\boldsymbol{x}}_n+B_2\boldsymbol{u}_n \qquad \text{otherwise} \qquad (1)$$

$$\hat{\boldsymbol{y}}_n=C_2\hat{\boldsymbol{x}}_n \ .$$

If an appropriate observer gain, designed for the system in which every state variables are digitized with an identical sampling period T_1, is L_1, the two observer gains have the following simple relationship as described in [1]:

$$L_2=\left(A_2^{N-1}\right)^{-1}L_1 \qquad (2)$$

This relationship theoretically guarantees the stability of the estimation by the proposed dual sampling rate observer.

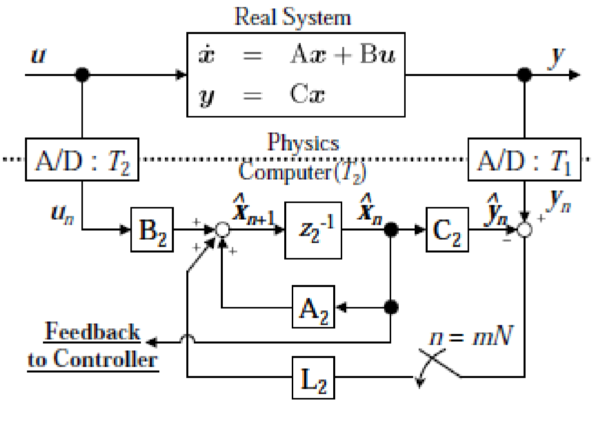


Fig. 1. Block diagram of the predictive dual sampling rate observer proposed in [1].

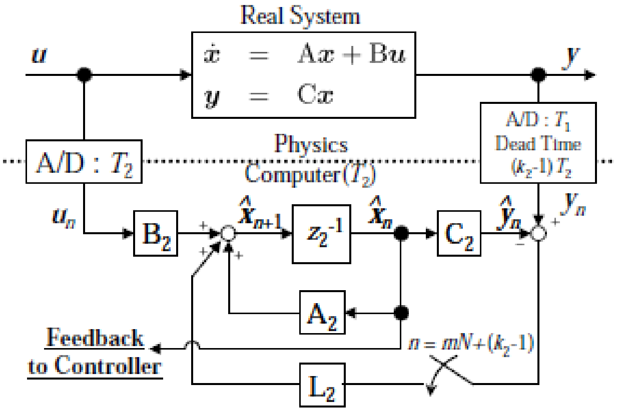


Fig. 2. Block diagram of the predictive dual sampling rate observer type I extended for handling small dead time in a output signal path.

III. DUAL RATE SAMPLING OBSERVER ALLOWING A CONSTANT DEAD TIME IN THE FEEDBACK PATH OF OUTPUT SIGNALS

The dual sampling rate observer shall be extended to allow a constant dead time in an output feedback path. The method are classified into two cases according to the length of the dead time.

A. Type I: the case when the dead time T_d is smaller than the output sampling period T_1

The configuration of the observer

When the dead time T_d is smaller than the output sampling period T_1, stable estimation is possible by applying the following minor modification to the gain tuning in the original dual sampling rate observer. When $T_d = (k_2 - 1)T_2$, one can modify the observer gain as

$$L_2 = (A_2^{N-k_2})^{-1} L_1$$

(3)

and the observer observer is designed as follows.

$$\hat{x}_{n+1} = A_2\hat{x}_n + B_2 U_n + L_2(y_{mN} - \hat{y}_{mN}) \quad n = mN + k_2 - 1$$

$$\hat{x}_{n+1} = A_2\hat{x}_n + b_2 u_n \quad \text{otherwise}$$

$$\hat{y}_n = C_2\hat{x}_n \quad (4)$$

The estimation is possible by the slight modification from the original observer configuration as shown in Fig. 2.

Simulation of the position feedback control of a linear synchronous motor using the observer type I

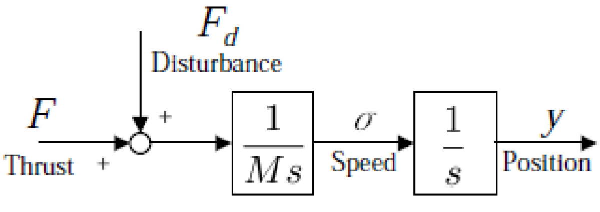
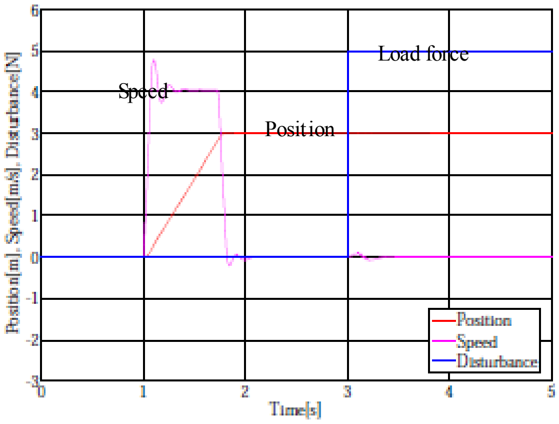
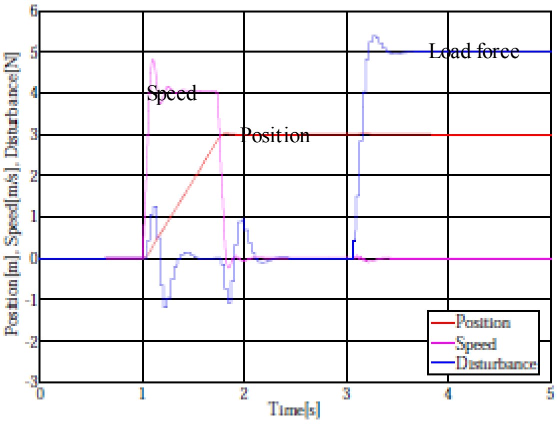


Fig. 3. Block diagram of the simulation of one-dimensional position control for a linear synchronous motor.



(a) Ideal direct measurements



(b) Estimated state variables

Fig. 4 Simulation results for the observer type I when the dead time is 25 msec.

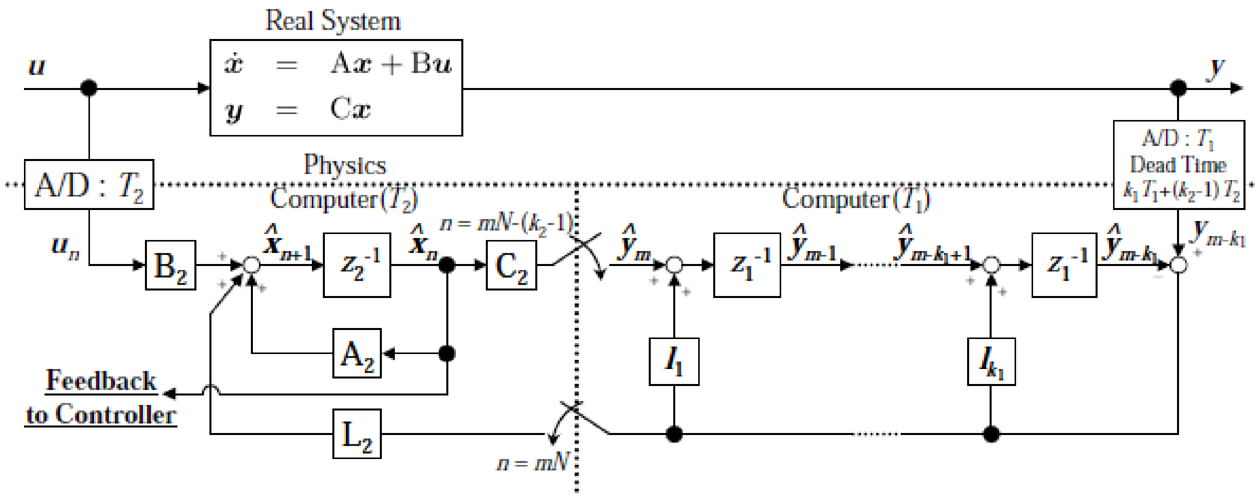


Fig. 5.Block diagram of the predictive dual sampling rate observer type II extended for handling large dead time in a output signal path.

For verifying the performance of the observer type I, a position feedback control of a linear synchronous motor has been simulated. The simulation scenario is as follows. The controller sampling period $T_2=1$msec, the sampling period of the video camera as a position sensor $T_1=33$ msec, the output signal dead time $T_d=25$ msec. At $t=1$ sec, the 3m-step position command is given, and the 5N-step load force is applied at $t=3$ sec. The result is shown in Fig. 4. The estimation of the load force is dependent on the position signal. Therefore the estimation has inherently the same dead time as the delayed position signal, and the waveform has stepwise changes with the period identical to T_1.

B. Type II: The case when the dead time T_d is larger than the output sampling period T_1

The configuration of the observer.

The observer type I cannot be used for the case of $T_d \geq T_1$. For allowing such bad cases, the observer type II, which has buffers for estimated output vectors during the dead time, has been proposed as illustrated in Fig. 5. The dead time T_d is divided into two parts as follows.

$$T_d = k_1 T_1 + (k_2-1)T_2$$

$$\text{where } 0<k_1 \text{ and } 1 \leq k_2 \leq N \quad (6)$$

The first term k_1T_1 is a major and the second term $(k_2-1)T_2$ is minor part. The left bottom block in Fig. 5 is the observer using input signal whose sampling period is T_2, which is identical to the observer type I. The right bottom block in Fig. 5 is buffers of the estimated output signals whose holding time is T_1 identical to the sampling period of a video camera as a position sensor.

The observer gains L_2 and $l_1,\cdots,l_{k_1}$ are designed as follows.

First of all, the following observer, whose sampling period is large T_1, and which holds the estimated output variables k_1 in the buffers, has the configuration shown in (7). The matrices A_1, B_1, and C_1 are digitized system, input and output matrices with their sampling period T_1.

$$\hat{\boldsymbol{X}}_{(m+1)N} = [A]\hat{\boldsymbol{X}}_{mN} + [B]\boldsymbol{u}_{mN} + [L](\boldsymbol{y}_{(m-k_1)N} - [C]\hat{\boldsymbol{X}}_{mN}) \quad (7)$$

where

$$\hat{\boldsymbol{X}}_{mN} = \left[\hat{\boldsymbol{x}}_{mN} | \hat{\boldsymbol{y}}_{(m-1)N} \ \cdots \ \hat{\boldsymbol{y}}_{(m-k_1)N}\right]^T \quad (8)$$

$$[A] = \begin{bmatrix} A_1 & | & O & \cdots & \cdots & O \\ C_1 & | & O & \cdots & \cdots & O \\ O & | & I & & & \vdots \\ \vdots & | & & \ddots & & \vdots \\ O & | & O & & I & O \end{bmatrix} \quad (9)$$

$$[B] = \left[B_1 \ | \ O \ \cdots \ O\right]^T \quad (10)$$

$$[C] = \left[O \ | \ O \ \cdots \ O \ I\right] \quad (11)$$

$$[L] = \left[L_1 \ | \ \boldsymbol{l}_1 \ \cdots \ \boldsymbol{l}_{k_1}\right] \quad (12)$$

The poles of the observer in *z*-domain are solutions of the following characteristic equation.

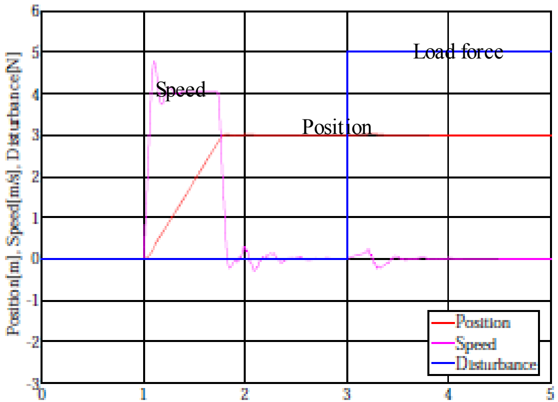
$$\det[zI - ([A]-[L][C])] = 0 \quad (13)$$

One shall determine the observer gain L so that all the poles z are in the unit circuit $|z|<1$ for the stability of the state estimation. The gain column vectors $l_1,\cdots,l_{k_1}$ are directly applied to the output feedback in the right bottom block in Fig. 5 for allowing the major partial dead time kT_1.

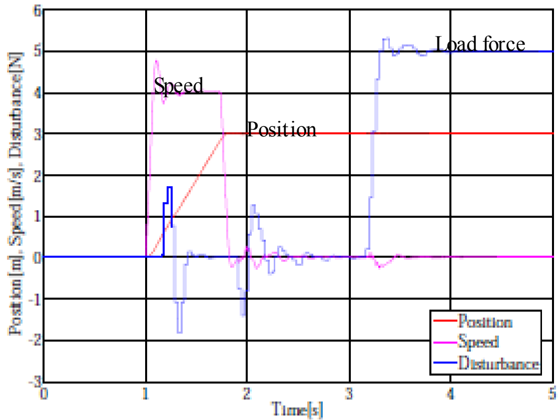
On the other hand, the observer gain in the left bottom block in Fig. 5 is derived by converting L_1 to L_2 in (3) for allowing the minor partial dead time $(k_2-1)T_2$.

Simulation of the position feedback control of a linear *synchronous motor using the observer type II*

The performance of observer type II has been verified in the simulation whose scenario is almost the same as the type I in except for the larger dead time $T_d = 150$ msec. The results are summarized in Fig. 6. Even with much larger dead time of 150msec, the state estimation and the control are still stable. Since $T_d = 34 \times 4 + 18$ msec,the observer type II has four more poles in addition to the original three poles as shown in Fig. 7. The pole location here is determined by Kessler's canonical form [2] with the equivalent time constant $\tau = 0.1$ sec.



(a) Ideal direct measurements



(b) Estimated state variables

Fig. 6. Simulation results for the observer type II when the dead time is 150 msec.

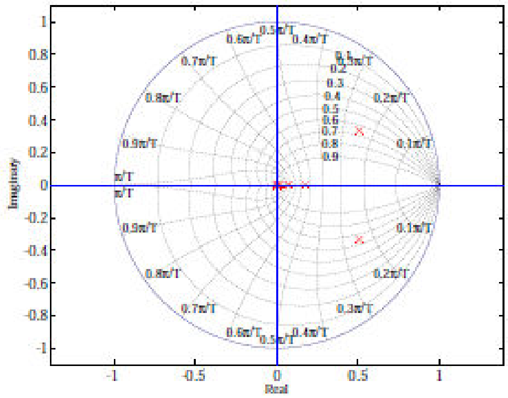


Fig. 7. Pole location of the extended observer type II in Fig. 6.

C. *Comparison of the two extended dual sampling rate observers*

The advantages and disadvantage of the observers are summarized in table 1.

TABLE I
COMPARISON OF THE EXTENDED DUAL SAMPLING RATE OBSERVERS EXTENDED FOR ALLOWING DEAD TIME IN OUTPUT SIGNAL PATH

Observer type	Type I	Type II
Applicable dead time T_d	$0 < T_d < T_1$	$T_1 \le T_d$ The configuration will be automatically identical when $0 < T_d < T_1$.
Advantage	Minor modification from the original dual sampling rate observer	Guarantee of the state estimation stability
Disadvantage	Applicable only to small dead time	Many pole allocation required for large dead time

IV. EXPERIMENTAL VERIFICATION –POSITION CONTROL USING GENERIC HOME VIDEO CAMERA AS A POSITION SENSOR

A position feedback control test has been executed for verifying the feasibility and the performance of the proposed observers.

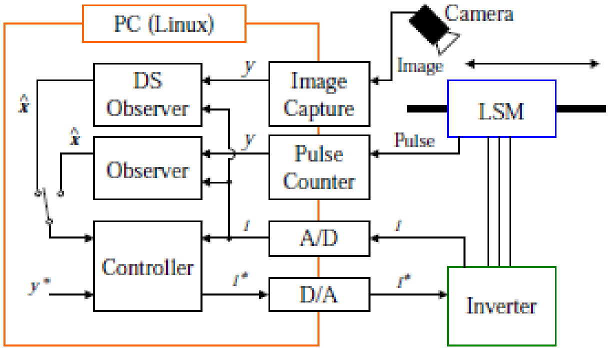
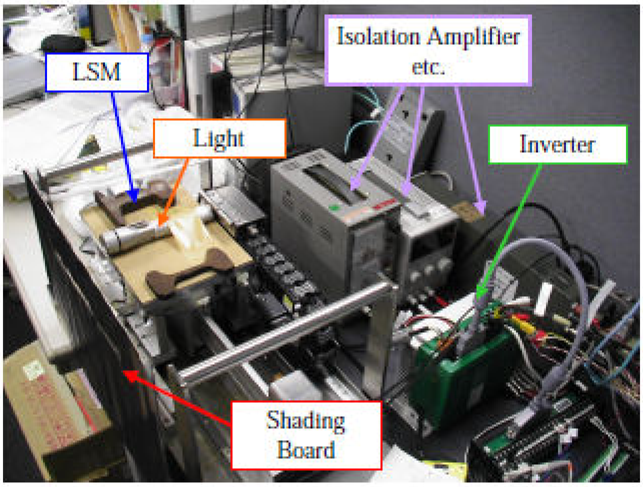
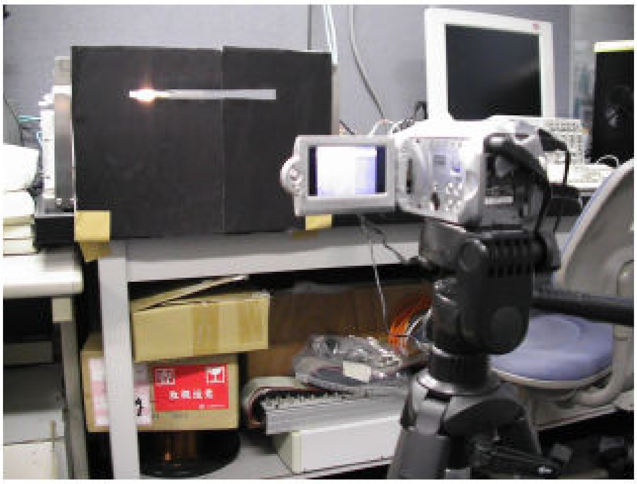


Fig. 8. Experimental setup of a linear synchronous position control.



(a) Overview



(b) View from the camera

Fig. 9. Photograph of the experimental setup.

A. Test Bench

The configuration of the experimental bench is shown in Fig. 8. The position of the mover is detected by a home video camera, and monitored by a linear pulse encoder. The position signals are processed by a picture capture board and a pulse-counter board to a digital computer. The coarse position information from the camera is sent to the dual sampling rate observer, and the fine position signal from the linear pulse encoder is delivered to an ordinary single rate observer whose sampling period is T_2. One of these two estimated state vectors are selected and delivered to the state feedback controller for positioning and the results are compared.

Fig. 9 shows the experimental bench. There is a lamp on the mover, whose position is captured by the video camera. For better detection of the one-dimensional motion, the light point is sent through a slit on a black shielding board as shown in Fig. 9.

The graphic capture board processes binary graphical data and the mover position is determined by calculating the weighting point of a bright area. The digital process sampling period $T_2=4$ msec and the sampling period of the camera is assumed to $T_1=32$ msec.

B. Detection of the dead time

For knowing the dead time of the graphical processing subsystem, the real time signals from the two position information sources, *i.e.*, the video camera and the linear pulse encoder, were directly compared by operating the mover from 0 to 10 cm at a constant speed. The dead time of the video capture system $T_d=54$ msec has been obtained from the preliminary measurement. Since this dead time is larger than $T_1=33$ msec, only the observer type II is applicable.

Furthermore, the quality of the position signal from the camera is much worse than the encoder. The resolution of the camera was only 400 μm/pixel, whereas the one of the linear encoder was 0.1 μm/pulse.

C. Position control using the observer type II

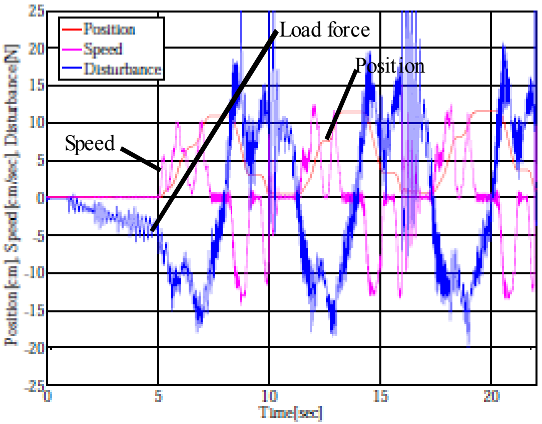
Position control of a linear synchronous motor using the observer type II was tested. The result is shown in Fig. 10. Since the equivalent time constant of the state estimator was selected as $\tau_{ob}=0.2$ sec, which was relatively large, for avoiding oscillatory estimated signals. Although the fast control was not possible for the reason, the linear motor was successfully stably controlled.

As expected from the simulated results, the control was weak for spontaneous change of the load force. The immediate load force compensation is substantially difficult when the system has a considerable dead time in its output signal feedback path, even though the proposed observer design guarantees the stable state estimation.

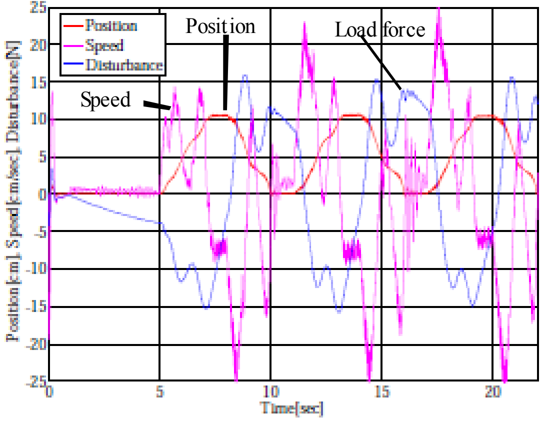
V. CONCLUSIONS

This paper describes the challenge to realize stable position control of a linear synchronous motor using coarse and slow position signal from a generic home video camera. The dual sampling rate digital observer has been extended for a stable position estimation in spite of considerable dead time and bad resolution in the position signal from the camera. The experimental verification of the observer-based state feedback was successful, but the experimental performance was not as good as preliminary simulation results. One assumed the two different digital sampling periods in the design of the estimator, but the experimental system had actually three different sampling periods; of the controller CPU, of AD/DA boards and of the video signal.

The signal processing theory shall be, therefore, furthermore extended for handling triple sampling rate systems in order to improve the estimation/control performances in the next step.



(a) State variables estimated by an ordinary single rate observer with the sampling period 4 msec based on the fine position signal directly obtained from the linear pulse encoder.



(b) State variables estimated by the dual rate observer type II based on the coarse and slow signal from the video camera.

Fig. 10. Experimental verification of the performance of the observer-based position control based on the state estimation using the observer type II when the dead time is 54 msec.

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