# LATERAL CONTROL OF A WEB USING ESTIMATED VELOCITY FEEDBACK

by

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## ABSTRACT

The focus of this paper is on lateral control of a web using estimated motor velocity feedback. A reduced state velocity observer is designed to estimate the motor velocity based on the measured lateral position of the web and the motor input. Estimated velocity is used for inner-loop motor velocity feedback instead of measured velocity from a tachometer. Two approaches are investigated in the design of the reduced state velocity observer; the first is based on the motor dynamics and the web lateral dynamics and the second is based on the motor dynamics and the static gain of the web lateral dynamics. The second approach results in a simple low-order velocity observer when compared to the first approach.

The proposed designs are experimentally investigated on a Fife remotely pivoted steering guide. The performance of the lateral control system with estimated motor velocity feedback is compared with the tachometer feedback and results are discussed. Representative experimental data from the two approaches indicated above is presented. Experimental results on the example considered shows that the observer can successfully replace the tachometer to close the inner velocity loop in lateral control systems.

## INTRODUCTION

Lateral control of a web involves controlling web fluctuations in the directions perpendicular to the travel of the web. Control of web guides to maintain lateral position of the web on the rollers prior to coating, printing and winding and other web processes is critical for successful operation of a web process line. For example, large lateral movements of the web on the rollers can cause slackness of the web, which may result in wrinkles when the web goes through a nip. Hence, tight control of the lateral position of the web on a roll is essential.

Modeling lateral dynamics is an important first step in understanding the lateral behavior of the web, which facilitates efficient design of lateral control systems. Mathematical modeling of lateral web dynamics was introduced in [1]; a first order model is derived under the assumption that the web behaves like a string. The first comprehensive fundamental study of the lateral dynamics of a moving web was done in [2]. Modeling of lateral dynamics of a moving web is dealt in detail and control of lateral movement of a web using different types of web guides is discussed. A comparison of the first and second order dynamics was presented in [2] to illustrate the inadequacies of the former for certain frequencies and operating conditions.

A study on practical application of unwind and rewind guides, their control systems, sensor configurations and locations, resonance characteristics, and lateral errors was reported in [5]. In [6], state estimation was used to predict lateral web position on a downstream sensor with use of feedforward sensor to achieve improved control. A stochastic model, which represents non-ideal webs and disturbances at the entering span roll, based on experimental data was introduced in [7]. A survey of the lateral dynamics and control was reported in [8].

A lateral control system typically consists of three feedback loops: an inner current loop; an inner motor velocity loop; and an outer feedback loop of web lateral position. The inner feedback loops are essential to obtain fast response of the motor and the outer feedback loop provides the required performance of the overall closed-loop system. The focus of this paper is on the inner velocity loop that uses motor velocity measured by a tachometer as feedback. It is assumed in this paper that the inner current loop dynamics is fast compared to the other two loops and hence ignored. Considerable reduction in cost can be achieved by eliminating the tachometer from the motor assembly. But simply eliminating the inner velocity loop may lead to sustained oscillations in the motor velocity and the lateral position of the web due to poor motor performance, especially in the presence of web lateral disturbances and/or poor web edge quality. This paper explores the possibility of replacing the tachometer by an observer that can estimate the motor velocity based on the measured signals.

In this paper, a reduced state observer is designed to estimate the velocity of the guide motor based on the web lateral position and the motor input. Estimated velocity is used in the inner feedback loop. Two approaches are investigated in the design of the reduced state observer. The first approach is based on the complete dynamics, i.e., motor dynamics and the lateral web dynamics. The second approach is based on the motor dynamics and the static gain of the lateral web dynamics; which results in a first-order dynamics of the observer.

An experimental platform is designed to investigate the velocity observer with a conventional PI controller. The experimental web platform consists of a Fife Kamberoller guide, an optical edge sensor, a Fife offset pivoted guide, an ultrasonic sensor, Fife analog A9 signal processor, and a computer system for closed-loop control. In the experiments, the offset pivoted guide is used to generate web lateral disturbances and the Fife Kamberoller guide is used to control the lateral position of the web. Experimental results with tachometer feedback and estimated velocity feedback are compared and discussed. Experimental results on the Fife Kamberoller guide show that the velocity observer designed with both the approaches can successfully replace the tachometer without sacrificing performance and stability of the closed-loop system.

## Nomenclature

| | | |
|---|---|---|
| $E$ | = | modulus of elasticity |
| $I$ | = | moment of inertia of web |
| $L$ | = | length of web span |
| $L_1$ | = | distance of the center of rotation of guide roll |
| $s$ | = | Laplace operator |
| $T$ | = | web tension |
| $u, U$ | = | actuator input |
| $v$ | = | web velocity |
| $w$ | = | web width |
| $y_L, Y_L$ | = | lateral web deflection from original position |
| $z, Z$ | = | lateral position of roller |
| $\theta_0$ | = | web angle error |
| $Y_0$ | = | lateral web position error |
| $\theta$ | = | angular position of the motor |
| $\omega, \Omega$ | = | angular velocity of the motor |
| $\widehat{\Omega}$ | = | estimate of the angular velocity of the motor |
| $a_m, k_m$ | = | motor constants |
| $\tau$ | = | transport lag ($= L/v$) |
| $K$ | = | a constant for a given web ($= \sqrt{T/EI}$) |

## LATERAL CONTROL WITH ESTIMATED MOTOR VELOCITY

A typical lateral control system uses a web guide to correct the lateral position of the web. Fig. 1 and Fig. 2 show two such guiding mechanisms. Fig. 1 shows a schematic of a Fife Kamberoller© guide, which is a steering type of guide. In this type of guide mechanism, the guide roller moves laterally and angularly to accomplish lateral correction. This action steers the web laterally in the entering span. Fig. 2 shows a schematic of an Offset Pivot Guide. This is a displacement type guide which provides web lateral position corrections by displacing the web between the entry and exit spans. with minimum entry and exit span requirements. This type of guide is designed with either a single roller or, more commonly, with two parallel rollers; and can utilize minimum entry and exit span requirements. The construction of the Offset Pivot Guides allows them to be used in the least amount of space. In both cases, an edge sensor, typically located immediately downstream of the guide roller, measures the lateral position of the edge of the web. In the rest of the paper, a Fife Kamberoller guide (steering guide) is used as an example.

Fig. 3 shows a block diagram of an analog lateral control system. This block diagram has two feedback loops; an outer feedback loop for positioning the web and an inner motor velocity feedback loop to stabilize the motor. An edge sensor measures the lateral web position and this measurement is used as feedback for the outer loop. The inner feedback loop is based on the velocity of the motor, which is measured by a tachometer. This study investigates the possibility of replacing the tachometer by an observer, which is built based on the measured signals.

The guide motor dynamics is given by

$$\theta(s) = \frac{k_m}{s(s+a_m)}U(s) \tag{1}$$

where $\theta(s)$ is the Laplace transform of the motor angle, $U(s)$ is the Laplace transform of the motor control input, and $a_m$ and $k_m$ are the motor constants. It is assumed in this paper that the amplifier gain and the current loop gain are reflected in the constant $k_m$. Also, throughout the paper, the upper case variables denote the Laplace transforms of the corresponding time functions.

The lateral dynamics of the web at the guiding roller for a remotely pivoted steering guide, as shown in Fig. 5, is given by

$$Y_L(s) = \underbrace{\left(\frac{s^2+\alpha_2 s+\beta}{s^2+\alpha_2 s+\alpha_1}\right)}_{G_p(s)} Z(s) + \underbrace{\left(\frac{\alpha_3}{s^2+\alpha_2 s+\alpha_1}\right)}_{G_1(s)} \theta_0(s) + \underbrace{\left(\frac{-\tau\alpha_3 s+\alpha_1}{s^2+\alpha_2 s+\alpha_1}\right)}_{G_2(s)} Y_0(s) \quad (2)$$

where $\theta_0(s)$ and $Y_0(s)$ are the web angle and displacement errors at the roller upstream of the guide roller, respectively, $\tau = L/v$, $\alpha_1 = f_1(KL)/\tau^2$, $\alpha_2 = f_2(KL)/\tau$, $\alpha_3 = f_3(KL)/\tau^2$, $\beta = Lf_2(KL)/L_1\tau^2$, $K^2 = T/EI$, and

$$\begin{aligned} f_1(KL) &= \frac{(KL)^2\sinh(KL)}{KL(\cosh(KL)+1)-2\sinh(KL)} \\ f_2(KL) &= \frac{(KL)^2\cosh(KL)-KL\sinh(KL)}{KL\sinh(KL)-2(\cosh(KL)-1)} \\ f_3(KL) &= \frac{KL\sinh(KL)-(KL)^2}{KL\sinh(KL)-2(\cosh(KL)-1)}. \end{aligned}$$

In this paper, the kinematics of the guide mechanism together with gear reductions are assumed to be linear and the guide correction($Z$) and the motor angular position ($\theta$) are assumed to be related according to

$$Z(s) = C_m\theta(s) \quad (3)$$

where $C_m$ is a constant that depends on the gear ratio, ball screw pitch and the kinematics of the guide mechanism.

As mentioned earlier, a tachometer feedback is typically used to implement the inner feedback loop as shown in Fig. 3. Considerable reduction in cost of the guide mechanism can be achieved if the velocity of the motor can be estimated from the measured signals such as input to the motor and the lateral web position of the web, rather than measuring the velocity using a tachometer. The tachometer can be replaced by an observer as shown in Fig. 4. Appendix shows the construction of a reduced state velocity observer based on two approaches, which are discussed below.

A reduced state observer based on the complete dynamics, i.e., motor dynamics and lateral web dynamics is derived in the appendix, which is given by

$$\widehat{\Omega}_c(s) = G^c_{y\omega}(s)Y_L(s) + G^c_{u\omega}(s)U(s) \quad (4)$$

where $\widehat{\Omega}(s)$ is the Laplace transform of estimated angular velocity using complete dynamics. The transfer functions $G^c_{y\omega}(s)$ and $G^c_{u\omega}(s)$ are derived in the appendix under the section entitled complete observer, and are given by

$$G^{c}_{y\omega}(s) = \frac{l_1(s^3+\alpha_2 s^2+\alpha_1 s)}{s^3+a_{11}s^2+a_{12}s+a_{13}}$$
$$G^{c}_{u\omega}(s) = \frac{k_m[s^2+(\alpha_2+l_3-l_1C_m)s+\beta C_m l_2]}{s^3+a_{11}s^2+a_{12}s+a_{13}} \tag{5}$$

where $l_1, l_2$, and $l_3$ are the observer gains, and $a_{11} = (\alpha_2 + a_m + l_3), a_{12} = (l_2\beta C_m + a_m\alpha_2 + a_m l_3) + l_1\alpha_2 C_m - l_1 a_m C_m)$, $a_{13} = \beta C_m(a_m l_2 + l_1)$. Notice that the zeros of the transfer function $G^{c}_{y\omega}(s)$ are given by the poles of the transfer function from $Z(s)$ to $Y_L(s)$ as given by equation (2) and a zero and the origin. The zero at the origin corresponds to converting the lateral web position to lateral web velocity and the other two zeros in a sense correspond to the inversion of the plant dynamics.

Based on the observation that the magnitude of the transfer function from the guide correction $(Z(s))$ to the lateral web position $(Y_L(s))$, $G_p(s)$, is constant in the low frequency range, a reduced state observer is constructed based on the motor dynamics. The static gain of $G_p(s)$ is used for the relationship between $Y_L(s)$ and $Z(s)$, i.e., $Y_L(s) = (\beta/\alpha_1)Z(s)$. The simplified observer is also constructed based on the measured lateral position and the motor input and is given by

$$\widehat{\Omega}(s) = G^{p}_{y\omega}(s)Y_L(s) + G^{p}_{u\omega}(s)U(s) \tag{6}$$

where $\widehat{\Omega}(s)$ is the Laplace transform of estimated angular velocity obtained using the motor dynamics and the static gain corresponding to the lateral web dynamics. The transfer functions $G^{p}_{y\omega}(s)$ and $G^{p}_{u\omega}(s)$ are derived in the appendix under the section entitled simplified observer, and are given by

$$G^{p}_{y\omega}(s) = \frac{\alpha_1(\lambda - a_m)s}{\beta C_m(s+\lambda)} \quad \text{and} \quad G^{p}_{u\omega}(s) = \frac{k_m}{(s+\lambda)} \tag{7}$$

where $\lambda$ is the desired observer pole. The simplified observer given by (6) is much simpler than the observer given by (4). Moreover, this observer has the same structure for all guide mechanisms except for the fact that the static gain constant $\beta C_m/\alpha_1$ is different. Further, if an adaptive scheme is used to estimate the the static gain constant, then the structure of the observer remains the same for all guide configurations. Although the simplified observer is easy to implement it is missing the phase difference between the angular position of the motor and the measured lateral position of the web. The simplified observer is well suited for low frequency lateral disturbances as the transfer function of the web lateral dynamics behaves like a low-pass filter.

## EXPERIMENTAL PLATFORM

An open-architecture experimental platform is developed for conducting lateral control experiments. The platform consists of an endless web line as shown in Fig. 6. The term endless web line refers to a web line without unwind and rewind rolls. This type of platform mimics most of the features of a process section of a web processing line.

Web guiding is accomplished by two guide mechanisms, a Kamberoller guide and an offset pivoted guide, as shown in Fig. 6. Each guide mechanism consists of a guide roller on a base which is actuated by a DC motor. An edge sensor downstream of the guide roller measures the web lateral position. In this paper, the offset pivoted guide is used to generate lateral disturbances and control of lateral position is achieved by the Kamberoller guide.

The analog lateral control system on the Kamberoller guide shown in Fig. 3 includes: (i) Fife A9 analog signal processor, (ii) Sensors (edge sensor, tachometer), (iii) DC motor. The A9 signal processor serves as an amplifier and an on-board analog controller. It implements a velocity inner-loop and a position outer-loop as shown in Figure 3. The velocity inner-loop is formed by feedback from the tachometer, which is used to regulate motor velocity by applying proportional control. The position outer-loop is formed by feedback of the web lateral position signal from the edge sensor, which regulates the web lateral position by applying proportional and integral control. The edge sensor is a Fife optical position sensor. The DC motor drives the guide roller based on the control signal from A9.

To obtain an open-architecture computer control system, the analog controller used in the A9 processor is emulated by a digital control algorithm generated in the computer. In the computer control system, The A9 processor simply serves as an amplifier only. The open-architecture computer control system can be used to implement any desired control algorithm.

The computer system consists of a 450 MHz Pentium computer with a digital data acquisition board. The data acquisition board is a Keithley DAS 1601, which consists of eight A/D and two D/A channels. The two D/A channels are used to send control input to the amplifiers of the guide actuator and the active dancer motor. The eight A/D channels are used to acquire the sensor signals.

The software for real-time control and data analysis is written in C++ programming language, and can be divided into off-line software and real-time software as shown in Fig. 7. MATLAB software and C++ programming language are used for data analysis and off-line simulation. The real-time software, which is written in C++ based on Windows platform, implements the following functions in a modular way: data acquisition, data storage, real-time data display and plotting, control algorithm, state observer algorithm, and control signal output.

## EXPERIMENTS

Two types of motor velocity observers are designed and implemented to circumvent the use of tachometer for inner-loop feedback. The following experimental conditions are used during lateral control experiments.

- Web velocity: 424 feet/min
- Average web tension: 9.7 lbf
- Computer control sampling period: 5 milli-seconds
- Web material: polyester film

To investigate the performance of the observers both in terms of tracking the tachometer signal and in terms of tracking the reference web position, two types of disturbances are created in the experiments. First, a non-transparent tape of fixed width is glued along the edge of the tape so that it is reflected as a step change at the infrared sensor on the Kamberoller guide (see Fig. 6). This effectively mimics a pulse disturbance. Second, the Offset Pivot Guide in the experimental platform is used to generate sinusoidal lateral web position disturbances and the Kamberoller guide is used to attenuate these disturbances.

Further discussion on the experiments is arranged as follows: importance of the inner velocity loop is discussed in the next subsection. Then, experiments conducted with a complete observer and a simplified observer, when sinusoidal disturbances are generated by the Offset Pivot Guide are discussed.

## Importance of Inner Velocity Loop

To investigate the importance of the velocity inner-loop, a digital lateral PI controller without the inner velocity loop is implemented for a pulse disturbance. Fig. 9 and Fig. 10 show the lateral web position as measured by the edge sensor and the motor velocity measured by the tachometer, respectively, without the inner velocity feedback loop. Experiments with two types of pulse disturbances are investigated. The following observations can be made from the experimental results.

- If there is no disturbance then the results with and without inner velocity feedback are similar. But when there is a disturbance, the performance of the lateral control system deteriorates; large unwanted overshoots in web lateral position can be observed.
- If the disturbance magnitude is not large with respect to the physical range of the edge sensor, then it is possible to control the web edge to the reference position without inner velocity feedback loop. However, the overshoot becomes large, and the oscillations last longer.
- If the disturbance magnitude is large then the oscillations in web position and motor velocity persist, which may result in the web rolling off the roller.

Thus, inner-loop velocity feedback is critical for desirable performance of the lateral control system in the presence of disturbances.

## Results with the Observer

Extensive experiments were conducted based on the two observer schemes illustrated in equations (4) and (6), respectively. In these experiments, a sinusoidal lateral web position disturbance is generated by the Offset Pivot Guide and the Kamberoller guide is used to attenuate this disturbance. The disturbance generated is about 0.3 inch in amplitude and 10 rad/sec in frequency. The proportional band of the ultrasonic sensor mounted immediately downstream of the Offset Pivot Guide is 0.39 inches and the proportional band of the infrared sensor mounted immediately downstream of the Kamberoller guide is 0.60 inches. The sinusoidal disturbances generated by the OPG are measured to be voltage signals with about 2.5 volts amplitude. Also, when the web reaches the outer edges of the active window on the ultrasonic sensor, flat lines are seen on the plots corresponding to the disturbances. A representative sample of experimental results are shown in Fig. 11 and Fig. 12.

Fig. 11 shows the performance of the Complete Observer. The graph on the top shows the disturbance generated by the OPG. The next graph shows the performance of the digital PI controller that uses the Complete Observer for inner velocity loop. The third graph shows the performance of the A9 analog controller with tachometer. The last graph in this figure shows the tachometer reading and the estimated velocity signal. Fig. 12 shows the performance of the Simplified Observer. The following observations can be made based on the experimental results:

- Digital control with a velocity observer scheme (both the Complete Observer and the Simplified Observer) perform as good as A9 analog control with tachometer feedback in terms of tracking the web position.

- Estimated velocity for both observers has similar waveform as the actual motor velocity obtained from the tachometer.

- From the last graph in Fig. 11 and Fig. 12 it can be observed that the tachometer signal is seen to lag behind the estimated velocity signal. This is due to low-pass filtering of the tachometer signal in the A9 processor, which introduces the time lag. The signal from the velocity observer does not suffer this disadvantage.

## CONCLUSION

Considerable reduction in cost can be achieved by eliminating the tachometer from the motor assembly. In this paper, we investigated the idea of using a motor velocity observer instead of a tachometer for inner velocity loop feedback. Two types of observers, a complete observer and a simplified observer, were discussed and experimentally evaluated. Comparison of the experimental results strongly indicate that the tachometer can be replaced with a velocity observer to close the inner velocity loop.

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## APPENDIX: OBSERVER DERIVATIONS

In this section a reduced state observer is designed to implement the block diagram shown in Fig. 4. In designing the observer, two approaches have been considered. In the first case, complete dynamics, i.e., motor dynamics and lateral web dynamics, is considered in the design of the observer. This observer has third order dynamics and is termed as a "complete observer". The second approach is based on the observation that the steady state gain between $y_L$ and z is $C_m\beta/\alpha_1$. This steady state gain equation can be used to design an observer for the motor velocity using (1). The next two subsections briefly outline the design of observer using these two approaches.

## Complete Observer

First, the motor dynamics and the lateral web dynamics given by (1) and (2) are represented in the state space form. Define the following state variables:

$$x_1 = y_L,\ x_2 = \dot{\theta},\ x_3 = \theta,\ x_4 = \dot{y}_L$$

Note that the first state variable is measured and the rest of the variables are not measured. With this definition of the stste variables, the state-space representation of the system in matrix form is

$$\begin{bmatrix} \dot{x}_1 \\ --- \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \left[\begin{array}{c|cccc} 0 & 0 & 0 & 1 \\ -- & -- & -- & -- \\ 0 & -a_m & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -\alpha_1 & (\alpha_2 - a_m)C_m & \beta C_m & -\alpha_2 \end{array}\right] \begin{bmatrix} x_1 \\ --- \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ -- \\ k_m \\ 0 \\ k_m C_m \end{bmatrix} u \quad (8)$$

$$y_L = \left[\begin{array}{c|ccc} 1 & 0 & 0 & 0 \end{array}\right] \begin{bmatrix} x_1 \\ --- \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \quad (9)$$

As indicated in (9) above, the state vector can be split into two groups such that the first group contains the state variables that can be measured and the second group contains the state variables that are to be estimated. Define the two groups of state variables as

$$\zeta_1 = x_1 \text{ and } \zeta_2 = [x_2, x_3, x_4]^T$$

Then the state space representation in the new variables becomes

$$\begin{aligned} \dot{\zeta}_1 &= A_{11}\zeta_1 + A_{12}\zeta_2 + B_1 u \\ \dot{\zeta}_2 &= A_{21}\zeta_1 + A_{22}\zeta_2 + B_2 u \\ y_L &= C_1\zeta_1 + C_2\zeta_2 \end{aligned} \quad (10)$$

where

$$A_{11} = [0],\ A_{12} = [0 \quad 0 \quad 1],\ A_{21} = \begin{bmatrix} 0 \\ 0 \\ -\alpha_1 \end{bmatrix},\ A_{22} = \begin{bmatrix} -a_m & 0 & 0 \\ 1 & 0 & 0 \\ (\alpha_2 - a_m)C_m & \beta C_m & -\alpha_2 \end{bmatrix}$$

$$B_1 = [0],\ B_2 = \begin{bmatrix} k_m \\ 0 \\ k_m C_m \end{bmatrix},\ C_1 = [1],\ C_2 = [0 \quad 0 \quad 0]$$

We are interested in estimating the first element of $\zeta_2$, namely, the angular velocity of the motor ($\dot{\theta}$). The observer dynamics for $\zeta_2$ can be written as [9]:

$$\dot{\hat{\zeta}}_2 = A_r\hat{\zeta}_2 + L_r y_r + z_r \quad (11)$$

where

$$\begin{aligned} A_r &= A_{22} - L_r A_{12} \\ y_r &= \dot{\zeta}_1 - A_{11}\zeta_1 - B_1 u \\ z_r &= A_{21}\zeta_1 + B_2 u \end{aligned} \quad (12)$$

The matrix $L_r$ is the observer gain matrix and is computed based on placing the poles of the observer at desired locations. If the desired poles of the observer are taken to be $\lambda_1$,$\lambda_2$, and, $\lambda_3$, then the elements of the observer gain vector, $L_r$, can be computed by equating the coefficients of the desired characteristic polynomial with the coefficients of the characteristic polynomial of $A_r$. The elements of the observer gain vector are

$$l_1 = \frac{a_m(\mu_2 - a_m\alpha_2 - a_m l_3) - \mu_3}{a_m(\alpha_2 - a_m)C_m - \beta C_m}, \quad l_2 = \frac{\mu_3 - l_1\beta C_m}{a_m\beta C_m}, \quad l_3 = \mu_1 - a_m - \alpha_2$$

where $\mu_1 = \lambda_1 + \lambda_2 + \lambda_3$, $\mu_2 = \lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1$, and $\mu_3 = \lambda_1\lambda_2\lambda_2$.

With the observer dynamics given by equations (11) and computed observer gains, the estimated velocity can be written as

$$\hat{\Omega}(s) = G^c_{y\omega}(s)Y_L(s) + G^c_{u\omega}(s)U(s) \tag{13}$$

where

$$G^c_{y\omega}(s) = \frac{l_1(s^3 + \alpha_2 s^2 + \alpha_1 s)}{s^3 + a_{11}s^2 + a_{12}s + a_{13}}$$
$$G^c_{u\omega}(s) = \frac{k_m[s^2 + (\alpha_2 + l_3 - l_1 C_m)s + \beta C_m l_2]}{s^3 + a_{11}s^2 + a_{12}s + a_{13}}$$

where $a_{11} = (\alpha_2 + a_m + l_3), a_{12} = (l_2\beta C_m + a_m\alpha_2 + a_m l_3) + l_1\alpha_2 C_m - l_1 a_m C_m)$ and $a_{13} = \beta C_m(a_m l_2 + l_1)$.

**Simplified Observer**

The observer designed earlier is of high order and guide specific (Kamberoller guide). Thus, for each guide configuration, the observer has to be designed separately. This can be obviated by noting that the position of the web edge as measured by the edge sensor and the motor angular position are related by a gain at the steady state. Considering the web dynamics given by (2), the position of the web edge and the motor angular position, at steady state, are related by

$$y_L = \frac{\beta C_m}{\alpha_1}\theta \tag{14}$$

A reduced state observer to estimate the motor angular velocity can be obtained along similar lines as in complete dynamics but using (14) and (1). The following reduced state observer results in this case:

$$\hat{\Omega}(s) = G^p_{y\omega}(s)Y_L(s) + G^p_{u\omega}(s)U(s) \tag{15}$$

where

$$G^p_{y\omega}(s) = \frac{\alpha_1(\lambda - a_m)s}{\beta C_m(s+\lambda)} \quad \text{and} \quad G^p_{u\omega}(s) = \frac{k_m}{(s+\lambda)} \tag{16}$$

where $\lambda$ is the desired observer pole.

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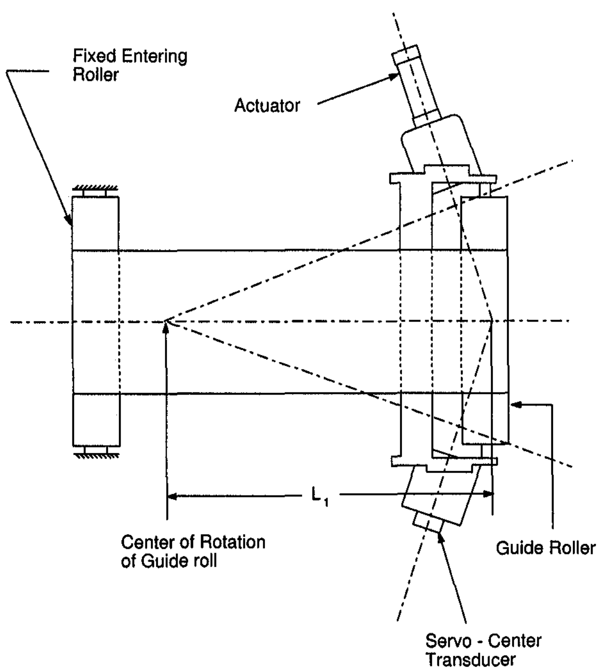


**Figure 1:** Remotely Pivoted Guide (Steering Guide)

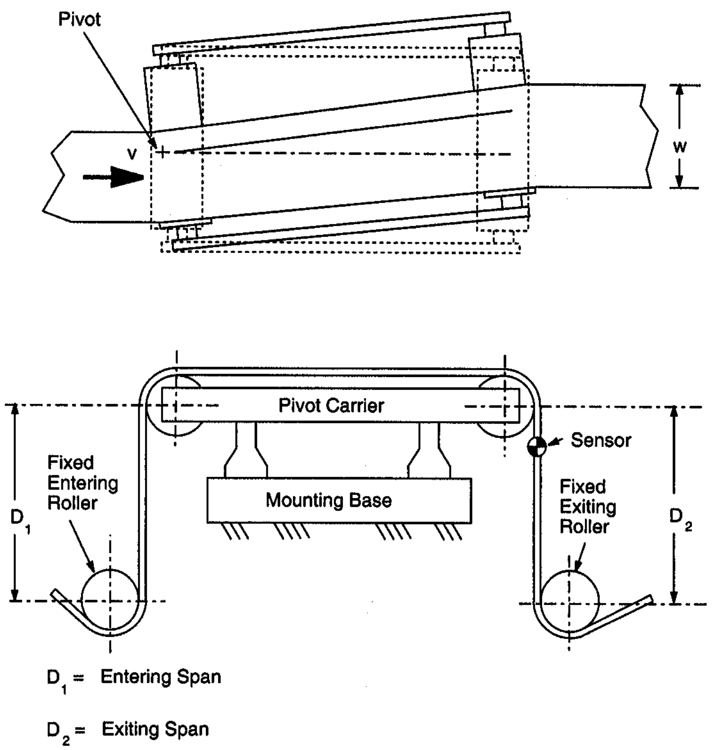


**Figure 2:** Offset Pivoted Guide (Displacement Guide)

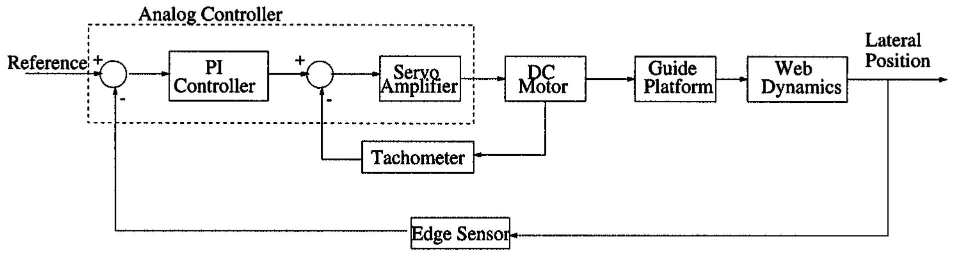


**Figure 3:** Analog lateral control system

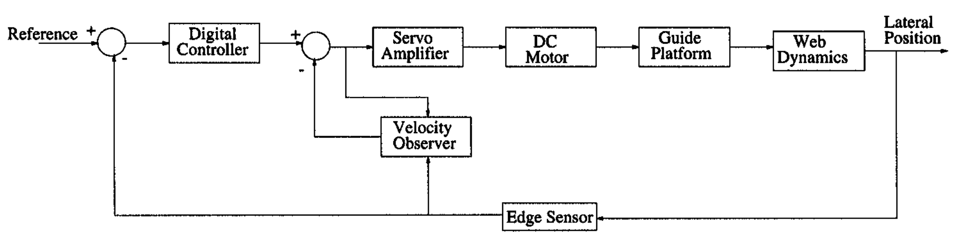


**Figure 4:** Lateral control system using velocity estimation

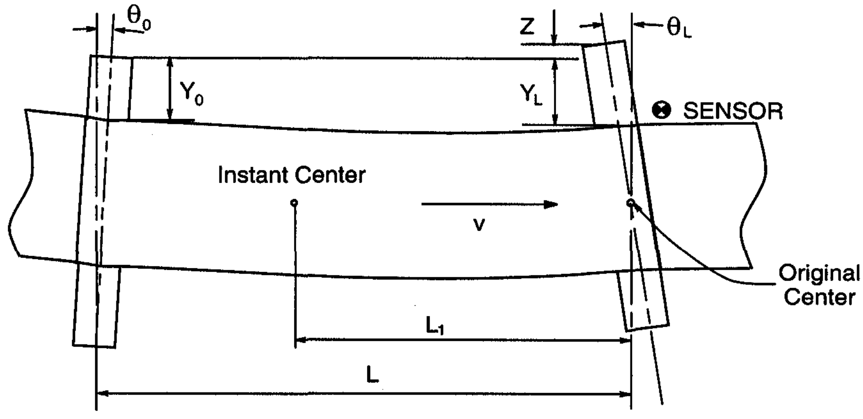


**Figure 5:** Lateral errors and response at steering guide roller

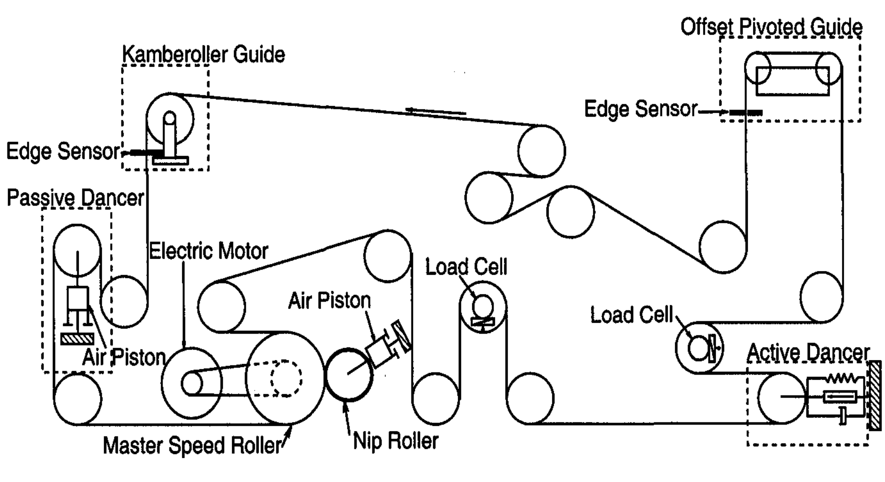


**Figure 6:** Experimental platform

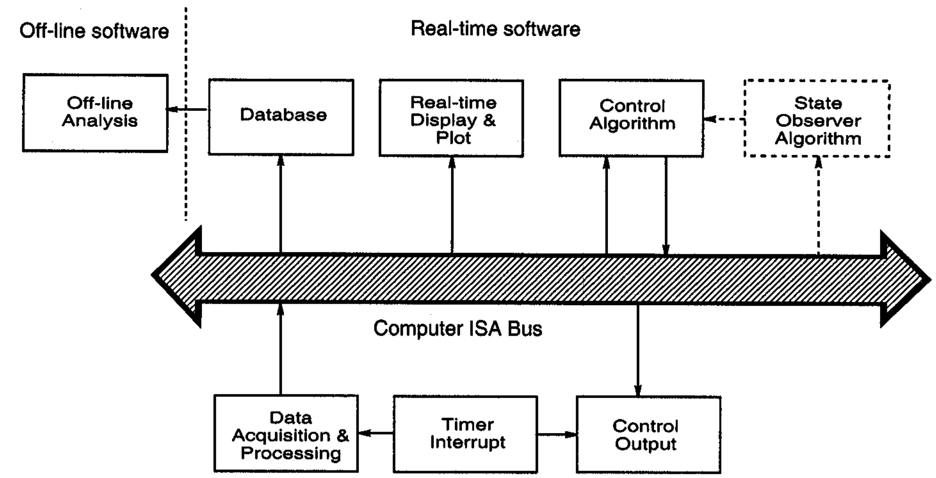


**Figure 7:** Software Structure

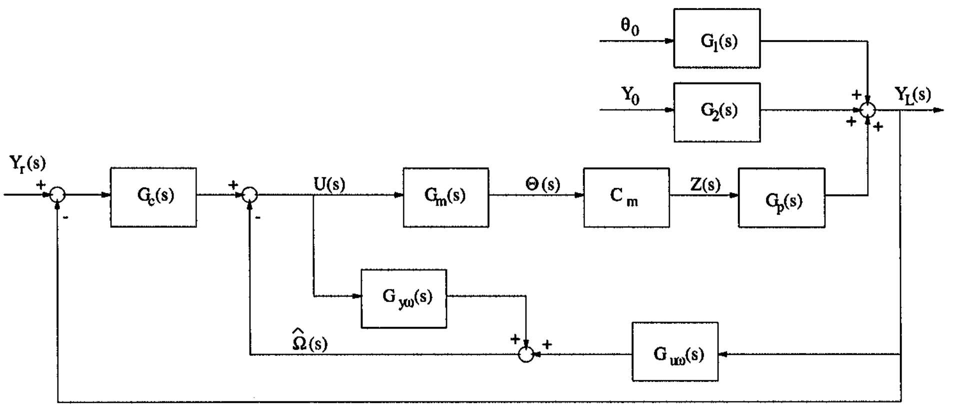


**Figure 8:** Lateral control system with estimated motor velocity feedback

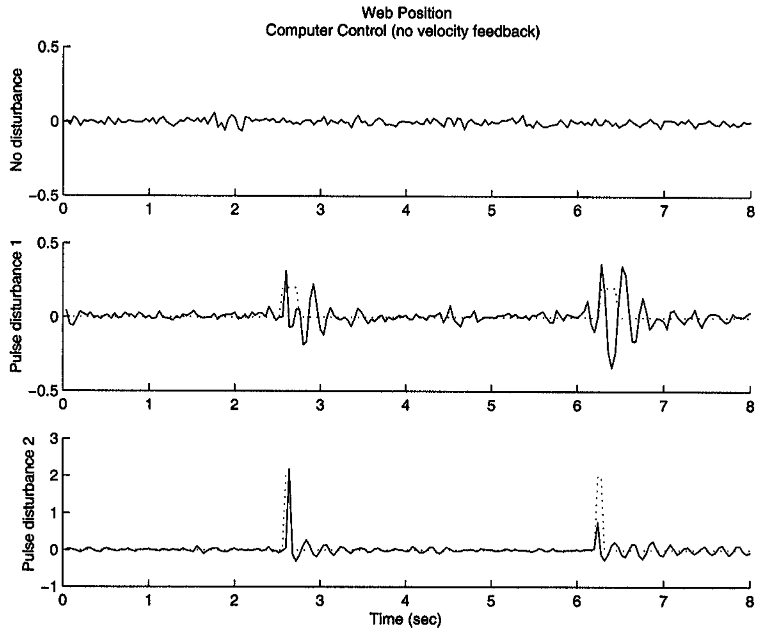


**Figure 9:** Web position: computer control without velocity feedback

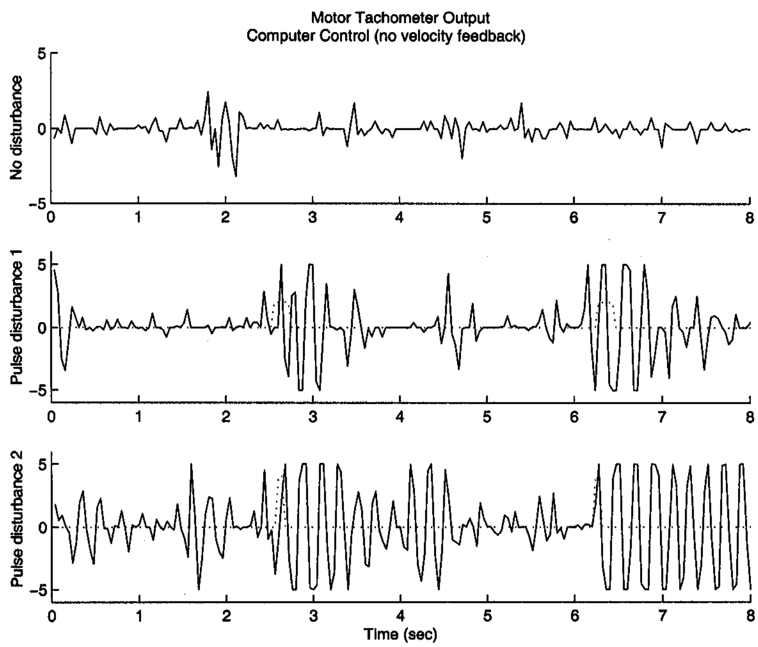


**Figure 10:** Motor velocity: computer control without velocity feedback

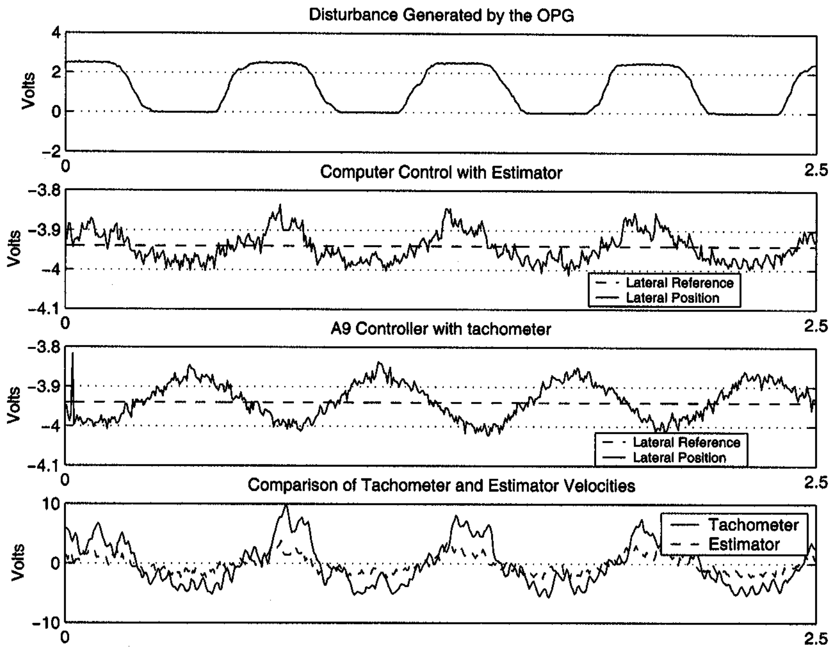


**Figure 11:** Performance of the rigorous Observer

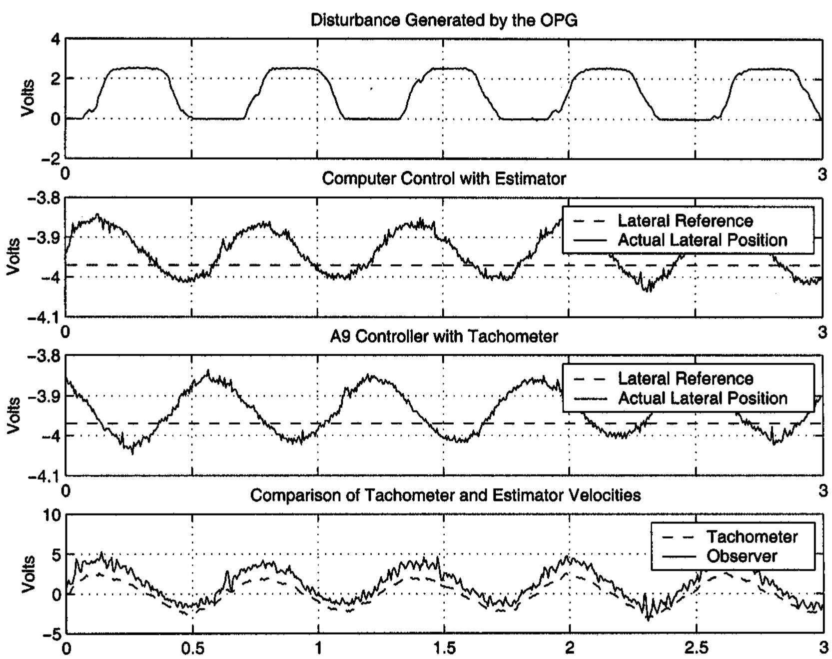


**Figure 12:** Performance of the Simplified Observer

*Lateral Control of a Web using Estimated Velocity Feedback*

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| **Name & Affiliation** | **Question** |
|---|---|
| H. Koc – Siemens | Your real-time system, its running on Windows? |
| **Name & Affiliation** | **Answer** |
| P. Pagilla – OSU | Yes, it is running on Windows98. |
| **Name & Affiliation** | **Question** |
| H. Koc – Siemens | How can you guarantee real-time? |
| **Name & Affiliation** | **Answer** |
| P. Pagilla – OSU | The interrupt is at 5 milliseconds, we ran experiments using a data acquisition board and real-time software running in Windows 98. We also ran this on a DSP board which is dedicated, so we know it is 5 milliseconds, especially with the DSP board. |
| **Name & Affiliation** | **Question** |
| H. Koc – Siemens | Can you guarantee that any other interrupt cannot appear, because it is a multitask system and it is possible that you have a crash of Windows? |
| **Name & Affiliation** | **Answer** |
| P. Pagilla – OSU | In Windows 98 we cannot say for sure it is 5 milliseconds. But on the DSP board we are sure, because it is only one task. |
| **Name & Affiliation** | **Question** |
| H. Koc – Siemens | Do you have an experimental result with pulse disturbance using the velocity feedback? You showed the pulse disturbance without velocity feedback. |
| **Name & Affiliation** | **Answer** |
| P. Pagilla – OSU | We do, they are in S. Mandal's thesis. |
| **Name & Affiliation** | **Question** |
| H. Koc – Siemens | How can you explain effect that your results are better with a simplified observer than with a complex one? |

| Name & Affiliation | Answer |
| --- | --- |
| P. Pagilla – OSU | The computations, probably, the filter, it doesn't do better all the time. But, the computations that we do, we go from continuous time to discrete time. So, when we do a continuous to discrete transform, desired order of estimated transfer function, there is an approximation there. So, whereas for the simplified observer, you go from continuous to discrete, of only a first order transfer function. I mean, that's the only thing that I can think of right now. |
| **Name & Affiliation** | **Question** |
| J. Brown – Essex Systems | Web edges are usually not smooth, they are very ragged and there's often a lot of noise in the edge sensor signal. Have you studied the effects of noise on your estimator? |
| **Name & Affiliation** | **Answer** |
| P. Pagilla – OSU | We have not. Our web edge is pretty good because it is a lab setting. But I think the filter helps. Filtering the signal just before you send it to the observer helps. You filter the high frequency noise due to the ragged edges. |
| **Name & Affiliation** | **Question** |
| P. Werner – Rockwell Automation | The intent here was to get an estimator for the motor speed. Is there any reason you didn't use the motor voltage? I mean, in a DC motor, the motor voltage is as good an estimator of motor speed as you can get. |
| **Name & Affiliation** | **Answer** |
| P. Pagilla – OSU | We could, but we did not. We did not have those measurements. Our assumption was that we have only edge sensor measurements to estimate motor velocity. But, I know, if it is available, we can use that to design an observer. So, we don't need the lateral dynamics part. |
| **Name & Affiliation** | **Question** |
| D. Pfeiffer – JDP Innovations | I just wanted to amplify what Pete said, you can use the motor voltage by correcting it for armature drop due to current by subtracting that out. You know the armature resistance and you can measure the current and take into account the brush voltage drop, so you get a tachometer signal that's better than 1% if you take a little care in doing it. That might be adequate. |
| **Name & Affiliation** | **Answer** |
| P. Pagilla – OSU | Yes, that is possible. We assumed in this work that we do not have any measurements other than measurement of web edge position. |