Adaptive Control of Web Guides

Aravind Seshadri and Prabhakar R. Pagilla

School of Mechanical & Aerospace Engg., Stillwater, OK 74078 USA
(corresponding author email: pagilla@okstate.edu)

Abstract: The focus of this paper is on the design and implementation of an adaptive algorithm for control of two common intermediate web guides used in the roll-to-roll manufacture of webs. Web guides are used to control the lateral position of the web on rollers in RTR processing of flexible materials (webs). We consider the design of a model reference adaptive controller for web guides. The feedback for this adaptive control system is the web edge position. The emphasis is on practical implementation issues such as selection of design parameters and improving the robustness of conventional adaptive control schemes. We consider modifications of the conventional model reference adaptive controller for it to provide improved performance for the web guiding application. We show via extensive experimentation that the designed model reference adaptive controller can provide much improved guiding performance in the presence of material variations and disturbances. We also compare the performance of the adaptive controller with an often used industrial PI control scheme. A representative sample of the experimental results are shown and discussed.

1. INTRODUCTION

Many manufacturing processes such as printing, lamination, coating etc., involve roll-to-roll (RTR) manufacture of thin, flexible materials often known as a “webs.” RTR manufacturing is widely used because it is economical to manufacture and process materials in rolled form when compared to batch manufacturing. A wide variety of consumer products are manufactured from web materials such as paper, plastic, textile and metals by transporting the webs through a series of machinery where the required operations are performed. The web transport is facilitated by a set of driven rollers and the web is supported by a number of idle rollers in between the driven rollers.

As the web is transported over a series of rollers, the moving web experiences fluctuations in all three dimensions. The machine direction fluctuations (change in web speed and tension in the web) are controlled by the driven rollers while the cross-machine direction fluctuations (lateral motion) are controlled using a device called a “web guide.” This paper deals with the design, development and implementation of an adaptive control algorithm for controlling web guides to minimize lateral fluctuations of a moving web. Control algorithms for two commonly used intermediate web guides are developed based on the lateral web dynamics presented in Seshadri and Pagilla [2010].

We consider two common intermediate guides referred to as remotely-pivoted guide (RPG) and the offset-pivot guide (OPG). The remotely-pivoted guide consists of an idle roller whose axis of rotation is changed by a moving platform on which the roller is mounted. The offset-pivot guide consists of two parallel rollers which are mechanically coupled and mounted on a moving platform that changes their axes of rotation. The effect of web guides on the lateral position of the web is based on the following well known fundamental principle: a web approaching a roller will tend to align itself perpendicular to the axis of rotation of the roller. Therefore, a web guide mechanism is constructed such that the motion of its platform, facilitated by using an electro-mechanical or an electro-hydraulic actuator, will change the axis of rotation of the guide roller, thereby manipulating the lateral position of the web. Optical or ultrasonic sensors, usually called as edge sensors or web edge sensors, are used to provide measurement of the lateral position of the web.

Current industrial practice is to use a PI control scheme based on web edge position measurement to control the lateral position of the web. Lateral web control strategies reported in the literature include Proportional, Proportional-Derivative (PD) controllers, observer based estimated velocity feedback control, frequency domain based control and feed-forward controllers based on identified disturbance models (see references in Seshadri and Pagilla [2010]). These are fixed gain controllers which rely on the knowledge of the model parameters. In practice the model parameters are seldom exactly known. Variations in process parameters and variables such as web transport velocity, web material, web tension, etc., could significantly affect the lateral web dynamics. In Seshadri and Pagilla [2010] an optimal web guiding strategy that provided guidelines for proper, guide installation, selection of operating conditions, design of an optimal controller, and sensor selection was reported.

With increasing demand to improve productivity, more and more web processing industries are moving towards faster transport of webs and transport of different types of webs on the same processing line; concurrently, there is a need to reduce material wastage due to wrinkling and other web defects caused by lateral and longitudinal control issues. Especially in web guiding, there is a need for a control strategy that is capable of providing good guiding...
performance with different web materials, transported at various operating conditions, with different types of web guides and sensors. It is desirable to have a control strategy that does not require retuning when operating condition changes and parameter variations are encountered.

In this paper we present an adaptive control scheme for intermediate guides which does not assume the knowledge of the model parameters or process conditions and provides good lateral guiding performance in the presence of disturbances and process conditions changes. The rest of the paper is organized as follows. In Section 2 the dynamic models for two commonly used intermediate guides are presented and a model reference adaptive control scheme for web guiding called the Guide Adaptive Controller (GAC) is developed based on the models presented; modifications and improvements to the model reference adaptive control schemes are also discussed in this section. Experimental results comparing the performance of the GAC and an often used industrial PI controller is presented in Section 3. Experimental results for a simplified (reduced number of estimated parameters) adaptive controller are also shown. Conclusions are given in Section 4.

2. GUIDE ADAPTIVE CONTROL

A model that describes the lateral behavior of the web on rollers as a function of the displacement of the axis of rotation of the guide roller is required for the development of the adaptive control scheme. In Seshadri and Pagilla [2010] a detailed discussion on obtaining the dynamic models for the RPG and the OPG were presented and those same models will be used in the development of the adaptive control scheme in this paper. Unlike the existing control strategies, the GAC strategy does not require exact knowledge of the model parameters but just the structure of the plant as given by the model. It will be later shown that with a simplified, reduced order model with the same relative degree as the full model, the GAC provides comparable performance. In the next few sections, for the sake of brevity, equations are interchangeably expressed both in the time domain and the transform domain.

2.1 Lateral Web Dynamics

For a detailed understanding of the lateral dynamics of web on rollers we refer the readers to Shelton and Reid [1971a,b]. Based on the lateral dynamics of web on two rollers, the dynamics of the web on intermediate guides were derived in Seshadri and Pagilla [2010]. Depending on the application and location of the web guide in a web processing plant, either an OPG (see Fig. 2) or a RPG (see Fig. 1) is used. Under the action of a RPG (or an OPG), the transfer function from the guide roller position \( Z_L \) to the lateral web position \( y_L \) is given by

\[
\frac{y_L}{Z_L} = \frac{s^2 + \beta_2 s + \alpha}{s^2 + \beta_2 s + \beta_0}
\]  

where \( \alpha, \beta_0, \beta_2 \) are model parameters which depend on the properties of the web material, span length, web transport velocity, guide installation, etc. The parameter \( \alpha \) is dependent on the distance from the pivot axis to the guide roller and hence this parameter is different for the two different guides. The guide roller position \( Z_L \) is controlled using an electro-mechanical actuator. Hence the overall transfer function from the actuator voltage input to web lateral position is given by

\[
\frac{y_L}{u_p} = \frac{K_m G_m (s^2 + \beta_2 s + \alpha)}{s(s + \alpha_m)(s^2 + \beta_2 s + \beta_0)}
\]  

Fig. 1. Schematic of a RPG. \( Z_L \): lateral position of the guide roller, \( \theta_L \): angular position of the axis of the guide roller, \( L \): length of the span between the guide roller and the upstream idle roller, \( x_L \): distance from the pivot axis to the guide roller.

Fig. 2. Schematic of an OPG.
2.2 Guide Adaptive Controller (GAC)

As noted earlier the model parameters depend on the process conditions such as web tension, speed, and material. Hence a direct model reference adaptive controller, as given in Ioannou and Sun [1996], with relative degree two is used to control the lateral position of the web.

A reference model with relative degree two is chosen as

\[ \frac{y_m}{r} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \]  

where \( y_m \) is the reference model output and \( r \) is the reference. The control and the adaptive law is given by

**Control Law:**

\[ u_p = \sum_{i=1}^{8} \theta_i \omega_i + \hat{\theta}_i \phi_i \]  

\[ \left[ \omega_1(s) \omega_2(s) \omega_3(s) \right] = \left[ s^2 s 1 \right] G_f(s) u_p \]  

\[ \left[ \omega_4(s) \omega_5(s) \omega_6(s) \right] = \left[ s^2 s 1 \right] G_f(s) y_L \]  

\[ \left[ \omega_7(s) \omega_8(s) \right] = \left[ y_L \ r \right] \]  

\[ \phi_i = \frac{1}{s + p_0} \omega_i \]  

\[ G_f(s) = \frac{1}{(s + a_0)^3} \]  

**Adaptive Law:**

\[ \dot{\theta}_i = -\lambda_1 e_1 \phi_i \]  

where \( \theta_i \)'s are the controller parameters, \( \omega_i \)'s are filtered signals for the adaptive estimator, \( \phi_i \)'s are the regressor signals, \( e_1 = y_L - y_m \), \( \lambda_i > 0 \) are the adaptation gains, \( p_0 > 0 \) and \( a_0 > 0 \) are design parameters.

2.3 Insights for Practical Implementation

To provide stable closed-loop behavior one must impose constraints on the selection of design parameters \( \omega_n, \zeta, p_0, a_0, \lambda_i \). Often the selection of these design parameters becomes a tedious task and some amount of tuning, or adjustment of these parameters, is required to achieve good performance. In this section we present some insights on how the design parameters can be systematically selected for the web guiding application. These insights are a result of extensive experimentation and model analysis.

The filtered regressor signals \( \phi_i \)'s are generated to satisfy the Strictly Positive Real (SPR) condition. The design parameter \( p_0 \) has to be chosen such that \( 0 < p_0 < 2 \zeta \omega_n \) (see Seshadri [2007]). It has been observed in experiments that the selection of large values for \( p_0 \) result in slower adaptation of the controller parameters while small values results in faster adaptation albeit the controller may be sensitive to disturbances; the rate of adaptation refers to the time taken for the controller parameters to settle. In order to choose the parameter \( p_0 \) the reference model parameters have to be chosen. The reference model parameters are chosen based on the required response speed and typically for this application a well damped model (\( \zeta \geq 1 \)) is chosen. The denominator monic polynomial (with degree three) in the filter \( G_f(s) \) of the adaptive observer can be chosen arbitrarily. For a simple design it is chosen as a polynomial with repeating roots located at \(-a_0\). The filter parameter \( a_0 \) is chosen so that the bandwidth of the filter \( G_f(s) \) is more than the bandwidth of the actuator and less than the sensor noise bandwidth.

Some modifications and improvements, that improved the robustness of the controller, are also considered as given below.

**Parameter Bounding:** Note that the adaptive law will continue to update as long as the error \( e_1 \) is non-zero. Hence to ensure that the control does not get unbounded due to disturbances, upper and lower bounds for each of the controller parameters were enforced; these bounds can be calculated analytically using plant models.

**Parameter Freezing:** Typically if the error is small, the estimated controller parameters reach steady-state values in finite amount of time. To reduce the computation burden and to increase the robustness, the controller parameters may be frozen by stopping the adaptation. The adaptation can be resumed from the frozen parameter values as soon as the lateral position error exceeds a predefined limit thereby retaining the adaptive properties of the controller. The decision to freeze controller parameters is based on the adaptation rate and the error; when \( \| \dot{\theta} \| < e_1 \) then all or a selective number of controller parameters may be frozen, where \( e > 0, \nu > 0 \) are small numbers.

**Resetting Parameters:** Instead of bounding the controller parameters to a fixed value, the parameters can be reinitialized/reset to zero when any of the parameters reach a predefined bound. Note that GAC assumes no knowledge of the plant parameters and hence the controller parameter adaptation is always started from zero initial conditions. Hence resetting the controller parameters to zero at any time would still retain the adaptive properties of the controller but would avoid the unnecessary drifting of parameters in the presence of impulsive disturbances that show up in the lateral position measurement which are a result of web splice. Unlike when the controller parameters are bounded, the reset parameters are free to adapt again to the process conditions. From the experiments it was observed that the parameter resetting modification to GAC provided the most robust performance.

3. EXPERIMENTAL RESULTS

The web platform used for conducting the experiments is shown in Fig. 3. The platform has one driven roller and several idle rollers; two intermediate guides are also installed on the platform for lateral position regulation and an active dancer is used to maintain appropriate tension in the web line. Extensive experiments were conducted on the web platform to evaluate the performance of the GAC under various operating conditions with different web materials and with different sensors. The GAC performance was compared with that of an industrial PI controller; the two guides were equipped with two different kinds of sensors: an infrared and an ultrasonic sensor. The sensors and actuators were also connected to a real-time dSPACE hardware.

Experiments to observe the performance of GAC in the presence of process variations were carried out. To simulate process variations, three different web materials with
GAC is capable of adapting to speed change variations and at the same time provide good guiding performance. Fig. 6 shows the performance of GAC with a transparent web. When a transparent web is used the gain of the sensor output changes significantly; it is evident from the plots that the GAC adapts to the process changes, sensor gain changes and provides good guiding performance. In all experiments the controller parameters were initialized to zero and were free to adapt. The initial values for the adaptation gains were obtained from simulations based on a nominal plant model. The gains were later adjusted based on a set of step reference change and pulse disturbance experiments for a specific operating condition with an opaque web. The adaptation gains corresponding to \( \omega_i \)'s which were not the output of the filter \( G_i(s) \), had smaller magnitudes compared to the rest of the controller parameters. Fig. 5 shows the performance of GAC with an opaque web transported at 300 and 500 feet-per-minute (fpm). In Seshadri and Pagilla [2010] it was shown that the change in transport velocity of the web, while keeping other process parameters the same, would change the gain cross-over frequency. Especially, when the web speed is increased the frequency range for which the guide over-steps is increased. The experimental results show that the

1 Small periodic streaks that are predominantly observed in these plots, less predominant in other plots, are sensor measurement disturbances when splices in the web pass the infrared sensor. This sensor measurement disturbance occurs with infrared sensor due to opacity changes at joints where the two ends of the webs are spliced together.

To evaluate the performance of the GAC a set of step reference change experiments were conducted. In all these experiments the controller parameters were initialized to zero and were free to adapt. The initial values for the adaptation gains were obtained from simulations based on a nominal plant model. The gains were later adjusted based on a set of step reference change and pulse disturbance experiments for a specific operating condition with an opaque web. The adaptation gains corresponding to \( \omega_i \)'s which were not the output of the filter \( G_i(s) \), had smaller magnitudes compared to the rest of the controller parameters. Fig. 5 shows the performance of GAC with an opaque web transported at 300 and 500 feet-per-minute (fpm). In Seshadri and Pagilla [2010] it was shown that the change in transport velocity of the web, while keeping other process parameters the same, would change the gain cross-over frequency. Especially, when the web speed is increased the frequency range for which the guide over-steps is increased. The experimental results show that the

Fig. 3. An experimental web platform
different web material properties and opacity were used and the webs were transported at various speeds and with different tension; opacity changes in the web material cause a significant change in slope and span of the sensor output when an infrared sensor is used (see Fig. 4); this can be considered as a change in the high frequency gain of the plant.

Fig. 4. The slope and the range of an infrared sensor changes when the opacity of the web material changes. Hence the gain and bias of the sensor output is different with different web materials.

Fig. 5. GAC performance with step reference change experiments

Fig. 6. GAC performance with step reference change experiments

3.1 Simplified GAC

As described in Seshadri and Pagilla [2010] with proper guide installation and proper choice of guiding parameters, it is possible to achieve neutral steering for the web guide. Motivated by that discussion, the lateral web dynamic model assumed to be a second order model with
relative degree two. A guide adaptive controller with four controller parameters is designed for the simplified model. The same second order reference model is chosen for the simplified GAC and the selection of the design parameters are exactly the same as in the regular GAC. The controller is given by

**Control Law**

\[
\begin{align*}
   u_p^i &= \sum_{i=1}^{4} \theta_i \omega_i^i + \hat{\theta}_i \phi_i \\
   \omega^i &= \frac{1}{s + \alpha_0} u_p^i - \frac{1}{s + \alpha_0} y_L^i \text{ and } r^i \\
   \phi_i &= \frac{1}{s + \omega_i^i}
\end{align*}
\]

**Adaptive Law**

\[\hat{\theta}_i = -\lambda_i e^i \phi_i \] (7)

Figures 7 and 8 show the performance of the four-parameter GAC with opaque and transparent webs. The main purpose for designing different GAC’s based on full-order and simplified models is for ease of implementation in industrial controllers. With lesser number of computations the simplified GAC may be an attractive choice for industrial controllers. Experimental results show that the performance of these different adaptive controllers is similar and the performance increases slightly as the number of parameters increase; practitioners can therefore choose the adaptive controller based on their guiding requirements and computational capabilities.

![Fig. 7. Simplified GAC performance: step reference change experiments](image)

### 3.2 Disturbance Rejection

Apart from adapting to process variations and web material changes, there is a need for the controller to reject disturbances. While transporting the web through the process lines, it is seldom possible to have no lateral disturbances. Typically these disturbances are caused due to misaligned rollers, spliced web, improper web edges, wrinkles in the web, telescoped unwind roll, etc. The disturbance due to misaligned upstream roller and entering span lateral web position misalignment can be modeled as

\[ y_L(s) = \frac{(s^2 + \beta_2 s + \alpha)Z_L(s) + \beta_2 \theta_0 s + (\beta_0 - \beta_3 s) y_0(s)}{s^2 + \beta_2 s + \beta_0} \] (8)

where \( \theta_0 \) is the misaligned upstream roller, \( y_0 \) is the upstream lateral misalignment, \( \beta_1, \beta_2 \) are parameters that depend on the web transport velocity, web material properties, roller installation, etc. Even though a model is available, the disturbance model parameters are unknown. Additionally, the roller misalignment and lateral position misalignment may occur in any of the upstream rollers and hence it may be impractical to try and compensate these disturbances based on the augmented model. It was shown in Narendra and Annaswamy [2005] that over parametrization of the controller parameters would help in attenuation of disturbances and in some cases may result in exact model matching.

Experiments were conducted to evaluate the disturbance rejection characteristics of the GAC. To simulate disturbances, the OPG was used to inject sinusoidal lateral position disturbances and the RPG was used to reject these using the adaptive controller. Also pulse disturbances were generated by attaching a strip of web material of a short length (one foot) along the original web edge. The performance of GAC is also compared with an industrial PI controller. In all the experiments none of the design parameters of the GAC were changed; likewise the gains of the industrial PI controller were not changed once the PI controller was tuned for a specific operating condition.

Plots in Fig. 9 show the performance of the GAC and the industrial PI controller with a sinusoidal disturbance; the disturbances were in the low frequency range where over-steering occurs (see Seshadri and Pagilla [2010]). The top plot shows the magnitude of the sinusoidal disturbance entering the guide roller (observed when the guide roller is not controlled), the middle plot shows the disturbance rejection performance of the PI controller while the bottom plot shows the disturbance rejection performance of the GAC. It is evident that GAC exhibits superior disturbance rejection characteristics. It is evident from Fig. 10 that the controller parameters (bottom plot) and hence the controller output (middle plot) remain bounded even in the presence of bounded disturbances while the adaptive controller provides good guiding performance (top plot).

As expected, significant change in performance between the GAC and the industrial PI controller is observed when a transparent web is used. As discussed earlier, the opacity change results in sensor gain change as well as the output.

![Fig. 8. Simplified GAC performance: step reference change experiments](image)
range of the sensor. Fig. 11 shows the experimental results with a transparent web transported at 300 fpm; top plot shows the disturbance entering the guide roller, the middle plot shows guiding performance with the PI controller and bottom plot shows the performance with the GAC. It is evident that the performance of GAC is unaffected by process variations, material property changes, sensor gain changes and in the presence of disturbances; similar results were observed with OPG. The readers are referred to Seshadri [2007] for these additional results.

4. CONCLUSIONS

An adaptive controller for web guides was presented in this paper. The guide adaptive controller (GAC) exhibited good guiding performance by adapting to process changes, change in operating conditions and also provided good disturbance rejection performance when compared to a fixed gain industrial PI controller. The performance of the industrial PI controller deteriorated with the sensor gain changes and with change in operating conditions. Issues with drifting of the parameters were overcome by using the parameter resetting technique. The improvements and modifications suggested in this paper increased the robustness of the GAC thereby making it suitable for industrial adoption.

REFERENCES