Lateral Position Control of a Moving Web in Roll-to-Roll Processes

Thanhtam Ho, Hyeunhun Shin, and Sangyoon Lee
Department of Mechanical Design and Production Engineering
Konkuk University
Seoul, Korea
thanhtamho82@gmail.com, shinhh28@konkuk.ac.kr, slee@konkuk.ac.kr

***Abstract*—This paper reports the development of a simulation software and a hardware simulator for the lateral position control of a moving web in roll-to-roll (R2R) systems. A mathematical model is described to explain the lateral dynamics of a moving web. Based on the model, a lateral control method using PID controller is designed, and a simulation software is implemented for simulating the lateral dynamics of a moving web and controlling the lateral position error in R2R systems. In addition an experimental apparatus for R2R processes is also developed to verify the control method. Both the simulation software and the hardware simulator are evaluated as useful tools for the development of a web guide system for R2R systems.**

***Keywords*—lateral position control, roll-to-roll(R2R), moving web, PID control**

I. Introduction

Roll-to-roll (R2R) systems employing a moving web made of plastic or metal have been an attractive choice for the mass production. In particular, R2R printing systems in the form of offset or gravure printing have been popularly used in the traditional packaging industry. Recently they are considered as an innovative solution for the printed electronics (also known as e-printing), which is a new field of electronic industry for the mass production of electronic devices by means of printing. A variety of devices including RFID, electronic paper, solar cells, displays, have been tested.

The R2R method has advantages in the printed electronics because it can be highly effective in the cost and also applicable to flexible and thin materials. However, unlike traditional printing processes, the printed electronics requires a much higher accuracy in every process, and so the precision in the lateral position control of a moving web is also a significant condition for the success of R2R printing systems in the printed electronics.

In general web guide systems that are usually composed of an electromagnetic motor and multiple sensors are used to correct the lateral position error of a web in R2R systems. When a web is thin and flexible like plastic and the width is small, the displacement guide system with a short span can be a suitable choice.

This paper reports the development of a simulation software and a hardware simulator for the lateral position control of a moving web in R2R systems. The software named LACOSIM is for the simulation and control of the lateral position of a moving web in R2R processes. It employs the mathematical model and control work in a graphical environment, and also it unifies the simulation and control of the lateral position of a web in a unique interface. In order to implement lateral control methods, mathematical models need to be set first to describe the lateral dynamics of a moving web. Shelton's model [1-3] is employed in this work because it can be more suitable for modeling a real web.

In addition to the software system, a hardware web simulator employing two displacement guide systems is designed and built for verifying simulation results and for determining specific conditions of web-guiding. The simulator is composed of one DC motor, nine rollers including the drive roller and the tension roller, and two load cells.

II. Mathematical Model

In order to build a control system of the lateral position, we introduce mathematical model that describe the dynamics of a moving web. Shelton's first order model [1, 2] presents the relation of the lateral velocity to the longitudinal velocity, the guide dynamics, and the input error that occurs at the previous roll in a single span guide.

Shelton's first order model is a simplified one based on the fundamental law of static steering. That is, the web in the entering span aligns itself perpendicularly to the roller. The model is built under the assumption that the mass and the lateral stiffness of the web are negligible. Accordingly the web is straight in each span and also it makes sharp angular breaks as it leaves each roller in a series of non-parallel rollers [1].

Fig. 1 shows the idealized web behaviour with an input error. The lateral displacement and the lateral velocity are expressed in (1) and (2), respectively where l is the distance between two rollers, V is the line speed, θ_r is the angle between the roller and y axis, and θ_L is the web angle measured with respect to the x axis [2].

$$\Delta y = l(\theta_L - \theta_r) \quad (1)$$

$$v_L = V(\theta_L - \theta_r) \quad (2)$$

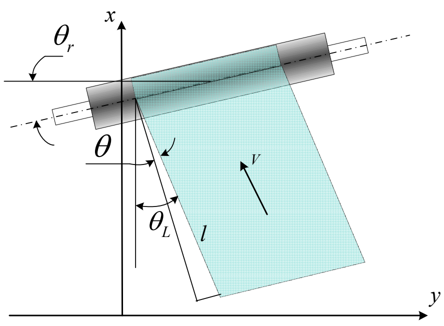


Figure 1. Behavior of an idealized web.

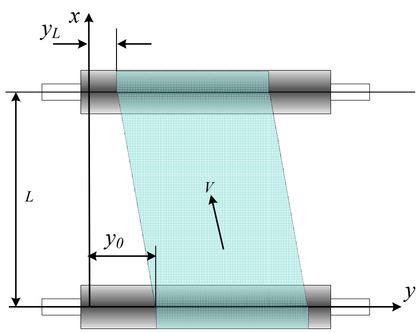


Figure 2. Model of fixed parallel guides.

If the roller moves laterally and has a position z, the movement should be included in the velocity of web edge. As a result the first order equation of lateral velocity is obtained in

$$\frac{dy}{dt} = V(\theta_L - \theta_r) + \frac{dz}{dt}. \tag{3}$$

There is a specific case is where two rollers are parallel and fixed as shown in Fig. 2. Since there is no roller movement component, the following equation is obtained by taking the Laplace transform with zero condition:

$$sY_L(s) = -\frac{V}{L}Y_L(s) + \frac{V}{L}Y_0(s). \tag{4}$$

If we let $\tau = L/V$ be the time constant, the result is

$$\frac{Y_L(s)}{Y_0(s)} = \frac{1}{\tau s + 1}. \tag{5}$$

III. SIMULATION SOFTWARE LACOSIM

Simulink of Matlab provides a large advantage in the simulation work due to numerous built-in functions and toolbox. However, this software lacks visualization ability in the simulation and is not easy to be connected to hardware systems. Several motion simulation softwares such as ADAMS, Nastran (MSC software corporation) or Recurdyn (FunctionBay, Inc.) can be useful for kinematics and dynamics analysis, but simulation work is usually more complicated and computationally expensive. In addition, the dynamics of a moving web is relatively complex, and the simulation model for R2R system is rarely found in motion simulation softwares.

Our software named LACOSIM (Lateral motion and Control Simulation) has several useful features: first it allows one to implement the dynamics of a moving web and the mathematical model of a DC motor; second several control algorithms such as PID and fuzzy methods can be applied in the software to control a virtual web guide system in R2R systems; third LACOSIM itself can also function as a control software for a real web guide system. Fig. 3 shows the model of web guide system in LACOSIM.

LACOSIM is constructed using C++ programming language with the graphic library OpenGL. The software interface has components including the main view, graph windows, control bars and dialog systems, as shown in Fig. 4. The main view window contains the 3D model of web guide system. The user interface system of LACOSIM allows users to set and change the parameters of guide system, web properties, and controller gains. The simulation results are shown in graph windows, and can be saved to files.

All the ordinary differential equations (ODE) in LACOSIM can be solved by the fourth order Runge-Kutta numerical method (RK4) [3, 4]. RK4 method is known to be very accurate and well-behaved for a wide range of problems. Since all the ODEs of mathematical models in the web simulator system are of higher order, RK4 could not be applied directly.

Therefore the mathematical models were converted to state variable forms and KR4 method was implemented. The results from solving ODE of mathematical models combined with the output of the controllers become the motions of guide and web in 3D graphics environments. As a result, both real motion and response graph can be observed.

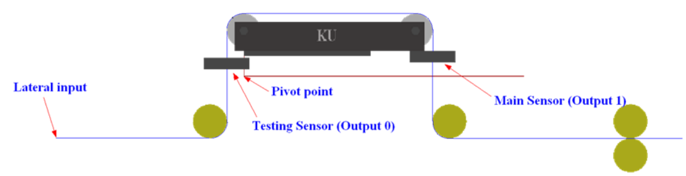


Figure 3. Web guide model in LACOSIM

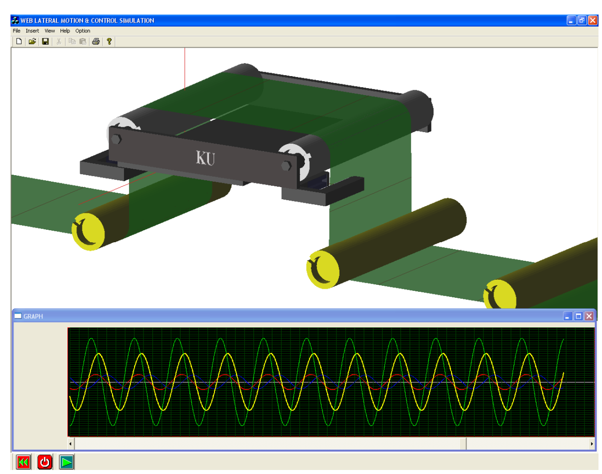


Figure 4. User interface of LACOSIM

IV. LATERAL POSITION CONTROL

A. PID Controller

This section describes the design of a PID controller for the web guide system and simulation results using LACOSIM. Fig. 5 illustrates the web simulator model, which is used for our lateral position control. The web simulator system includes two displacement guides (DG1 and DG2) in which DG2 is the main guide that corrects the lateral position error as the web runs, while DG1 serves as a disturbance generation source to generate sine or step input errors [5].

Fig. 6 shows the block diagram of the lateral control system where the guide system is the combination of a DC motor model, a guidance platform and web dynamics model. Fig. 6 also displays the block diagram of lateral disturbance generation and transfer process. The lateral disturbance generated by DG1 is transferred to the downstream roller of guide DG2 through four free web spans, and the configuration of this span is considered similar to the fixed parallel rollers configuration.

In the guide system, the mathematical model of motor is

$$G_m(s) = \frac{\theta(s)}{U(s)} = \frac{K/LJ}{s\left(s^2 + \left(\frac{b}{J} + \frac{R}{L}\right)s + \frac{Rb + K^2}{LJ}\right)} \tag{6}$$

where K, R, L, b and J are parameters of motor and mechanical system, U is the input voltage, and θ denotes the motor angular position.

The mathematical model for the displacement guide is

$$G_G(s) = \frac{Y_L(s)}{Z(s)} = \frac{\tau^2(L_2/L_P)s^2 + (1+L_2/L_P)\tau s + L_2/L_P}{\tau^2(L_2/L_P)s^2 + (1+L_2/L_P)\tau s + 1}, \tau = \frac{L_2}{V}. \tag{7}$$

Here L_2 is the length of displacement guide DG2, L_P is the distance from the guide roller to its instant centre, and z is the lateral motion of the downstream roller. In the guide DG2, z is proportional to the angular position of motor by constant C_m.

$$Z(s) = C_m \theta(s) \tag{8}$$

In the web simulator model in Fig. 5, three sensors are set at S, T, and O immediately after the exit of each guide. The sensors can be ultrasonic or infrared edge detector sensor (EDS). The sensor EDS1 at S measures the output from the guide DG1 and also gives the value of lateral position error at the point, while the sensor EDS2 determines the lateral position error at T. The sensor EDS3 is used for the feedback controller, i.e. the output value of this sensor is the lateral position error at the controlled position, O. The EDS3 signal is fed back to the controller. The lateral control acts on the guide DG2 to keep the lateral position at the controlled point with any lateral disturbance input.

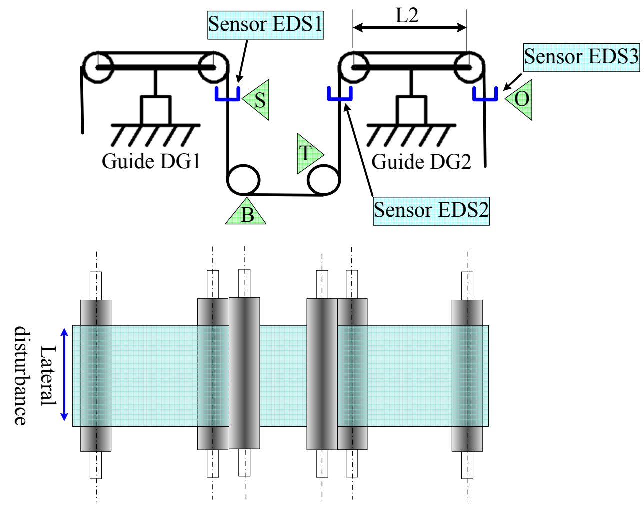


Figure 5. Web simulator model.

B. Simulation Results

Numerous simulations were conducted with the web simulator model and PID controller. In the simulation using LACOSIM, there is only one guide, that is, the guide DG1 in Fig. 5 is removed from the point B and the disturbance is generated directly at B.

The operating tension is set 3 kg and the line speed is 2 m/sec [4]. The parameters of the motor model are from DC brush motor ID23007 of MCG motion control group. The detailed information for simulation is presented in Table I.

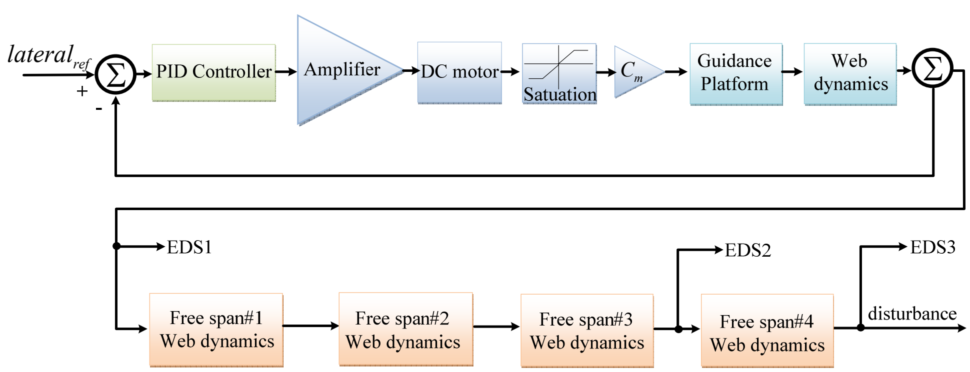


Figure 6. PID control and lateral disturbance generation system.

In the simulation work, the P, I and D gains of PID controller are set 98, 21 and 15, respectively. Simulation results show that the controller performs well with several kinds of input disturbance. Fig. 9 shows the response of system to the step or pulse input and Fig. 10 displays the result of sine signal. The lateral position error at the downstream roller is about 5% of the input disturbance at the previous roll.

However, when the lateral disturbance is applied directly at the point B, the lateral error becomes a little larger because the point B is near the position O where we want to reject the lateral error. In a real web transport system, a web guide system should be set up immediately before an important process begins. The results verify that the controller performs well enough to reject the lateral disturbance in R2R systems.

TABLE I. SIMULATION CONDITIONS

Parameter	Symbol	Value
Length span on guide	L_1, L_2	0.380 m
Distance from roller to centre point	L_p	0.380 m
Operating tension	T	3 kg
Web line speed	V	2 m/s
Web material		PET
Frequency of sine lateral disturbance source	f	0.1 Hz
Amplitude of sine lateral disturbance source	A	0.02 m
P gain of PID controller	P	98
I gain of PID controller	I	21
D gain of PID controller	D	15

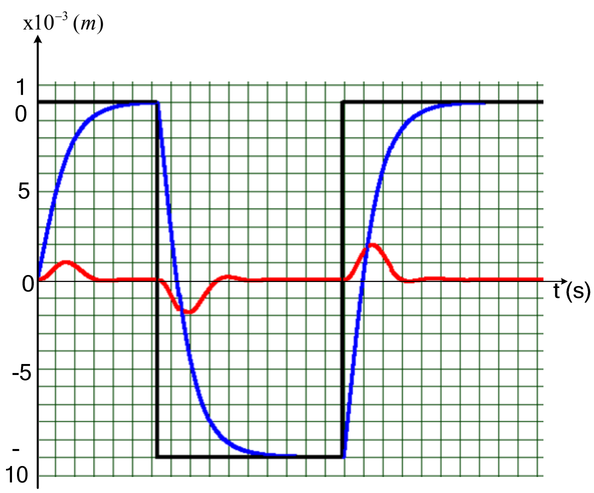


Figure 7. Response to step input

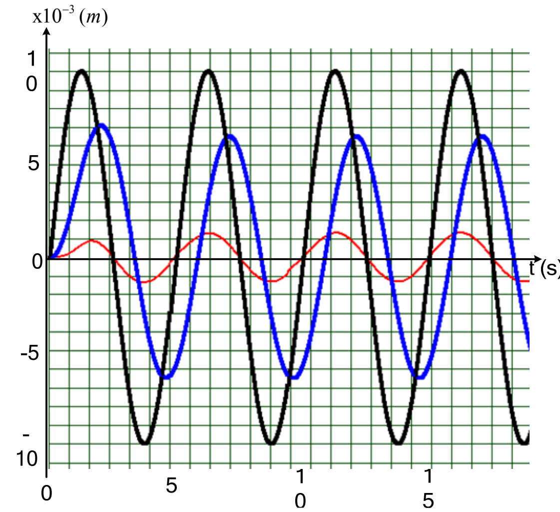


Figure 8. Response to sine input

V. HARDWARE SIMULATOR AND EXPERIMENTS

In addition to the simulation software, we designed and built an R2R web simulator to verify the simulation results. As shown in Fig. 9, the web simulator is composed of one DC motor, nine rollers including the drive roller and the tension roller, two load cells, and two displacement guiders.

The drive roller speed is controlled by the DC motor and the digital RPM controller. The linear velocity of the web is adjustable up to 100 m/min. The tension is measured by the load cell and is indicated by the indicator panel. A compact design of the R2R web simulator was obtained by employing the structure of an infinite loop of web motion instead of separate components for unwinding and winding.

Although the front guider is designed to generate a lateral position error, the controller is not completed at the time of submission of the paper. Therefore a static position error was made by deforming the web at a certain region (see Fig. 10). When the region of the web passes the infrared sensor that is installed in front of the rear guider, a lateral position error is supposed to be detected. Fig. 11 shows the arrangement of two infrared sensors. The front sensor is for detecting a position error of the web, while the rear one checks if the error is corrected.

The PID controller is embedded in the rear guider system such that the rear one corrects a lateral position error. Several experiments were done to check the performance of controller for removing a lateral position error. Fig. 12 shows the experimental results for the tension of 2 kgf and two line speeds of 0.25 m/sec and 0.5 m/sec. Similar results were obtained for 1 kgf tension. Because the experiments are designed for the verification of lateral control of a moving web, the tension is not changed but kept constant.

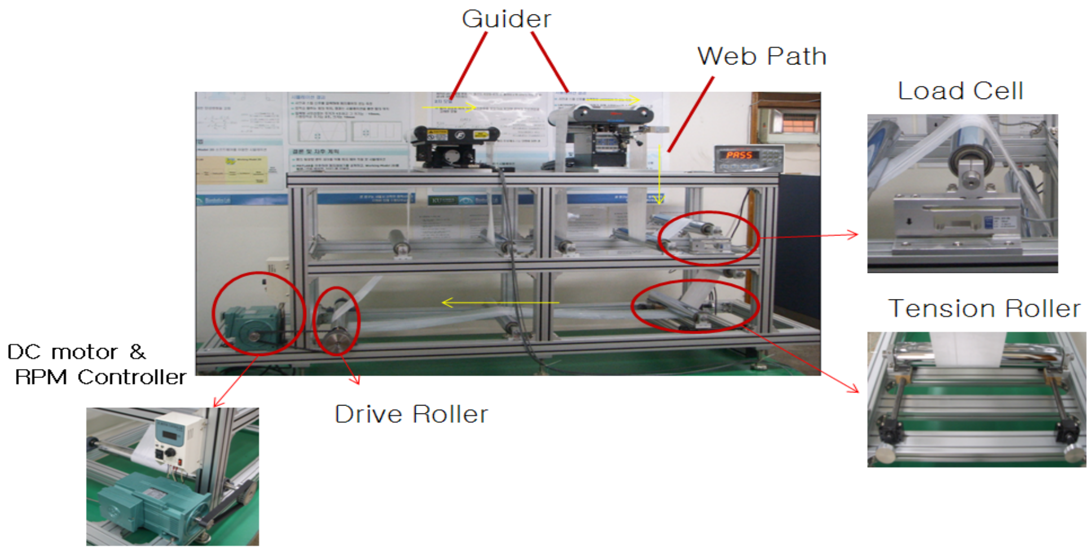


Figure 9. Web simulator for web guiding test

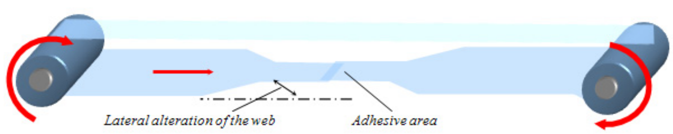


Figure 10. Sketch of the web with the width variance at a certain region

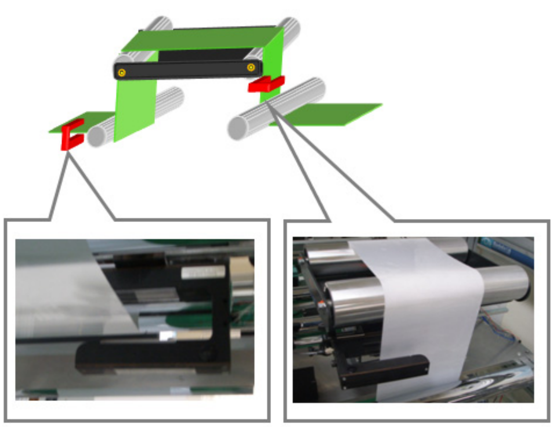
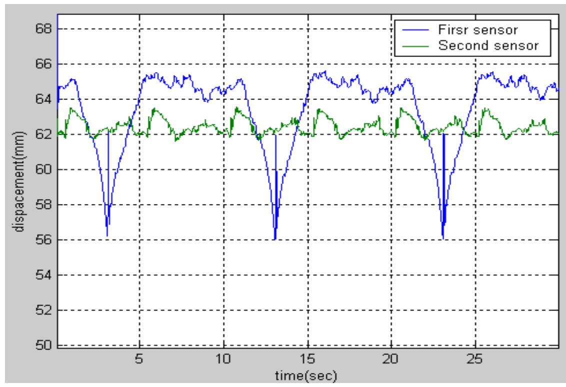
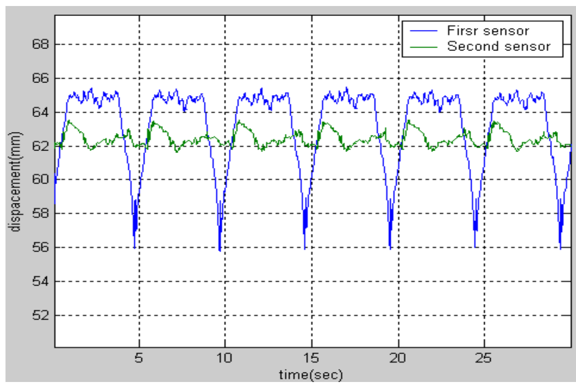


Figure 11. Infrared sensors installed in the R2R web simulator



(a) At the velocity of 0.25 m/sec



(b) At the velocity of 0.5 m/sec

Figure 12. Experimental results for different velocities (Tension = 2 kgf)

VI. CONCLUSIONS

We reported the development of both a simulation software and a hardware simulator for the lateral control of a moving web in R2R systems. The LACOSIM software is designed to provide users with a unified environment where they work with the dynamics of a moving web and web guider system, a control method, and a visualization interface. The web simulator has the structure of R2R process by employing nine rollers and two displacement guiders.

We designed a PID controller for the lateral position control, and tested in the simulation software. The control algorithm was also tested as an embedded controller of the R2R simulator. Both tests verified that the algorithm worked properly and LACOSIM and the web simulator are useful tools for developing a lateral control algorithm.

Both the simulation software and the web simulator are considered as an important step toward building a web guide system in R2R process. In particular, since R2R methodology can be an ideal solution to the mass production of electronic devices and the new application requires a higher accuracy in the control, our software and simulator can be even more useful. However some aspects still need to be improved. We first consider a fuzzy control approach to reduce the overshoot in the response.

ACKNOWLEDGMENT

This work was supported by Seoul R&BD Program and LAB 07-1-254.

REFERENCES

[1] J. J. Shelton, Lateral Dynamics of a Moving Web, Ph.D dissertation, Oklahoma State University, 1968.

[2] J. J. Shelton and K. N. Reid, “Lateral Dynamics of an Idealized Moving Web,” Trans. ASME J. Dyn. Syst. Meas. Control, ser G, no. 3, pp. 187-192, 1971.

[3] R. L. Johnston, Numerical Methods: A Software Approach, John Wiley, 1982.

[4] S. Salleh, A. Y. Zomaya, S. Olariu, B. Sanugi, Numerical Simulations and Case Studies Using Visual C++, John Wiley, 2005.

[5] K. H. Shin, S. O. Kwon, S. H. Song, “Feedforward Control of the Lateral Position of a Moving Web Using System Identification,” IEEE Transactions of Industry Application, vol. 40, pp. 1637-1643, 2004.

[6] R. C. Dorf and R. H. Bishop, Modern Control System, Prentice Hall, 2000.