Controlling Web Position with an End-Pivoted Guide

by

Jerry Brown

NormalEntry.com

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Introduction

- This began when I found a 1967 Fife memo by John Shelton on the subject of “End-Pivoted or Center-Pivoted Steering Rollers”.
- In it, John explains a way to make this kind of guide work.
- While reading it, 46 years later, it occurred to me that explaining the problems of end-pivoted guides would be a good way to explain some of the mysteries of lateral behavior.

The worst guide of all

- Deliberately misaligning a roller is the easiest way to adjust the lateral position of a web.
- That's why it's common to see a roller with a screw adjustment on one end and a spherical bearing on the other.
- For a web that requires an occasional lateral tweak, this works well.
- Why, then, shouldn't it be possible to automate such a roller by simply adding a sensor, controller and actuator?
- That is the question that I will try to answer in the following slides.

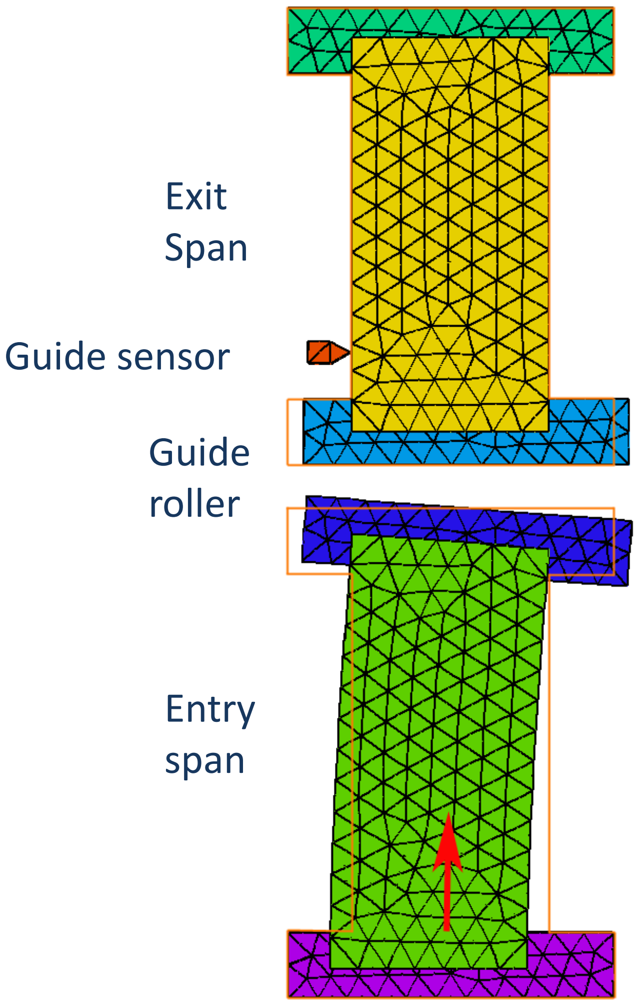
A little history

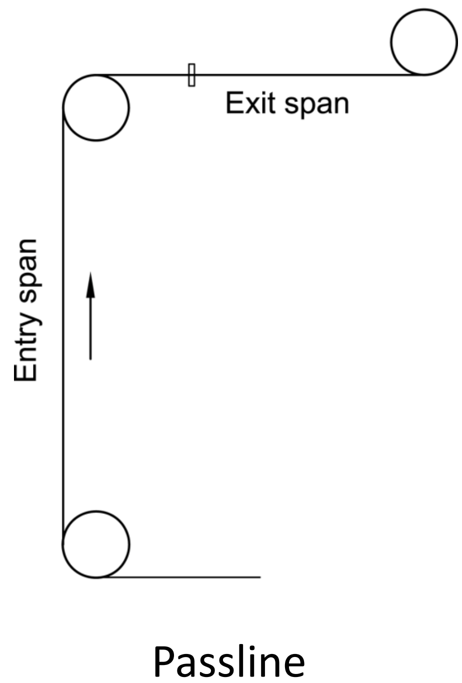
- Webs don’t bend like strings. They bend like beams.
- The first beam model was developed by John Shelton in his 1968 PhD dissertation.
- He showed that webs follow a curved path in moving from one roller to the next.
- The real payoff is in a chapter titled “Second Order Dynamics of a Massless Web.
- There, John combined the curvature information with other physics to develop equations that define the lateral motion of a web in response to changes such as upstream web position, roller angle and roller position.

- John’s work broke new ground and contributed greatly to establishing web handling as a respected field of engineering.
- Remarkable as it was, though, its potential for better lateral control systems wasn’t realized.
- Control theory was up to the job, but the web equations involved lengthy expressions, full of hyperbolic sines and cosines. These required powerful computers that were far too expensive for online guiding systems
- That has obviously changed and since the ’90s, papers describing controllers based on John’s work, and those who followed him, have appeared with growing frequency.

Avoiding equations

- The objective of this paper is to provide an intuitive grasp of lateral behavior, so I've avoided the equations of web dynamics by creating animated illustrations which are driven by them.
- The model includes two spans as well as a web guide controller.
- On the next slide is a snapshot of the endpoint of a typical animation.





Snapshot of animation showing entry and exit spans of a steering guide.

The guide roller is shown twice, once for the entry span and once for the exit span.

Since the guide roller pivots only in the entry span, none of its angular motion is visible in the exit span view.

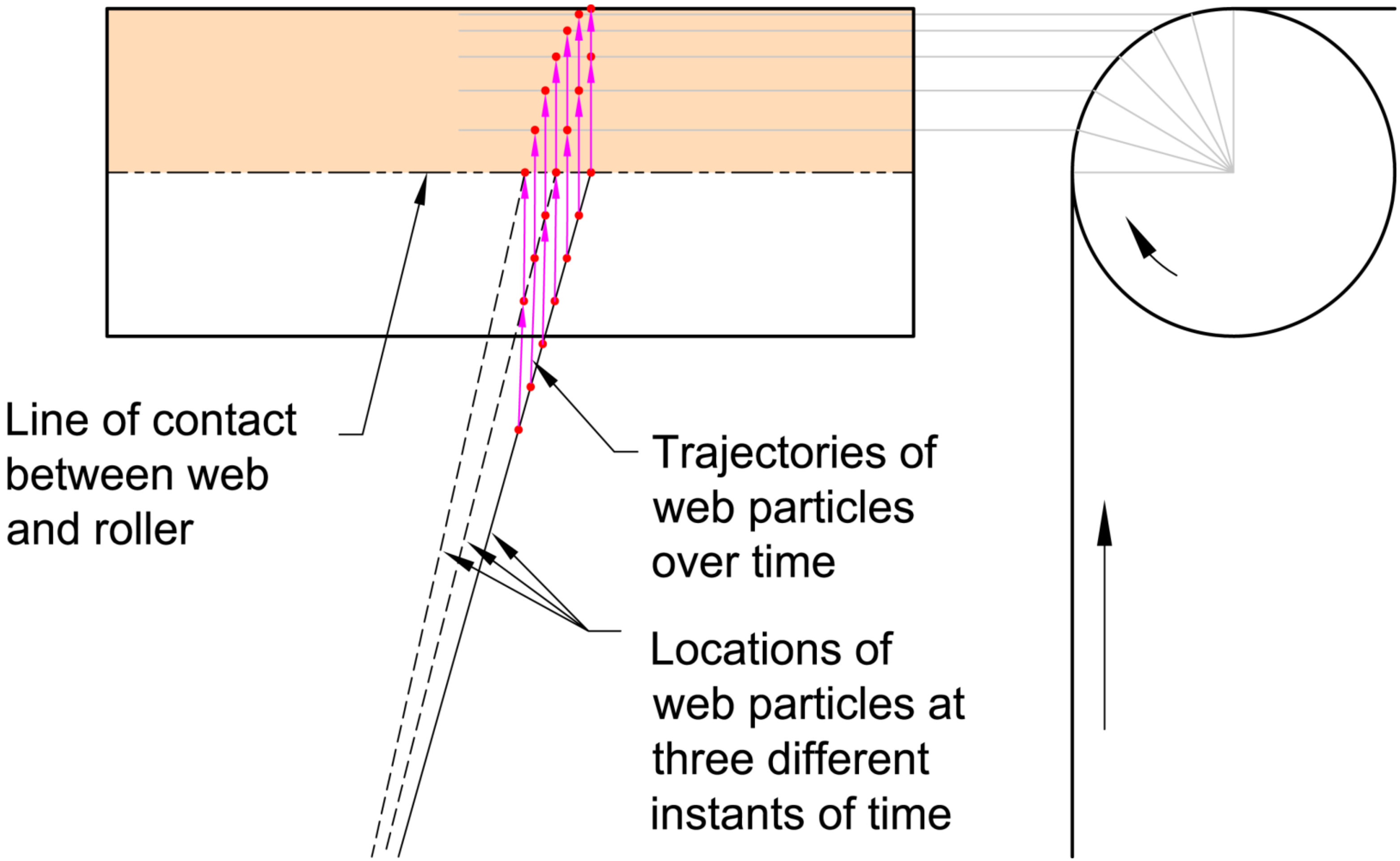
An orange outline of the original position makes it easier to follow the changes in position.

- To make the lateral behavior easier to see, most of the model inputs are much larger than real world limits such as roller traction would permit.
- Time won’t permit a detailed discussion of these limits. That would require several more papers.
- The model parameters for the spans were taken from the first test case shown on page 45 of Shelton’s dissertation.

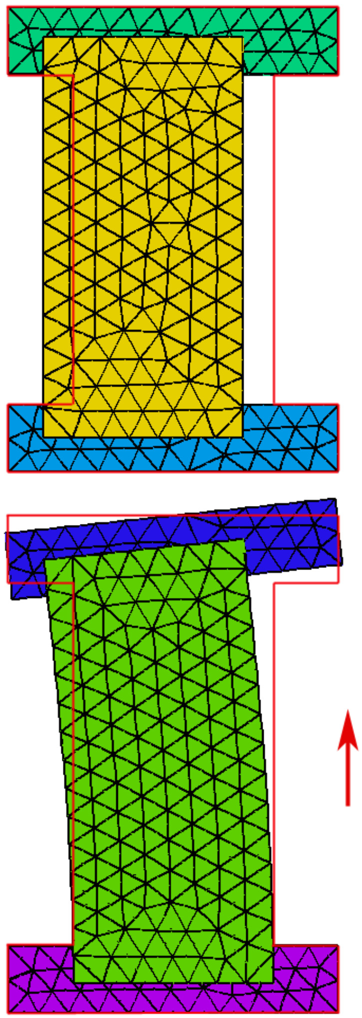
Length (entry span) = 19.5 inches	Tension = 36.7 Lbf
Length (exit span) = 18 inches	Thickness = 0.009 inch
Width = 9.03 inches	Modulus = 450,000 psi
	Line speed = 500 ft/min

Normal Entry

- The most important concept in lateral behavior is the normal entry rule.
- It says that given adequate traction, a web will always move laterally at the entry to a roller so as to align itself perpendicular to the roller axis.
- Normal is just another word for perpendicular.
- The illustration on the next page shows the web as a flexible string.
- The fact that the web has stiffness and must bend, changes the details of the motion but the basic principle is still the same.


Line of contact between web and roller
Trajectories of web particles over time
Locations of web particles at three different instants of time

- As particles of the string approach the line of entry onto the roller, their direction of motion becomes parallel to the motion of the roller surface, so that each successive particle arrives at the point of entry a little to the side (left in this case) of the one before it.
- Eventually, the string path becomes perpendicular to the roller axis, at which point, each particle entering the roller will follow the same path as the one preceding it. The lateral speed at which the web path moves toward the normal position is approximately proportional to the entry angle.
- It's interesting to note that the web particles themselves do not move laterally. It is the point of contact with the line of entry that moves. However it looks and acts like ordinary lateral motion and for purposes of this discussion, nothing is lost by calling it that.



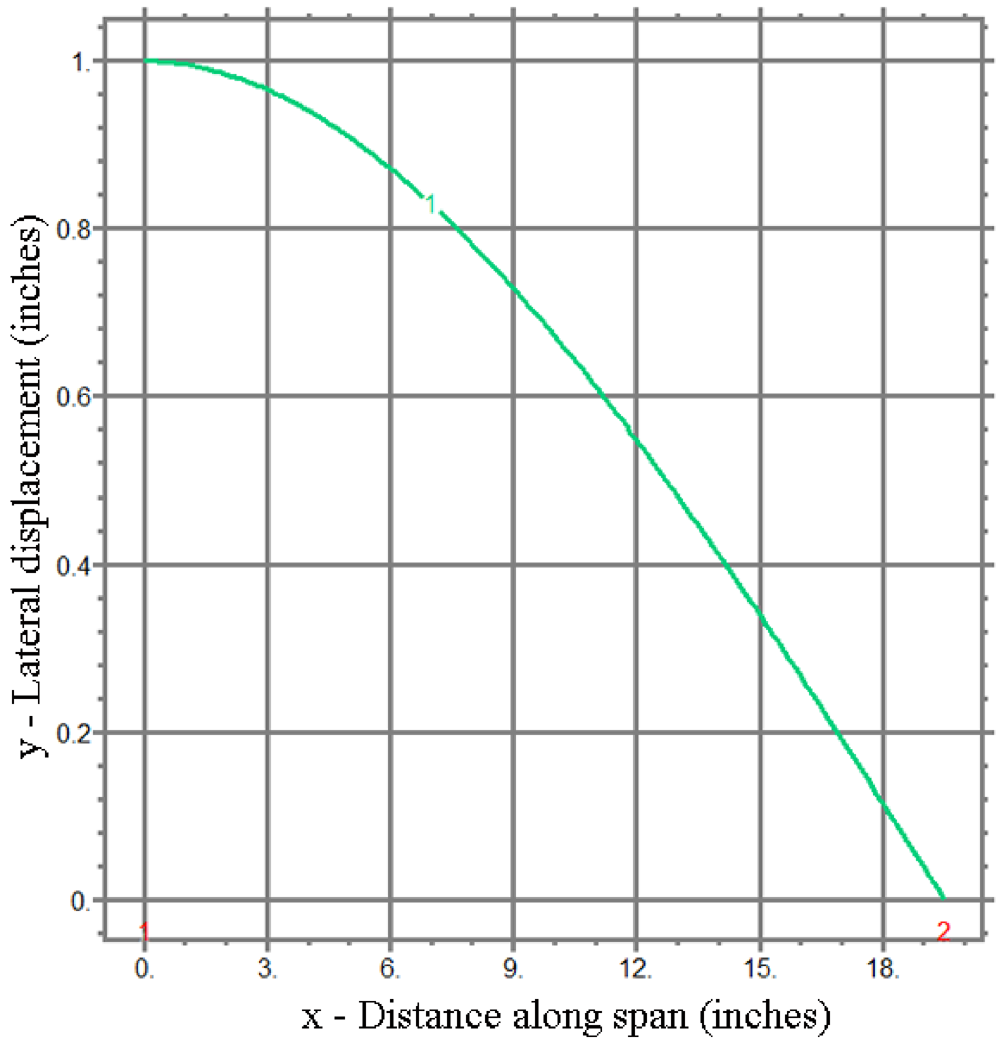
In this animation the roller between the two spans is quickly pivoted 6 degrees.

Then, both webs move to the left until normal entry is achieved.

- The normal entry rule is sometimes called the parallel entry rule, referring the web direction to the surface velocity of the roller instead of its axis.
- However, normal entry has historical precedence and wider use.
- There is no normal entry behavior at the exit of a roller.

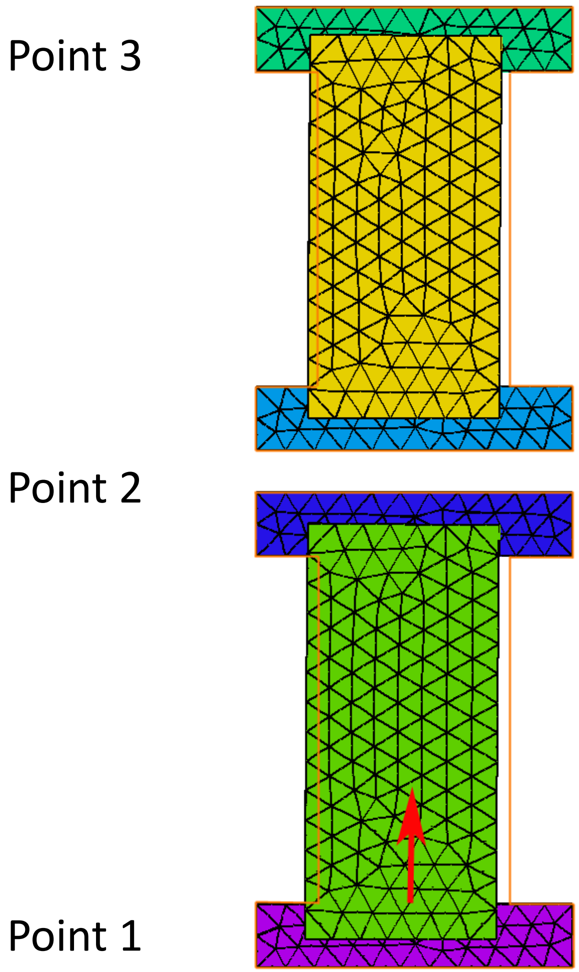
Web curvature

- If a roller is misaligned, forcing the web to move laterally, it has to bend to make the adjustment.
- When running in a steady state, all the curvature is near the upstream roller.
- When the web is changing position (for example, because of a telescoped unwind roll) the shape becomes more complicated and can be curved at both ends of a span.


1.
0.8
0.6
0.4
0.2
0.
y - Lateral displacement (inches)
0.
3.
6.
9.
12.
15.
18.
x - Distance along span (inches)
1
1
2

Time lag caused by rollers

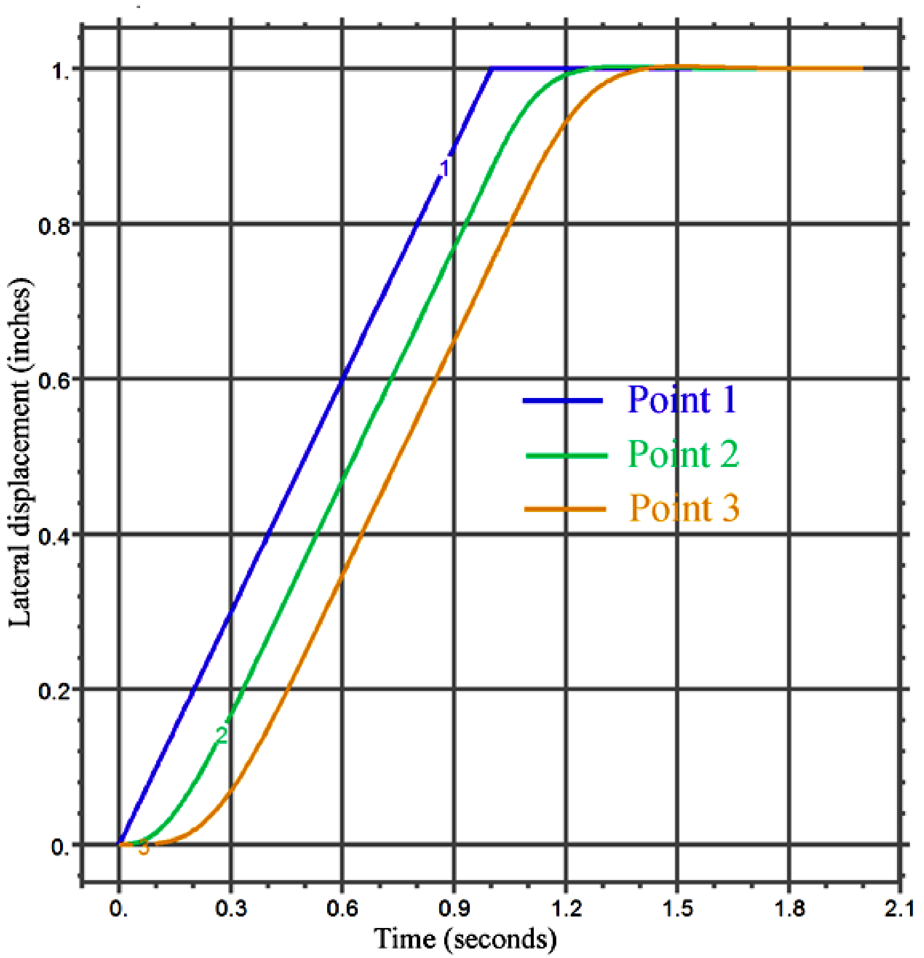
- When the lateral motion at a fixed roller is controlled by the normal entry rule, a lateral disturbance experiences a time lag as it moves past.
- The lag is proportional to L/V, where L is the span length and V is the web speed.
- L/V is called the first order time constant, τ.
- In the next slide we will see the effect of a sudden shift in roller position.



In this simulation all the rollers remain parallel as the web shifts to the left at roller 1.

As the web angle at roller 2 changes, the normal entry rule causes the web to start shifting there as well.

The same thing happens at roller 3.



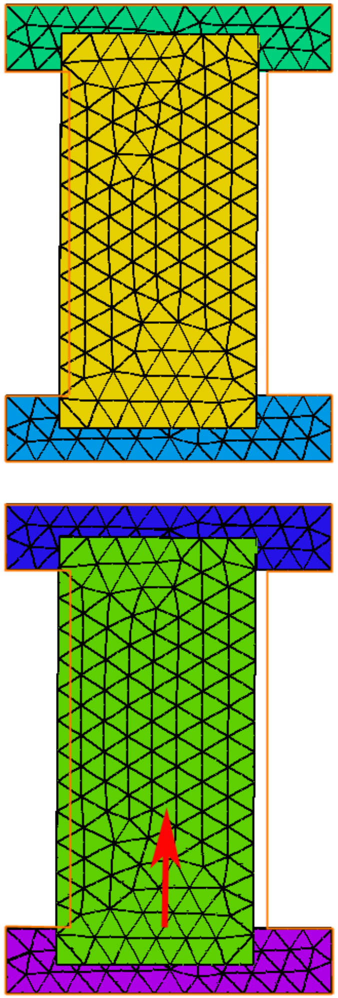
1.
0.8
0.6
0.4
0.2
0.
Lateral displacement (inches)
0.
0.3
0.6
0.9
1.2
1.5
1.8
2.1
Time (seconds)
Point 1
Point 2
Point 3
1
2
3

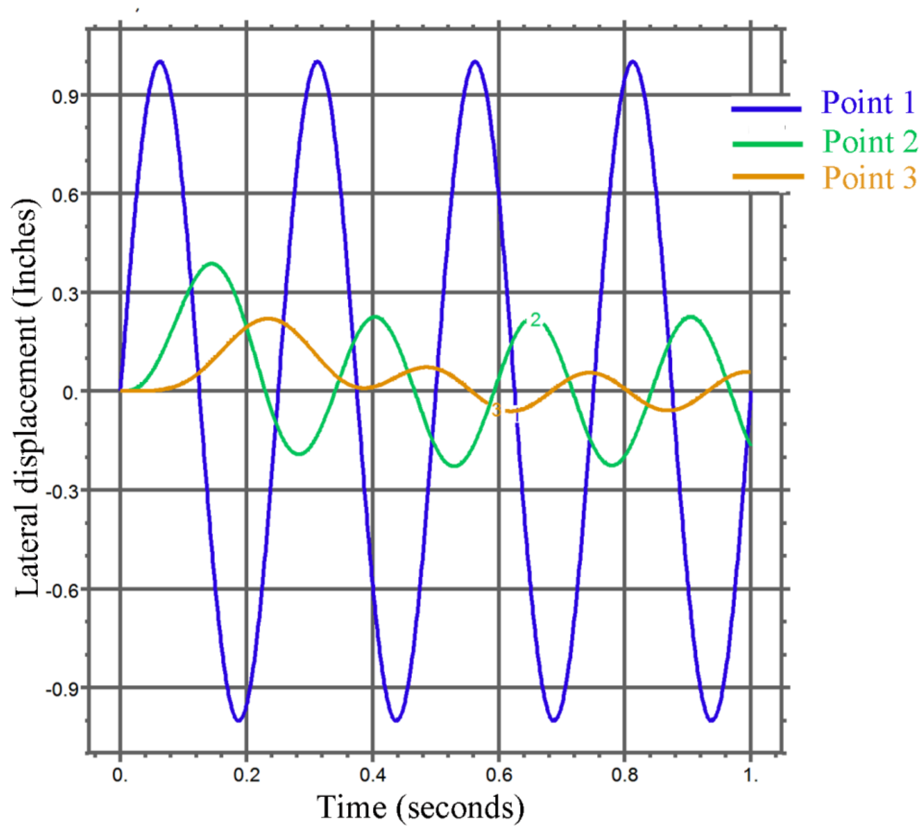
- It’s important to bear in mind that the time lag seen in the previous graph isn’t simply due to transport delay.
- L, the span length, and V, the line speed, enter in to the dynamics because of the time it takes the web to travel laterally on a roller as it responds to the normal entry effect.
- If a disturbance is cyclical it will be attenuated as it passes over an idler because the downstream displacement can’t fully react to the upstream change before the direction of the input motion reverses.
- This is shown graphically in the next slide.

Point 3

Point 2

Point 1





So, rollers are low pass filters that attenuate and phase shift periodic disturbances as they progress through a process line.

Controllers

- Customers expect guiding systems to be adjusted once and then forgotten. This makes things tough for vendors because:
  - The behavior of the web degrades system stability
    - For example, putting a single roller between the guide roller and its sensor will add enough time lag to completely destabilize a system.
  - Structural vibration can be misinterpreted by a guiding system as web position error. Inertial reactions to the guide's response can then reinforce the vibration, causing it to build up to unacceptable levels.
  - Systems are limited by the amount of distortion the web can tolerate.

- In the early years of web guiding, suppliers used a type of controller that provided a reasonably safe compromise between simplicity, speed and accuracy. It is called a rank 1 controller.
- For guiding, a rank 1 controller takes the form of one in which the output is velocity (position in velocity out). It becomes a position control system only when the loop is closed between the guide sensor and the input of the controller.
- Many of the systems in your plants are this type.

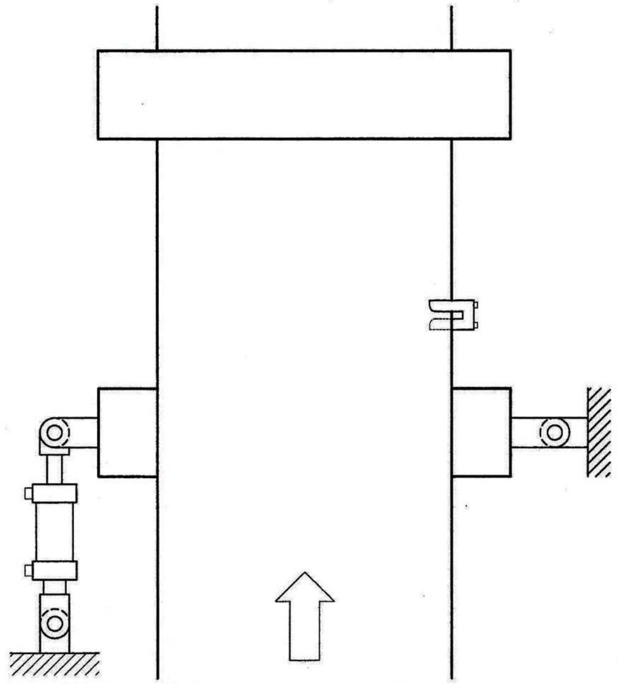
- A typical system might have a loop gain of 30 inches/sec per inch of error. This means it would take 0.067 inches of error at the sensor to produce 2 inches per second at the actuator.
- The actuator could be a hydraulic cylinder or a motor-driven ball screw. The sensor might be pneumatic or electronic.
- The simplest such system relies on a pressure signal from an air-jet sensor to move the spool of a hydraulic valve which then controls the flow of fluid to a hydraulic cylinder.
- An attractive feature of a rank 1 controller is that it can have zero error at the guide sensor when correcting a static error in web position.
- Today, rank 0 controllers have become popular.

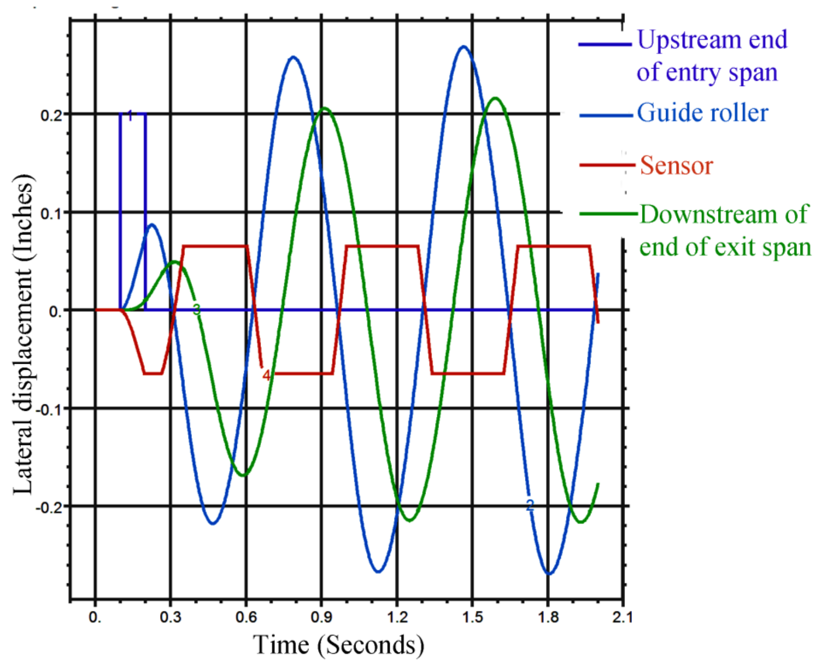
- A rank 0 controller forces the actuator position (rather than velocity) to be proportional to the error at the guide sensor.
- A rank 1 controller can be converted to a rank 0 controller by using a signal from a position sensor to close an internal control loop that converts the output from velocity to position.
- A rank 0 controller will not bring a static error to zero. There will always be a small residual error at the sensor.
- An advantage of a rank 0 controller is that it knows and controls the exact position of the guide roller at all times. This facilitates coordination of guiding system operation with operation of the process line.
- For customers who need zero static error, some vendors offer an integrating function similar to that found in PID controllers.

- As mentioned earlier, computer technology is now equal to the task of implementing adaptive control techniques which are capable of improving performance and stability across a wide range of operating conditions.
- Systems of this kind will likely be necessary to meet the high performance demands of roll-to-roll organic semiconductor manufacturing. This is currently a research focus at the OSU Web Handling Research Center.

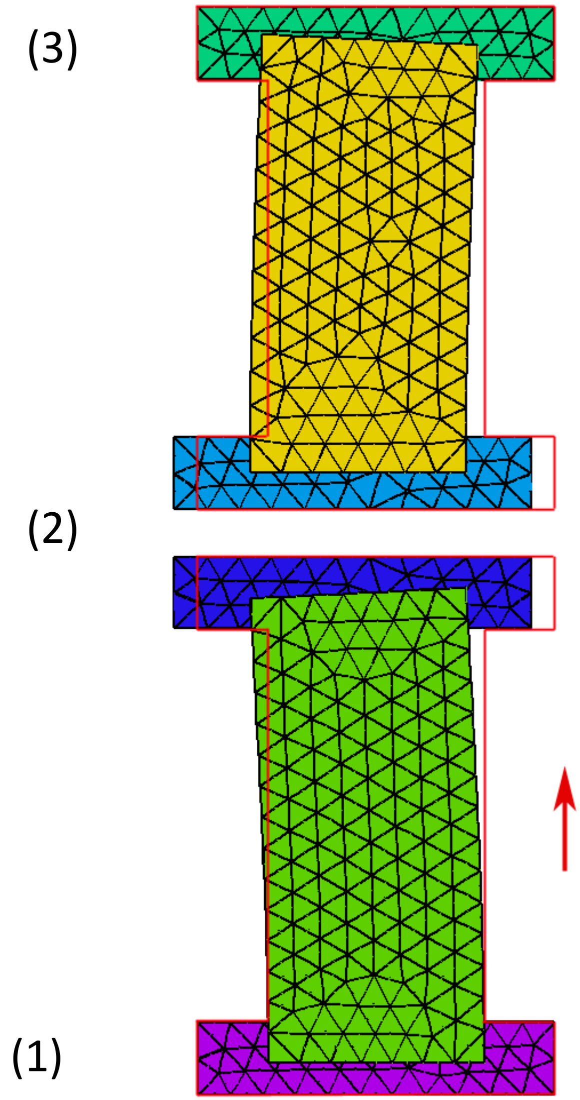
Shifting and pivoting

- Guiding systems have little tolerance for time lag. Vendors have two primary strategies for coping with it.
  - First, they keep the time lag as small as possible by locating the sensor close to the guide roller and they never put a fixed idler between the guide roller and the sensor.
  - Second, they design the guide mechanisms so that the roller shifts laterally as it pivots. The lateral shift provides immediate feedback that keeps the system stable.
- In an ideally designed application, the relationship between the lateral shifting and pivoting is such that a lateral shift pivots the roller to exactly the right position to maintain normal entry.
- This condition is usually satisfied by locating the instant center of the guide roller mechanism near the upstream roller with a radius of motion equal to 2/3 of the entering span length.

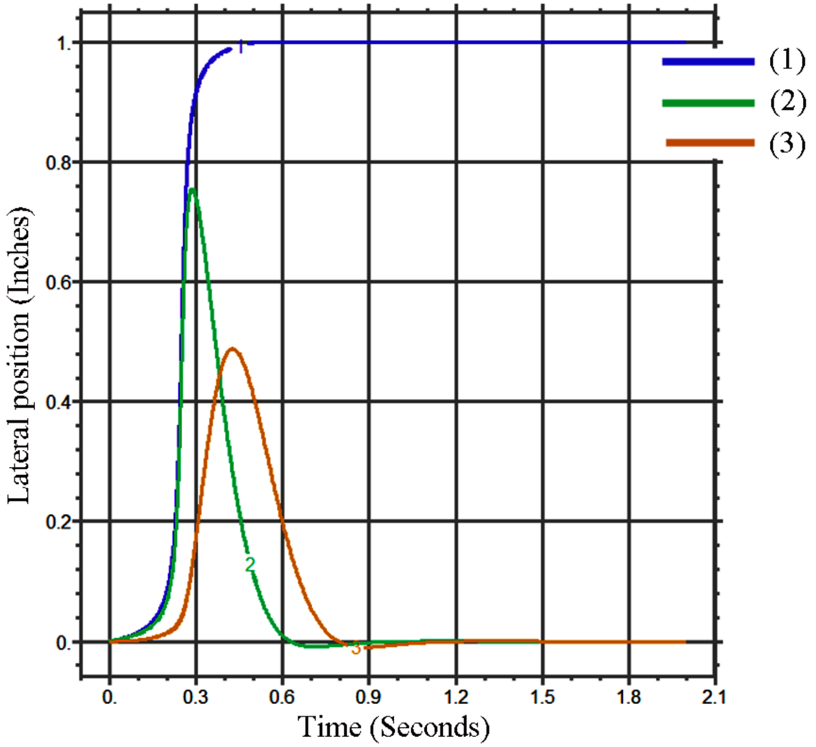


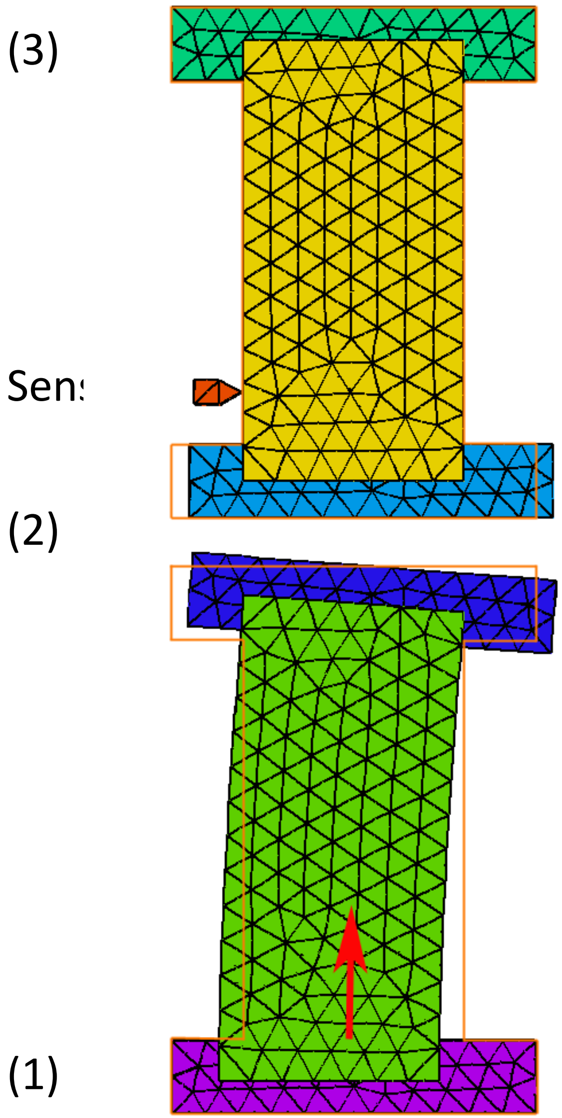


We are finally able to answer the question posed at the beginning. Why doesn't an end-pivoted guide work? The answer is that it only uses pivoting to move the web. That means that the only lateral motion is due to the normal entry effect and that comes with a time lag (phase shift) that is too big for system stability.

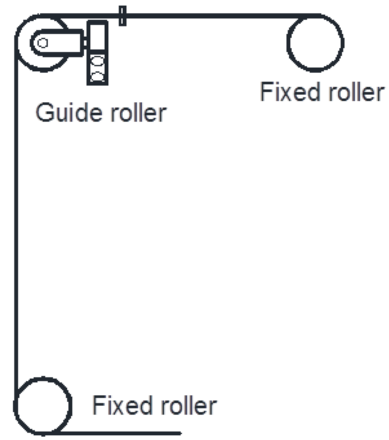


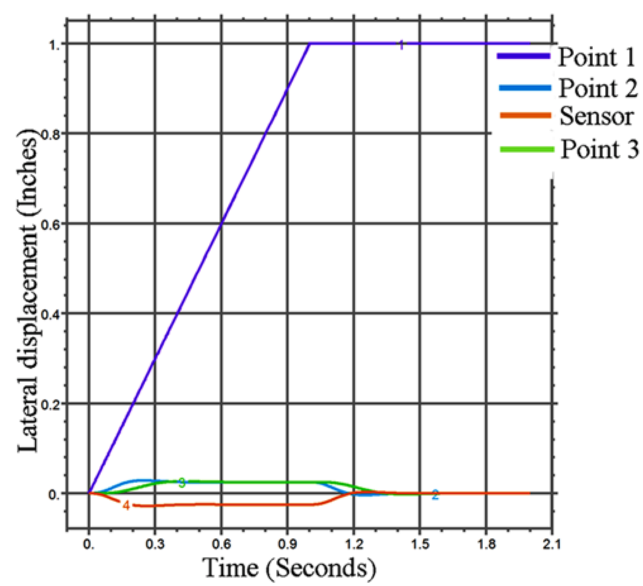
Here we see the result of shifting without pivoting. Shifting produces a quick shift in web position. That makes the control system momentarily happy. But, the normal entry effect brings the web back to its initial position.





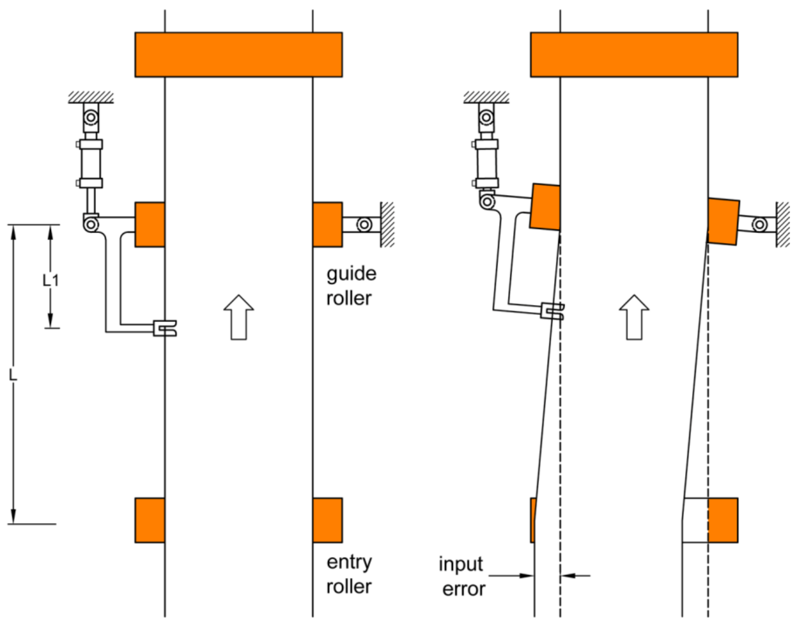
The best guides combine pivoting with shifting. A steering guide is the most common example.





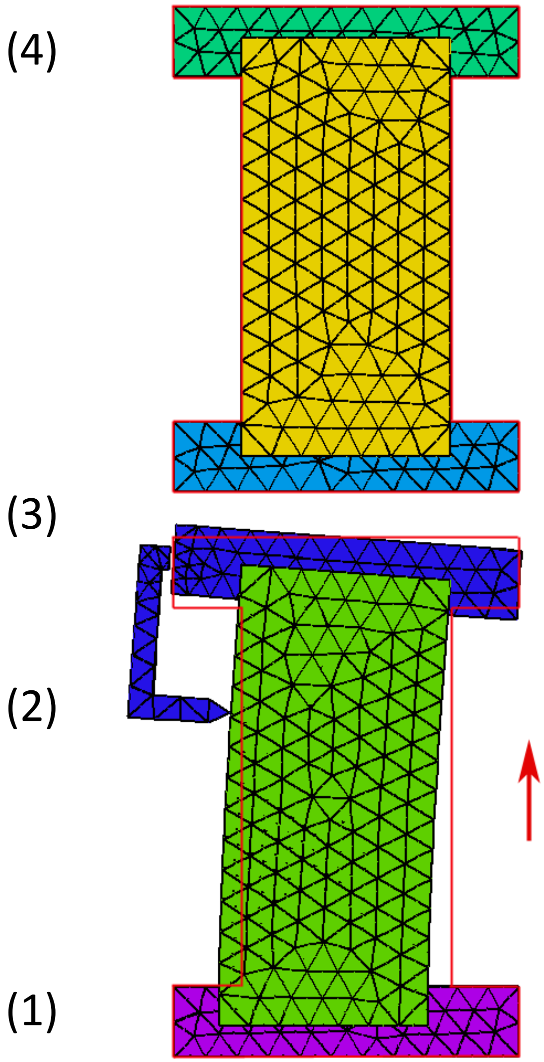
The idea of the 1967 memo

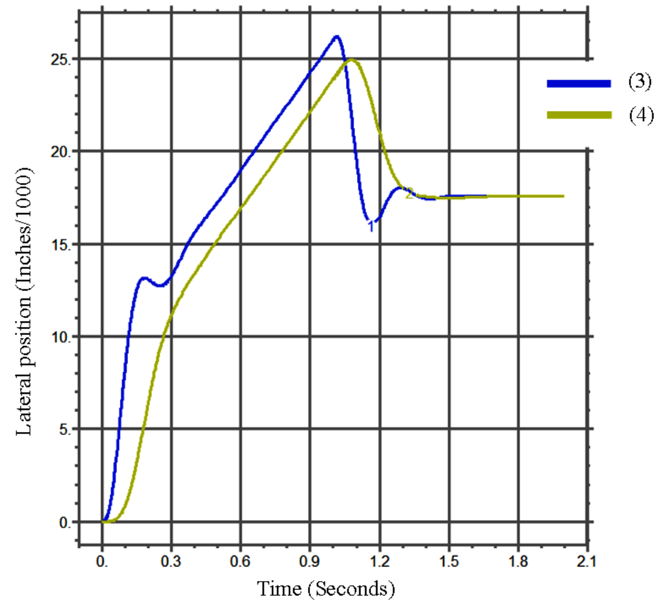
- The sensor is mounted on a bracket that pivots in the entry span with the guide roller.

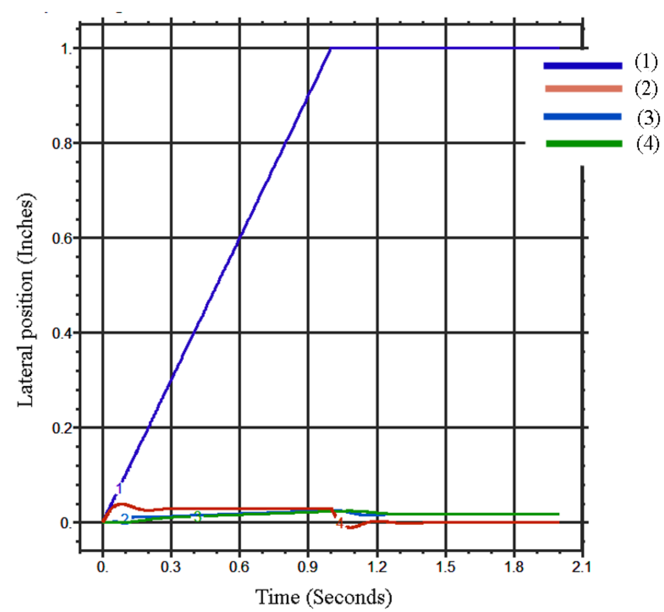


- When an error appears at the entry roller, the sensor sees part of it, causing the control system to tilt the roller until the until the error at the sensor is zero.
- The geometry of motion is such that the tilted axis of the roller will be normal to the new path of the web so that at the guide roller the web remains in its original position, unaffected by the upstream disturbance.
- This is completely different than the usual web guide. The web isn't being steered. It is the guide roller that is steered to keep the web from moving
- The need for immediate feedback to the controller is satisfied by the motion of the sensor. So, it's stable.

- Accuracy can never be as good as a conventional guiding system because there is no error feedback from the virtual guide point at the guide roller. But, there are many applications for which it is good enough.
- The memo mentioned that a small steady state error could be expected due to curvature of the web and that this could be minimized by keeping the sensor close to the guide roller. That’s true, but if L1 gets smaller than L/4, the system will be only marginally stable.
- Stability is best when the sensor is farthest from the guide roller, but that is where the curvature error is worst.
- A good compromise value for L1 is L/3. The next slide shows the results of a simulation.

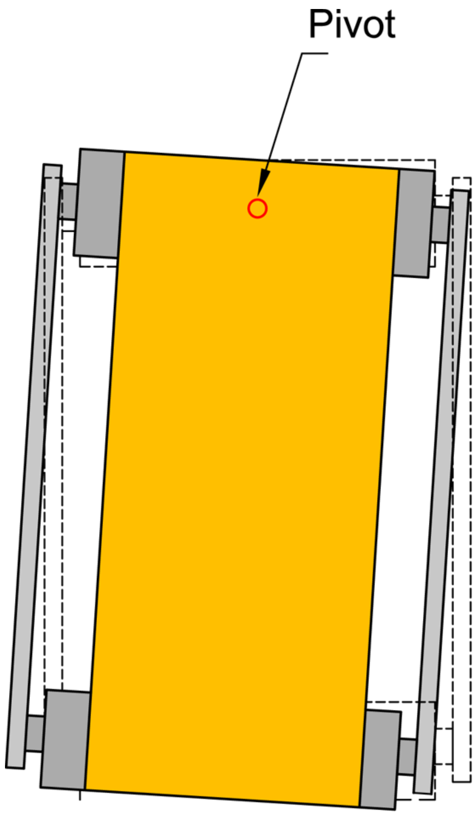

(4)
(3)
(2)
(1)

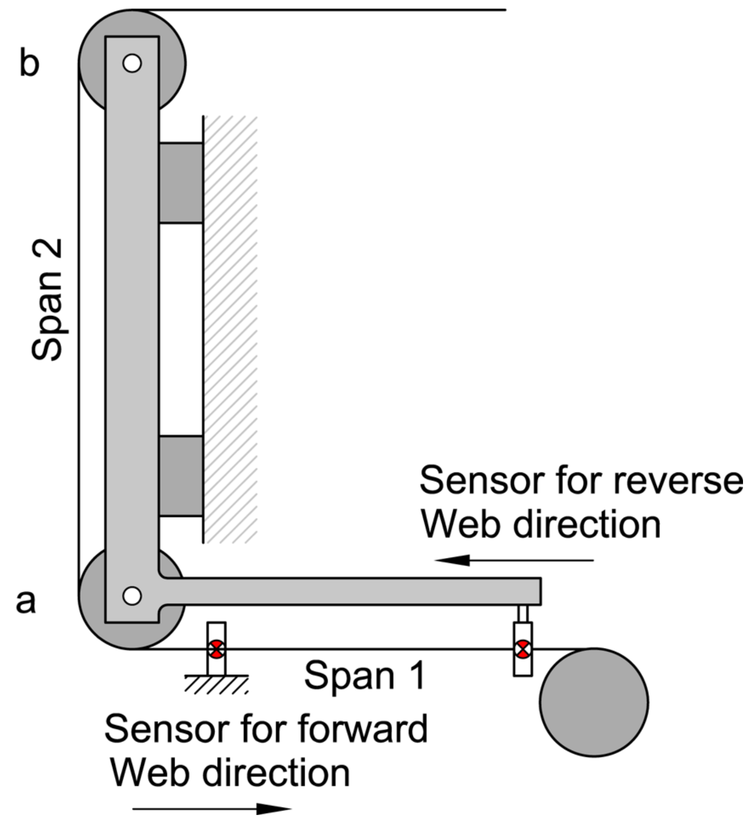

Lateral position (Inches/1000)
Time (Seconds)
(3)
(4)
0.
5.
10.
15.
20.
25.
0.
0.3
0.6
0.9
1.2
1.5
1.8
2.1


Lateral position (Inches)
Time (Seconds)
(1)
(2)
(3)
(4)
0.
0.2
0.4
0.6
0.8
1.
0.
0.3
0.6
0.9
1.2
1.5
1.8
2.1

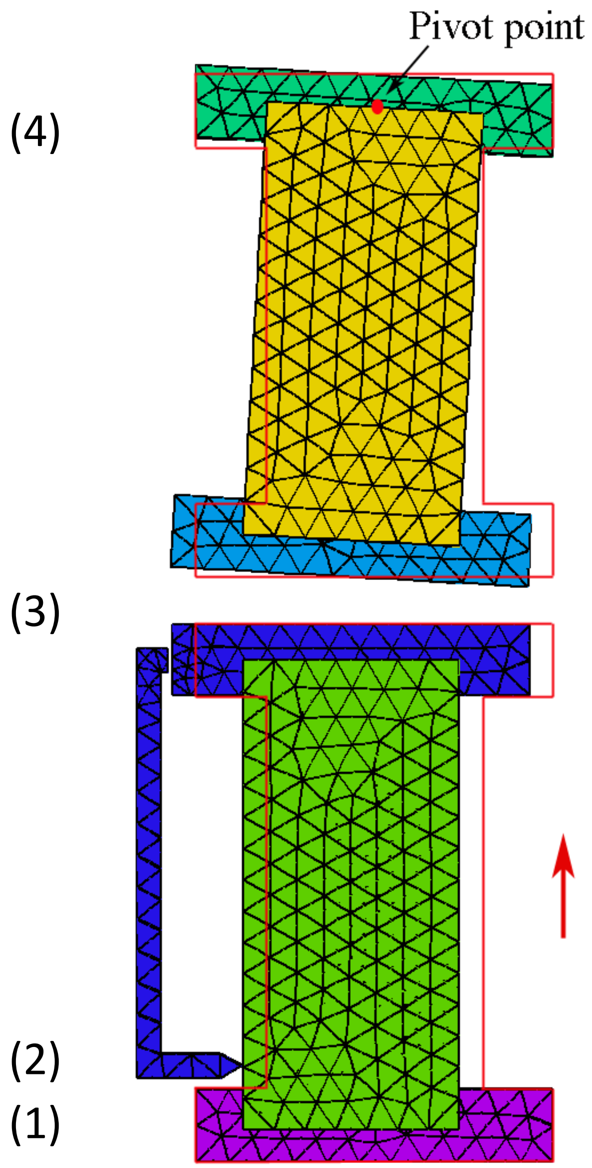
A related idea
The bi-directional guide

- The high speed winder at Oklahoma State University's Web Handling Research Center is designed to run in both directions. This presented a particular challenge for the intermediate web guiding systems.
- It's my understanding that John Shelton and Bruce Feiertag proposed the arrangement shown in the next slide. In the forward direction, it's a conventional displacement guide. In the reverse direction, it's like the end-pivoted guide of the previous section. It steers the guide rather than the web and it's stable because it satisfies the need for immediate feedback.
- It has a stability advantage over the end-pivoted design because of better web dynamics.
- Like the end-pivoted design, this guide lacks error feedback from the virtual guide point, but it does not have any error due to curvature and accuracy is adequate for the machine's purpose.





When running in the reverse direction, the guide operates to keep the web from moving laterally at roller (b) (the virtual guide point).



Roller (1) is fixed. Roller (3) pivots with roller (4) about the pivot point. Roller (4) is where the web is being held in position. Curve 1 is the incoming ramp error. Curve 4 is the error that remains at the exit of the guide. Curve (2) is the error input to the control system (sensor).